KOMUNIKÁCIE

COMMUNICATIONS

SCIENTIFIC LETTERS OF THE UNIVERSITY OF ŽILINA

Volume 25

UNIVERSITY OF ŽILINA

ISSN 1335-4205

1953 70 2023

1/2023

UNIVERSITY OF ŽILINA
EDIS-Publishing House
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GREY MODEL ANALYSIS OF VEHICLE POPULATION, ROAD TRANSPORT ENERGY CONSUMPTION AND VEHICULAR EMISSIONS

Nuhu Caleb Amulah[1,*], Ekwe Bassey Ekwe[2], Muhammad Idriss Ishaq[1], Fasiu Ajani Oluwole[1]

[1]Department of Mechanical Engineering, Faculty of Engineering, University of Maiduguri, Maiduguri, Nigeria
[2]Energy, Exergy and Environment Research Group (EEERG), Department of Mechanical Engineering, Michael Okpara University of Agriculture Umudike, Umuahia, Nigeria

*E-mail of corresponding author: amulahn@unimaid.edu.ng

Nuhu Caleb Amulah 0000-0003-0515-6357

Resume

This study employs the grey models to explore Nigeria's road transport energy consumption, vehicle population and vehicular emissions. The vehicular emissions were evaluated using the European Environment Agency Tier 1 Approach, based on the fuel consumption. A baseline scenario, based on historical data and three other alternative scenarios were developed. The study considered fuel quality, vehicle technology and survival rates as the key drivers of scenario formulation. Results show that vehicle population increases by about 3.58 % annually from 12.9 million units in 2018 to 38.5 million in 2050. Analysis of the alternative pathways reveals that their adoption would significantly reduce road transport energy consumption and air pollutant emissions.

Article info

Received 18 July 2022
Accepted 4 November 2022
Online 29 November 2022

Keywords:

road transport
energy consumption
air pollutant emissions
vehicle survival rate

Available online: https://doi.org/10.26552/com.C.2023.006

ISSN 1335-4205 (print version)
ISSN 2585-7878 (online version)

1 Introduction

The transport system forms an integral part of human activity; it necessitates mobility, enhances socio-economic interaction and contributes greatly to economic growth and development [1-2]. Nigeria's transportation sector in 2017 accounts for about 13 % of the total final energy consumption and about 92 % of the total final oil product consumption [3]. Of all the modes of transportation, road transport is the most commonly used in Nigeria [4] and it accounts for about 98 % of the total fossil fuel consumption in the transport sector [3]. The demand for energy in this sector is expected to rapidly increase due to many factors, including but not limited to an increase in population, urbanization and household income and the resulting increase in the number of vehicles and movement of people [5].

The challenges facing Nigeria's road transport system are twofold; on one hand, there is a poor infrastructure; on the other hand, there is a poor state of vehicle technology and fuel quality. Only about 27 % of the federal road network is in good condition, another 30 % is in fair condition and about 40 % is not in a condition fit for use [6]. Similar or worse can be said of the condition of state and local government roads. The infrastructural challenges are due to problems of design specifications and function below the required standards [7], lack of proper maintenance and non-continuity of projects by successive governments [8], as well as lack of equipment and funding for maintenance agencies [9]. The state of the vehicles plying the roads also poses a significant challenge. It is estimated that about 90 % of vehicles imported into the country have already been used somewhere [10] and these vehicles stay on the road for up to 40 years [11]. The fossil fuel and fossil fuel products used in Nigeria's vehicles contain approximately 100 times the sulphur level permissible in Europe [10]. In 2020, the ECOWAS[1] Commission

[1]The Economic Community of West African States (ECOWAS) is a 15-member regional organization whose principal purpose is to promote economic integration and shared development among the west African sub-regions. Benin, Burkina Faso, Cape Verde, Gambia, Ghana, Guinea, Guinea-Bissau, Ivory Coast, Liberia, Mali, Niger, Nigeria, Senegal, Sierra Leone and Togo make up its membership.

proposed a vehicle emission policy that seeks to limit fuel sulphur content to 50 ppm for both diesel and petrol[2] and also reduce the age of used vehicles imported to the region to 5 years for light vehicles and 10 years for heavy vehicles [12]. Critics of this policy posit that it will likely pose a significant economic challenge to the populace while having minimal environmental benefits [13-14]. More recently, in the first quarter of 2022, off-the-specification petroleum products were imported by the Nigerian National Petroleum Corporation (NNPC) and were widely distributed across the country[3]. The state of the quality of such fuels makes the implementation of vehicle emission standards very difficult. Despite the efforts by the Ministry of Transport to ban the importation of vehicles that have already been used for over 15 years, efforts to enforce this law are still lacking, mainly due to the porous state of the country's border, smuggling and corruption [10]. The state of the road transport sector makes it one of the key contributors to greenhouse gas (GHG) emissions and the resulting ambient air pollution.

The studies on Nigeria's transport sector cut across energy utilization, GHG emissions as well as vehicle ownership and its determinants. Badmus *et al.* [4] analyse the consumption of energy in the transportation sector using exergy methods by employing historical data of transport energy consumption from 1980 to 2010. They reported a 17.11 % overall mean energy efficiency and an overall mean exergy efficiency of 15.97 % for the period under study. The results further inferred that the importation of already used vehicles into the country has negatively affected the performance of the road subsector. Maduekwe *et al.* [11] used the Long-Range Energy Alternative Planning (LEAP) model to determine the best A-S-I (avoid, shift and improve) option for Lagos State by projecting future energy consumption and GHG emissions from vehicles in the road transport sector. They concluded that a 50 % emission reduction by 2032 is achievable if the age limit of vehicles and the growth in vehicle ownership are reduced from 40 years to 22 years and from 5 % to 2 %, respectively. Abam *et al.* [15] studied the Nigerian transport sector through decomposition and decoupling analysis using historical data from 1988 to 2019. The study, based on the Logarithmic Mean Divisa Index (LMDI) and the Tapio approach, estimated the overall impact of carbon emissions from the transport sector at 44.45 million tonnes of CO_2, which is about a 163 % increase in the overall country's carbon emissions during the period under study. Dioha and Kumar [5] considered five alternative policy pathways for the Nigerian transport sector based on fuel switching, improved fuel economy, modal shifting, improved logistics and carbon tax for the period 2010-2050 using the TIMES model. The results indicate that, compared to the reference scenario, the alternative pathways would lead to a considerable reduction in CO_2 emissions. Gujba *et al.*'s [16] study on passenger transportation in Nigeria, using life cycle assessment and economic costs highlights that the more environmentally and economically sustainable option is the promotion of the use of passenger transport (public bus). Although many of such studies reported on the road transport energy consumption, only a few studies discussed the effects of fuel quality and vehicle technology on the environment; and air pollutant emissions are often not considered.

On vehicle ownership, Ukonze *et al.* [17] mention a gross domestic product, per capita income, fuel price, literacy level and stock of public transport vehicles as the determinants of vehicle ownership in Nigeria. The extent to which these vehicles stay on the road depends on vehicle mileage [18], economy [19], as well as users' travel-behavioural attitudes [20]. Road transportation's impact on the environment can be greatly influenced by factors related to the vehicle population, such as fleet renewal rates, new technology penetration in the vehicle market, age-related emissions degradation and the significance of additional technological measures that apply to both new and used vehicles [21]. There is however, dearth of research in the lifespan distribution and survival rates of vehicles in Nigeria.

There are many techniques and approaches for analysing and projecting energy demand and GHG emissions ranging from the LEAP model [11, 22-23], TIMES model [5, 24], artificial neural network [25-26], as well as econometric approaches [25, 27]. However, most of these approaches require a lot of input. For instance, LEAP requires a lot of demographic and macroeconomic data, which is either not recorded in Nigeria or not publicly available. Of the models used in future projections, one fascinating model is the grey forecasting model, established in 1982 [28], which makes use of partially known information that describes an uncertain system to generate useful information. Since then, many variations of the model have been developed to improve its accuracy. The model has been used to investigate the CO_2 emissions in Asia-Pacific Economic Cooperation (APEC) member countries [29], to forecast route passenger demand in the air transport industry, to project natural gas consumption [30], to forecast municipal waste generation [31], to investigate biofuel production and consumption in top CO_2 emitting countries [32], to forecast electricity consumption [33-34] among many other applications in several fields. The model has found wide applications because of its simplicity, low data requirement and high prediction accuracy [35-36]. The grey system theory posits that a system whose information structure, functions and connections with its environment are partially known

[2]All imported fuels to the region must comply with this standard by January 2021, while local refinery production is to meet the standard by 2025.

[3]A lot of vehicles were affected by the distribution of these adulterated products. The article can be found at https://guardian.ng/features/motorists-lose-engines-pay-more-for-repairs-over-dirty-fuel-purchase/ [Last accessed 09 May 2022]

and partially unknown is called grey[4].

A good and well-functioning transport system provides an important framework for a country's growth and development. The growth in energy demand in the transport sector and its associated environmental effects, has prompted the shift towards the improvement of road transport infrastructure and network, as well as vehicle standards and this has been a key point on the policy agenda of many nations. Consequently, the interconnectivity between road transport energy consumption, vehicle population and vehicular emissions is complex and has so many determinants. There is, however, paucity of research that captures this relationship. Therefore, the objective of this study is to explore the development trend in vehicle population and energy demand in Nigeria's road transport, as well as the resulting GHG and air pollutant emissions from the sector. The study considers Nigeria's road transport sector as a "grey system". The grey forecasting model is employed to study the trend in these three dynamic complexities under four different scenarios. The baseline scenario is developed to reflect the country's historical trend in road transport energy consumption and vehicle population; the improved fuel scenario is designed to reflect improvement in fuel quality and vehicle technology according to Euro 3 Standards; the proposed ECOWAS scenario adopts some of the components of the proposed ECOWAS vehicle emissions regulation; and finally, the electric vehicle substitution scenario assumes the gradual substitution of fossil fuel-powered vehicles with electric vehicles in the future.

2 Methodology

In developing the models, both the first-order grey model in one variable (GM(1,1)) [28, 37] and a novel optimised grey model with quadratic polynomials term (BNGM(1,1,k²)) proposed by [38] were employed. The European Monitoring and Evaluation Programme/ European Environment Agency (EMEP/EEA) Tier 1 Approach[5] was used to calculate air pollutant emissions [39].

2.1 Model construction

I GM(1,1) model formation

The GM(1,1) model construction involves conversion of the sequence of raw data into a grey differential equation to create a time response function.

Let the sequence of raw data be denoted as

$$X^{(0)} = (x^{(0)}(i))_{i=1}^{n} = (x^{(0)}(1), x^{(0)}(2), x^{(0)}(3), \dots, x^{(0)}(n)), \tag{1}$$

where $X^{(0)}$ represents historical data sequence for energy consumption and vehicle registration.

Let the accumulated generated sequence be denoted as

$$X^{(1)} = (x^{(1)}(i))_{i=1}^{n} = (x^{(1)}(1), x^{(1)}(2), x^{(1)}(3), \dots, x^{(1)}(n)), \tag{2}$$

Then, the original form of the GM(1,1) model is given as

$$x^{(0)}(k) + ax^{(1)}(k) = b\,. \tag{3}$$

If the background value, $Z^{(1)} = (z^{(1)}(i))_{i=2}^{n} = (z^{(1)}(2), z^{(1)}(3), \dots, z^{(1)}(n))$ is the sequence generated from the adjacent neighbour means, i.e.,

$$z^{(1)}(k) = \frac{1}{2}(x^{(1)}(k) + x^{(1)}(k-1)), k = 2,3,\dots,n\,, \tag{4}$$

then the basic form of the GM(1,1) model is given as

$$x^{(0)}(k) + az^{(1)}(k) = b\,. \tag{5}$$

For a given sequence of raw data, the accumulated sequence and the sequence generated from the adjacent means, if $\hat{a} = (a,b)^T$ represents a sequence of parameters such that

$$Y = \begin{bmatrix} x^{(0)}(2) \\ x^{(0)}(3) \\ \vdots \\ x^{(0)}(n) \end{bmatrix}, X_N = \begin{bmatrix} -z^{(1)}(2) & 1 \\ -z^{(1)}(3) & 1 \\ \vdots & \vdots \\ -z^{(1)}(n) & 1 \end{bmatrix}, \tag{6}$$

using all the notations from Equation (3) and providing that $[a,b]^T = (B^T B)^{-1} B^T X_N$, then

$$\frac{dx^{(1)}}{dt} + ax^{(1)} = b \tag{7}$$

is called the whitenization or image equation of the GM(1,1) model.

Consequently, the solution of Equation (7) is given as

$$x^{(1)}(t) = \left(x^{(1)}(1) - \frac{b}{a}\right)e^{-at} + \frac{b}{a} \tag{8}$$

and the time response sequence of the GM(1,1) model is given as

$$\hat{x}^{(1)}(k+1) = \left(x^{(0)}(1) - \frac{b}{a}\right)e^{-ak} + \frac{b}{a}, \quad k = 1,2,\dots,n, \tag{9}$$

where $\hat{x}^{(1)}$ is the simulated accumulated value.

[4] "Black" is used to denote unknown or no information, and "white" is used to indicate that all the characteristic features of the system are known. "Grey" is between black and white.

[5] The Tier 2 approach (distance driven based) and Tier 3 approach (derived from experimental data) are more accurate, but they cannot be applied to Nigeria because of inconsistent statistical records and lack of data such as vehicle kilometre, mean speed of travel and specific vehicle technology.

The parameters a and b are the development coefficient and the grey action quantity, respectively. The development coefficient reflects the variation in the raw data and is paramount in the development of $\hat{x}$. Since GM(1,1) is a model developed on a single sequence, it uses only the behavioural sequence (referred to as output sequence or background values) of the system without considering any externally acting sequences (or referred to as input sequences, or driving quantities). Therefore, it is generally recommended that variables that affect the system of interest be external or predetermined. Proof of the development of this model can be found in [37, 40].

II BNGM(1,1,k²) model formation

The BNGM(1,1,k²) model, in which the background value is reconstructed based on the Simpson formula, was developed to increase the effectiveness and applications of the grey models. The general modelling procedure for this model is as follows:

The first step is to generate $X^{(1)}$ from $X^{(0)}$ as in Equations (1) and (2). The background value of the model is then calculated according to the Simpson formula

$$z^{(1)}(k) = \int_{k-1}^{k+1} x^{(1)}(t)dt = \frac{1}{6}[x^{(1)}(k-1) + \\ + 4x^{(1)} + x^{(1)}(k+1)], \quad k = 2,3,...,n\text{-}1. \tag{10}$$

The development coefficient and the grey quantity parameters are estimated as $[a_1, b_1, c_1, d_1]^T = (B_1^T B_1)^{-1} B_1^T Y_1$, where B_1 and Y_1 are as given in equation (11).

The model's time response sequence is then given by Equation (12). [38] provides proof of the development of this model.

III Error evaluation

The accuracy and effectiveness of the two models are assessed by comparing the values of their mean relative errors. The absolute relative error for each data entry in the sequence is given by Equation (13) and the mean relative error of prediction is given by Equation (14).

2.2 GHG and air pollutant emissions computation

Yearly road transport energy consumption data was entered into the EnergyPLAN simulation software to simulate CO_2 emissions[6] [41]. Air pollutant emissions (CO, NO_x and PM) are considered to be a function of energy consumption and fuel-specific emission factors. The EMEP/EEA Tier 1 Approach is applied to calculate for these emissions using Equation (15). The emission factors are given in Table 1.

$$E_i = \sum_j \left(\sum_m (FC_{j,m} \cdot EF_{i,j,m}) \right), \tag{15}$$

where: E_i = emission of pollutant i [g],
$EC_{j,m}$ = fuel consumption of vehicle category j using fuel m [kg],
$EF_{i,j,m}$ = fuel consumption-specific emission factor of pollutant i for vehicle category j and fuel m [g/kg].

The SO_2 emissions for each fuel type are calculated using the formula

$$E_{SO2,m} = 2 \cdot k_{s,m} \cdot FC_m, \tag{16}$$

where: $E_{SO_2,m}$ = emissions of SO_2 per fuel m [g],
$k_{s,m}$ = weight-related sulphur content in fuel of type m [g/g fuel],
FC_m = fuel consumption of fuel m [g].

2.3 Vehicle survivability

Oguchi and Fuse [42] provide an expression for the vehicle survival rate in Equation (17). However, the expression does not account for used imported vehicles and can only be applied to countries with a negligible number of used vehicle imports. For countries whose car market is highly dominated by the import of used vehicles (such as Nigeria), Held *et al.* [43] proposed a method to correct for the imports in definition of survival rates by Oguchi and Fuse [42], as shown in Equation (18).

[6]The EnergyPLAN assumes a CO_2 content of 74kg/GJ for both petrol and diesel. More on the tool can be found at https://www.energyplan.eu

$$B_1 = \begin{bmatrix} -\dfrac{x^{(1)}(1)+4x^{(1)}(2)+x^{(1)}(3)}{6} & \dfrac{13}{3} & 2 & 1 \\ -\dfrac{x^{(1)}(2)+4x^{(1)}(3)+x^{(1)}(4)}{6} & \dfrac{28}{3} & 3 & 1 \\ \vdots & \vdots & \vdots & \vdots \\ -\dfrac{x^{(1)}(n-2)+4x^{(1)}(n-1)+x^{(1)}(3)}{6} & \dfrac{3n^2-6n+4}{3} & n-1 & 1 \end{bmatrix}, Y_1 = \begin{bmatrix} \dfrac{x^{(0)}(2)+x^{(0)}(3)}{2} \\ \dfrac{x^{(0)}(3)+x^{(0)}(4)}{2} \\ \vdots \\ \dfrac{x^{(0)}(n-1)+x^{(0)}(n)}{2} \end{bmatrix} \tag{11}$$

$$\hat{x}^{(1)}(k) = \left(x^{(0)}(1)\frac{b_1+c_1+d_1}{a_1} + \frac{2b_1+c_1}{a_1^2} + \frac{2b_1}{a_1^2} \right) e^{-a_1(k-1)} + \frac{b_1}{a_1}k^2 + \left(\frac{c_1}{a_1} - \frac{2b_1}{a_1} \right) k + \frac{d_1}{a_1} - \frac{c_1}{a_1^2} + \frac{2b_1}{a_1^3} \tag{12}$$

$$\Delta_k = \frac{x^{(0)} - \hat{x}^{(0)}}{x^{(0)}} \tag{13}$$

$$\Delta = \frac{1}{n} \sum_{k=2}^{n} \Delta_k \tag{14}$$

***Table 1** Tier 1 Emission standards for air pollutants, [39]*

Vehicle Category	Fuel	CO (g/kg fuel)		NO_x (g/kg fuel)		PM (g/kg fuel)	
		Min.*	Max.[a]	Min.*	Max.[a]	Min.*	Max.[a]
Passenger Car	Petrol	49.0	269.5	4.48	29.89	0.02	0.04
	Diesel	2.05	8.19	11.20	13.88	0.80	2.64
Light Commercial Vehicle	Petrol	68.7	238.3	3.24	25.46	0.02	0.03
	Diesel	6.37	11.71	13.36	18.43	1.10	2.99
Heavy-Duty Vehicle	Diesel	2.20	15.00	28.34	38.29	0.61	1.57

*The minimum value of the emission factor, which corresponds to Euro 3 emission factors, was used for the improved fuel scenario.

[a]The maximum values were used for the baseline scenario where the vehicle technology and fuel standards were considered to be uncontrolled.

$$R_t(c) = \frac{N_t(c)}{RP_{t-c}}, \tag{17}$$

$$R_t(c) = \frac{N_t(c)}{RP_{t-c} + Imp_{t-c}^{used} - Exp_{t-c}^{used}}, \tag{18}$$

where c corresponds to the first (initial) registration, RP_{t-c} as the number of new car registrations at time $t - c$, Imp_{t-c}^{used} is the number of imported used cars that are in the stock of the observed country at time t and that have been registered for the first time (abroad) in the year $t - c$ and Exp_{t-c}^{used} is the number of exported used cars that have been registered in the observed country in the year $t - c$ but have been exported until year t.

Equation (18) requires data such as c, Imp_{t-c}^{used} and the number of vehicles in stock with their corresponding age distribution. The data obtained from the Federal Road Safety Corps (FRSC) does not include the age distribution of the registered vehicles. However, pwC Nigeria [44] estimated that about 11 %, 26 %,50 % and 13 % of vehicles in Nigeria are, respectively, within the age range of 0-5 years, 6-11 years, 12-18 years and 19+ years. Cervigni et al. [45] surveyed vehicle fleet characteristics and reported an average vehicle age of 14 years, 24 years and 16 years for private (passenger) cars, light commercial vehicles and large buses, respectively. Maduekwe et al. [11] also reported that vehicles in Nigeria stay on the road for close to 40 years. Based on these reports and reports on the road traffic accidents [46-47], we regressed vehicle survival rate based on data on vehicle registration from 1993 to 2020 and vehicle stock population from 2018 to 2020 using the exponential function in:

$$SR_{j,y} = b_0 e^{b1d}, \tag{19}$$

where $SR_{j,y}$ is the survival rate of a vehicle of category j in stock at the end of year y, b_0, b_1 are the estimated parameters and d is the age of the vehicle in Nigeria at the end of year y.

In using Equation (19), one takes into consideration the fact that the total population of vehicles at the end of year y is the summation of the previously registered vehicles that are still in the fleet, including the registered vehicles in year y. In that way, a survival rate profile was created for each vehicle classification (see Part C of the supporting information (SI)). A passenger car (PC) was estimated to last for about 25 years after its first registration in Nigeria, a light commercial vehicle (LCV) 30 years and a heavy-duty vehicle (HDV) 35 years.

2.4 Data sources

The energy consumption in the road transport sector from 1998 to 2017 was extracted from the IEA Energy Statistics records. Petrol fuel consumption increased from 3193 thousand tonnes of oil equivalent (ktoe) in 1998 to 12823 ktoe in 2017, a 301.6 % increase. Diesel fuel consumption grew by 50.8 % over the same period. The data is in a random vibrating sequence; for instance, diesel fuel consumption was 2198 ktoe in 1998, 519 ktoe in 2015 and 3314 ktoe in 2017. The data were adjusted to reflect data from later years (2016, 2017), which were thought to be more accurate and models were created using this adjusted data.

***Table 2** Transposition of the vehicle classification*

FRSC Data Classification	EMEP/EEA Classification	% Transposed
Private car	Passenger car	100
Commercial car	Light commercial vehicle	80
	Heavy-duty vehicle	20
Government	Passenger car	50
	Light commercial vehicle	25
	Heavy-duty vehicle	25

***Table 3** PE-S Emission factors*

Vehicle Category	Fuel	CO (g/kg fuel)	NO_x (g/kg fuel)	PM (g/kg fuel)
Passenger Car	Petrol	46.83	4.50	
	Diesel	1.99	11.24	
Light Commercial Vehicle	Petrol	65.66	3.26	0.69
	Diesel	6.19	13.40	0.94
Heavy-Duty Vehicle	Petrol	2.25	28.16	0.59

Vehicle registration data was obtained from the Federal Road Safety Corps (FRSC) [48]. The data is based on number plate production data from 1933 to 2020 and is categorized into private, commercial and government (Federal and state parastatals/ agencies/departments, as well as military and paramilitaries) vehicles. The data was transposed to meet the EMEP/EEA [39] vehicle classification as shown in Table 2.

2.5 Developing scenarios

Upon developing the model for prediction of the vehicle registration, energy consumption and the resulting GHG and air pollutant emissions, four scenarios are developed to study the long-term road transport energy demand and its corresponding effect on the environment. The drivers for the scenarios' development are improved fuels and vehicle technology. All projections for the road transport fuel consumption and vehicle population are based on historical data. Although the economic situations, such as changes in household income, as well as the population, could result in a change in vehicle population and the resulting change in energy demand [17, 49], the study assumes that this change would continue as reflected in the historical data.

I Baseline scenario (B-S)

In this scenario, it is expected that there would be no change in the trend of the road transport energy demand, vehicle technology and quality of fuel. The scenario assumes that there is no regulation on the age of vehicles being imported into the country and that the sulphur content for petrol and diesel is set at 1000 ppm and 3000 ppm, respectively.

II Improved fuel scenario (IF-S)

The scenario assumes that by the year 2025, there will be an improvement in the fuel quality and vehicle technology, according to Euro 3 standards (see Table 1 for the emission factors used). The sulphur content for diesel and petrol for this scenario is set at 300 ppm and 130 ppm, respectively.

III Proposed ECOWAS scenario (PE-S)

This scenario adopts some of the components of the proposed ECOWAS vehicle emission regulation. The components of the regulations are:

a) Imported vehicles (used and new) will conform to EURO 4/IV vehicle emission standards;
b) improved vehicle technology and fuel efficiency;
c) fuel sulphur standard of 50 ppm for both diesel and petrol.

The emission factors used for this scenario were corrected to account for improved fuel properties based on Equation (20).

$$EF_{i,k,m,PE-S} = \frac{F_{C,i,k,PE-s}}{F_{C,i,k,base}} \cdot EF_{i,k,m,base}\,, \tag{20}$$

where: $EF_{i,k,m,PE-S}$ = fuel consumption-specific emission factor of pollutant i for vehicle category k and fuel m used for PE-S [g/kg],
$F_{C,i,k,PE-s}$ = the PE-S fuel standard correction for pollutant i, vehicle category k, determined from the equations in Table B2 of the SI using improved fuel properties in Table B1 of the SI,
$F_{C,i,k,base}$ = the base fuel correction for pollutant i, determined from the equations in Table B2 using base fuel properties (for IF-S) in Table B1,
$EF_{i,k,m,base}$ = fuel consumption-specific emission factor of pollutant i for vehicle category k and fuel m used for IF-S[g/kg].

The result of the emission factor obtained from Equation (20) is tabulated in Table 3.

IV Electric vehicle substitution scenario (EVS-S)

This scenario assumes that there is a gradual technological switch to electric vehicles (EVs). Due to the impracticability of phasing out the use of fossil fuel-powered cars in the near future[7], the scenario assumes a geometric increase in electric vehicle acceptability beginning at 40,000 units in 2025 until they make up about 24 % of the total passenger car population over a 25-year period. Fuel sulphur standards for PE-S are adopted in this scenario.

[7]The Nigerian Senate rejected a bill seeking to adopt the use of electric vehicles and phase out fossil fuel-powered vehicles by 2035, citing economic challenges as one of the threats to the bill. More information is available at https://www.vanguardngr.com/2019/04/breaking-senate-rejects-bill-to-phase-out-petrol-cars-adopt-electric-ones/amp/ [Last accessed 11 May 2022].

3 Results and discussion

3.1 Model development and prediction

The development coefficients and the grey action quantity for the two grey models are tabulated in Table A1 of the SI. The GM(1,1) and BNGM(1,1, k^2) simulation results based on historical data are shown in Tables A2-A6 of the SI. Petrol and diesel fuel energy consumption, respectively, have an average simulation error of 3.69 % and 1.65 % for the GM(1,1) model and 2.09 % and 0.67 % for the BNGM(1,1,k^2) model. The BNGM(1,1, k^2) model is thus adopted to predict future energy consumption. Vehicle registration simulation results show an average simulation error of 34.47 %, 19.43 % and 18.51 % for PC, LCV and HDV, respectively. The BNGM(1,1, k^2) model likewise has an error of 39.46 %, 25.31 % and 24.63 %. The GM(1,1) was slightly adjusted to reduce the error and is being adopted to forecast future vehicle registration.

Predictions of petrol and diesel energy consumption and cumulative vehicle population are shown in Figure 1. The demand for petrol increases gradually from 14800.09 ktoe in 2020 to 30097.49 ktoe in 2050 for B-S, IF-S and PE-S, but decreases to 24979.24 ktoe in 2050 for EVS-S. Diesel fuel increases by about 1.80 % annually for B-S, IF-S and PE-S and increases by 1.47 % per year for EVS-S. In the process of projecting the vehicle population, we used the predicted vehicle survival rates and the vehicle registration projection for each year. The vehicle population prediction resulting from the model shows an annual increase of 3.58 % from 12.9 million units in 2018 to 38.5 million in 2050, with PC, LCV and HDV representing about 69.09 %, 24.03 % and 6.88 % of the total population, respectively.

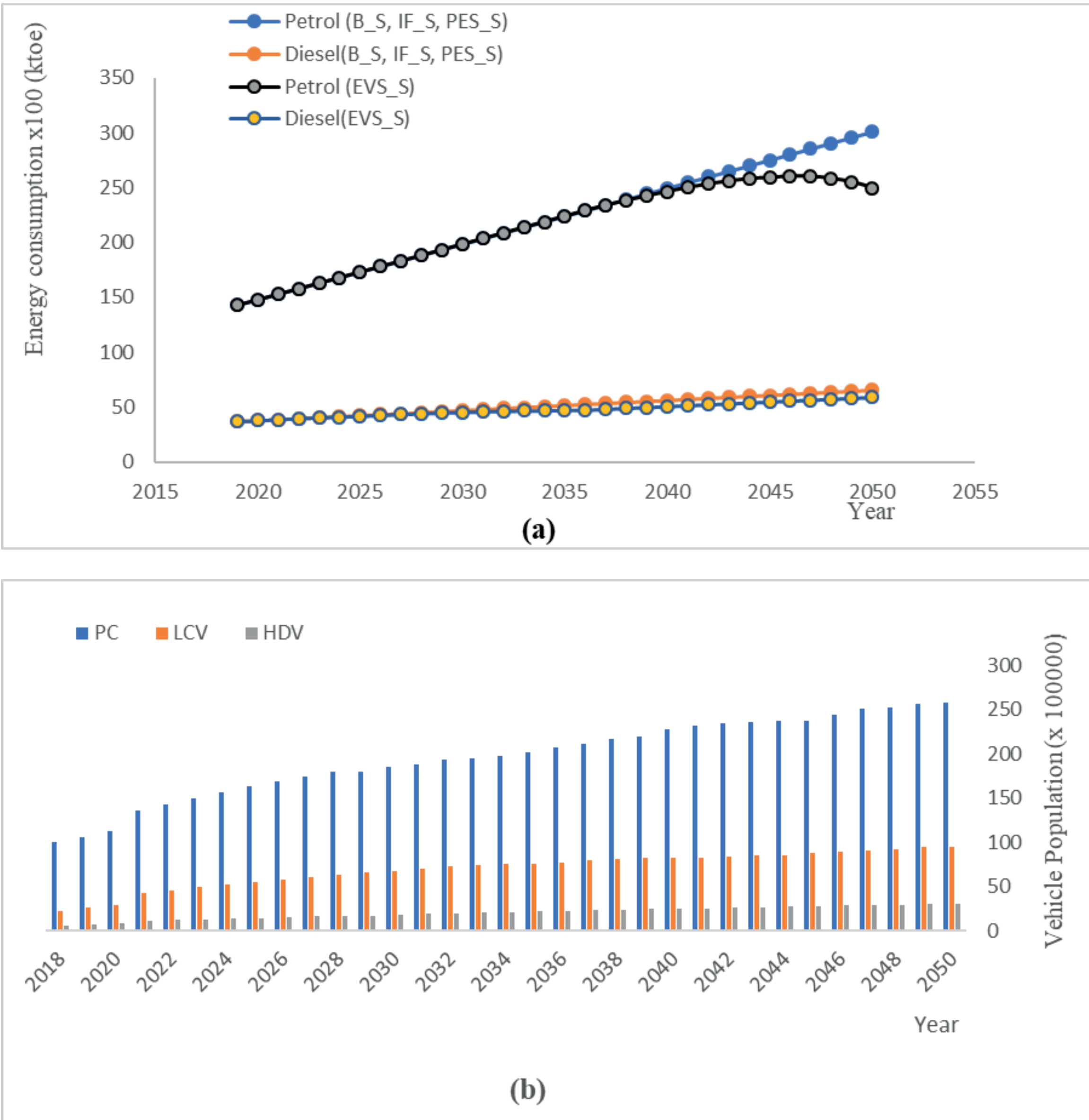

Figure 1 ***(a)*** *Projection of the road transport energy consumption through 2050.* ***(b)*** *Vehicle population forecast through 2050*

3.2 Comparing scenarios

I Energy consumption and vehicle population

The energy demand in all the scenarios, except for the EVS-S, is the same. It is assessed that introducing electric vehicles to the vehicle fleet will reduce the demand for petrol and diesel in the road transportation. Electric vehicles are expected to replace fossil fuel-powered passenger cars starting from 40, 000 units in 2025 to about 6.3 million in 2050 making about 24.22 % of the total passenger cars. The net reduction in energy consumption, obtained by subtracting EVS-S energy consumption from the energy B-S energy consumption for each year, is shown in Figure 2. By implementing EVS-S, there will be a 10.00 % and 17.00 % decrease in petrol and diesel consumption respectively as compared to other scenarios.

II CO_2 emissions

The CO_2 emission calculation is based on the total fuel consumption and as such, the emissions for all the scenarios are the same, except for the EVS-S, where there is a reduction in fuel consumption due to the introduction of EVs. The CO_2 emissions, ensuing from the implementation of each scenario, are shown in Figure 3. The emissions for EVS-S start to decline in 2025 when EVs are introduced, whereas they increase 2.32 % annually until they reach 113.545 Mtoe in 2050 for the other scenarios.

III Air pollutants

The air pollutants emissions, covered in this study, include CO, NO_x, SO_2 and PM[8]. Air pollutants emission

[8]The emission of PM in vehicle exhaust usually falls in the size range of $PM_{2.5}$. Therefore, we refer to $PM_{2.5}$ as PM throughout this paper.

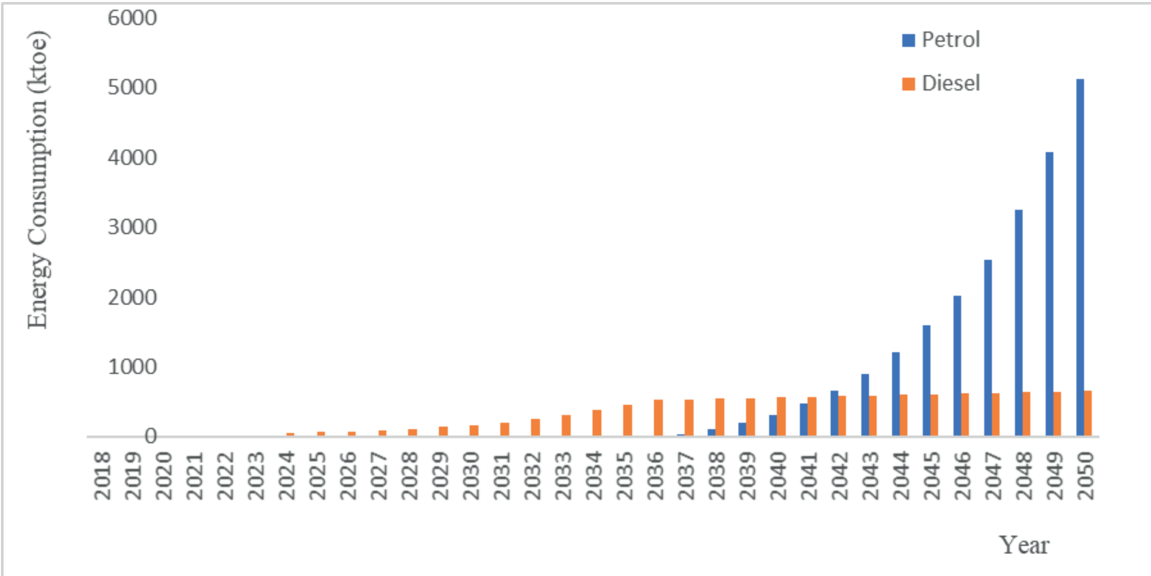

Figure 2 *Net reduction in energy consumption by implementing EVS-S*

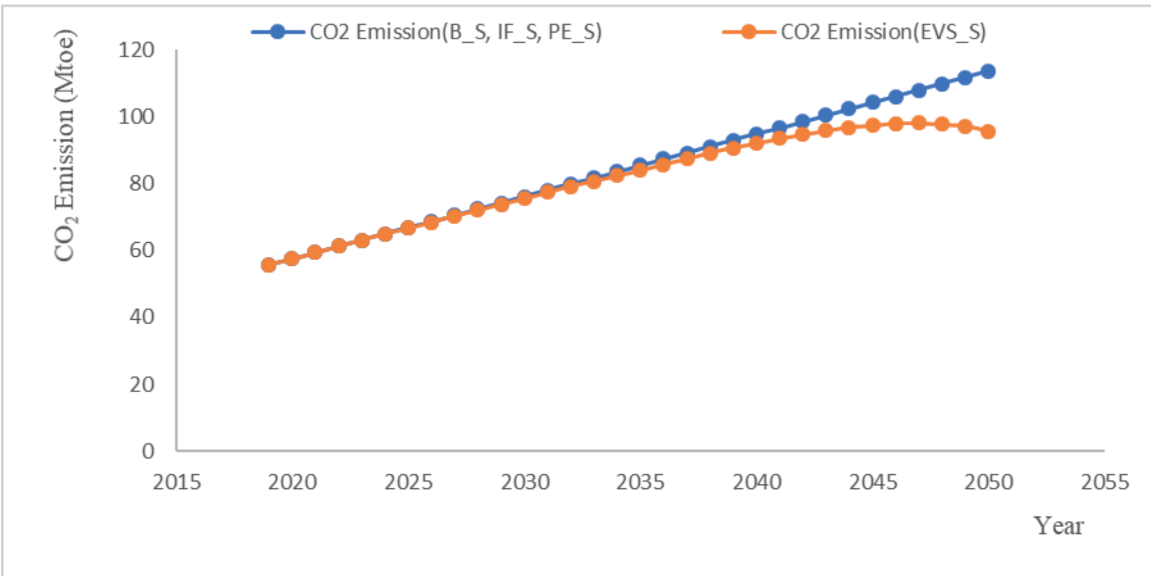

Figure 3 *The CO_2 emission projections through 2050*

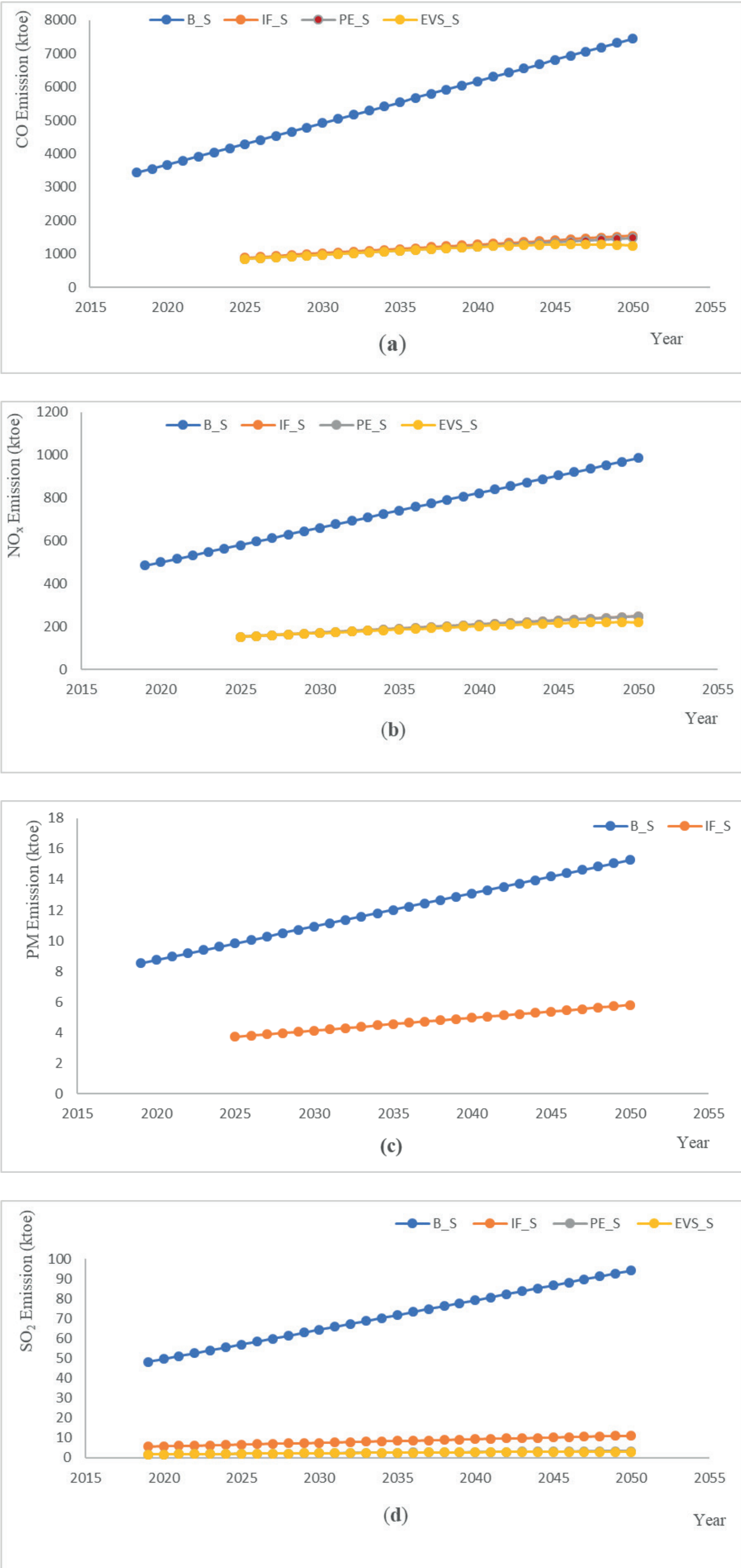

***Figure 4** Scenario projections of air pollutants. (**a**) CO, (**b**) NO_x, (**c**) PM and (**d**) SO_2*

projections for the scenarios are shown in Figure 4. The rise in air pollutant emissions for the baseline is due to uncontrolled fuel standards and vehicle technology in the country. The key premise of the other scenarios is an improvement in the quality of fuel. This is particularly shown in the striking reduction of air pollutant emissions in the other scenarios as compared to the baseline. While there seem to be commonalities between the three other scenarios, there is, however, a substantial difference between them. The CO emissions for B-S continue to increase from 3434.84 ktoe in 2018 to about 7443.39 ktoe in 2050 (216.70 % increase). It rises from 888.68 ktoe, 849.82 ktoe and 849.70 ktoe in 2025 to 1541.19 ktoe, 1473.70 ktoe and 1248.44 ktoe in 2050 for the IF-S, PE-S and EVS-S, respectively. NO_x emissions increase by 2.32 % per year from 2018 to 2025 for B-S and by 1.97 %, 197 % and 1.50 % for IF-S, PE-S and EVS-S, respectively. Total PM emissions were calculated for B-S and IF-S only. The result is shown in Figure 4(c). The SO_2 emissions in 2050 are 94.24 ktoe, 11.11 ktoe, 3.45 ktoe and 2.90 ktoe, respectively for B-S, IF-S, PE-S and EVS-S. The reduction in the amount of SO_2 emitted, as compared to the baseline, is due to an improvement in the sulphur content of fuels. A comparison of emissions, based on the fuel type, is given in Part D of the SI.

4 Concluding remarks

In this paper, the grey model and the EMEP/EEA Tier 1 approach were used to predict energy consumption, vehicle population and the resultant environmental effects of the road transportation in Nigeria. While there are more accurate approaches to evaluating the road transport emissions, implementation of such approaches requires additional data about vehicular activities. The available statistical data for Nigeria does not allow for the use of such approaches. All the projections were based on historical data. The vehicle population in 2050 is projected at 38.5 million, which is about 94 cars per 1000 people[9], as compared to 60 in 2018 [50]. Energy consumption is expected to increase to about 30097.49 ktoe for petrol and 6550.96 ktoe for diesel for the same year.

The baseline scenario's projected road transport CO_2 emissions in 2050 are 113.545 Mtoe. This compares to the United Kingdom's 2018 value (113.20 Mtoe) [51]. Although Nigeria emits less than 1 % of the global emissions, an increase in economic activity and standard of living beyond the historical trend will result in higher emissions. The baseline scenario assumes that vehicle technology in the country is uncontrolled and older vehicles are imported into the country leading to higher emission factors. There have been policies to curtail the import of these older vehicles. For instance, in 1993, Nigeria formulated a policy known as the Nigerian National Automotive Act to ensure the growth and development of the automotive industry using locally available materials [52]. In 2014, Nigeria announced the introduction of a new automotive policy, which was geared towards the same aim of discouraging the importation of automobiles and encouraging local manufacturing. The policy was intended to provide subsidies for the production and assembly of automobiles by local assembly plants and raise import duties on fully assembled cars from 10 percent to 35 percent [53]. However, several years later, this policy failed to achieve the desired outcome. Such a commitment towards the policy implementation may constitute a major impediment to adoption and reception of better measures and policies. On another level are the SO_2 emissions of the baseline scenario. Because of the higher level of sulphur in the fuel used in this scenario, the SO_2 emission stands at 94.24 ktoe in 2050, which is about 5.4 times the combined SO_2 emission for 3 other scenarios.

The improved fuel scenario records a CO_2 emission of 113.55 Mtoe and reduced SO_2 emission of 11.11 ktoe, a difference of 87.58 % from the baseline scenario. If the proposed ECOWAS Scenario is implemented by the adoption of EURO 4/IV vehicle emission standards, SO_2 emission will be reduced to 3.45 ktoe in 2050. In addition, if the fossil fuel-powered vehicles are gradually replaced by the EVs, the SO_2 emission would further drop to 2.90 ktoe.

Results from this study provide an insight into the growth pattern of the vehicle population, energy consumption and the resulting emissions. Several policy measures for curbing transportation emissions are country-specific due to differences in technology and transportation infrastructure. However, with the country's current transportation infrastructure, the adoption of the scenarios outlined herein is feasible. For instance, there should be strict adherence to the importation of vehicles (used and new) in conformity with EURO 4/IV vehicle emission standards. A vehicle emission policy to limit the fuel sulphur content to 50 ppm for both diesel and petrol, as well as limiting the age of used vehicles imported into the country to no more than 10 and 15 years, respectively, for the light and heavy-duty vehicles, can as well be adopted. The latter will come with current and improved vehicle technologies and fuel efficiency. An evaluation of these alternative scenarios reveals that there are several benefits to their adoption and subsequent implementation. Since the environmental effects of these emissions are an "all-affected" phenomenon, there is a need for an "all-inclusive" approach to tackle this challenge. The study provides decision-makers with a lens to frame the challenges of road transport and to set robust policies in the long run. The government should

[9]Nigeria's population in 2018 was 198 million and is projected by the United Nations, Department of Economic and Social Affairs, Population Division to reach 411 million in 2050.

not only stop at formulating policies but go through with their implementations, encouraging community compliance and participation and stakeholders' support.

As noted previously, the study's central hypothesis is that the current and projected patterns in vehicle population and energy consumption are, in proportion, reproducing prior historical trends and that there is not enough information to employ a more precise method of evaluating emissions. There may, however, be fundamental divergences in the future. For instance, higher Tier techniques, particularly Tier 3, should be explored if the precise data like vehicle age distribution, vehicle kilometres and mean travelling speed available per mode and vehicle technology are known.

Supplementary information

The paper includes the following supplementary resources, which may be available online at https://doi.org/10.5281/zenodo.6951467

Supporting information (SI)

Provides additional information to the paper.

Supplementary data

Excel sheets that contain data used for the analysis.

Acknowledgement

The Vehicle Administration Department of the Federal Road Safety Corps, Nigeria provided the statistical information on vehicle registration, for which the authors are grateful.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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MEASURES TO IMPROVE THE OPERATION OF PASSENGER TRANSPORT AND URBAN MOBILITY

Denis Kapski*, Sergey Semtchenkov, Liudmila Khmelnitskaya

Automotive and Tractor Faculty, Belarusian National Technical University, Minsk, Republic of Belarus

*E-mail of corresponding author: millakhmelnitskaya@gmail.com

Denis Kapski 0000-0001-9300-3857, Sergey Semtchenkov 0000-0001-7943-2938,
Liudmila Khmelnitskaya 0000-0002-0400-5453

Resume

The article discusses the types of urban electric transport used in Belarusian cities, gives a detailed classification and comparison of available vehicles. Various options for increasing the share of environmentally friendly transport through the use of electric buses and trolleybuses are considered, an assessment and a comparative analysis of the options are given. Features of the drivers' work planning and drawing up of the schedule taking into account safety requirements are considered.

A methodology for assessing the efficiency of urban passenger transport has been developed, taking into account the development of electric vehicles.

Article info

Received 18 September 2022
Accepted 6 November 2022
Online 5 December 2022

Keywords:

urban electric transport
electric bus
hybrid bus
charging electric buses
safety
schedule
workplan

Available online: https://doi.org/10.26552/com.C.2023.007

ISSN 1335-4205 (print version)
ISSN 2585-7878 (online version)

1 Introduction

The creation of a favourable urban space for life and work is impossible without a developed system of route passenger transport, which is a clear and well-coordinated mechanism that combines various types of transport and offers a decent and effective alternative to personal cars. It is known that the share of private car owners depends on a number of factors: cultural, economic, social. The growth of motorization, the increase in the number of privately owned cars, is a challenge to the route of passenger transport, which must respond to it with a systematic approach and rational organization of work, responding in a timely manner to the changing situation.

In the conditions of a vague response to a changing situation, a certain kind of "vicious circle" arises, when the growth of motorization, in the conditions of the existing street network leads to its overload, which inevitably leads to deterioration of conditions for the movement of route vehicles, reduces the speed of route vehicles movement, worsens the quality of passenger transportation services, which, in turn, leads to the loss of passengers of fixed-route passenger transport, further reducing the number of route vehicles on routes (there is a superficial impression that the existing regular route is not needed, since fixed-route vehicles are not sufficiently filled, etc.), which further removes passengers from the fixed-route passenger transport and determines their choice in favour of personal, which again leads to an increase in motorization and so this circle "closes", aggravating the problems of cities.

In the current situation, it is necessary to take all possible measures and use any available means to break the "vicious circle" and improve the organization of the work of route passenger transport in cities. The concept of sustainable mobility has become highly relevant today. It is worth noting that in this regard, the concept of "mobility" is used in combination with the concept of "sustainability". This suggests that it is no longer enough for people to simply move from one point to another. This movement must meet a number of requirements, such as convenience, accessibility, speed, safety, reliability, environmental friendliness (the corresponding CO_2 emissions per passenger-kilometer are always lower for public transport compared to cars). Moreover, these requirements must be met constantly in time and not be of a one-time or episodic nature. Therefore, the issues of improving the transport services and choosing the type of transport are relevant for many cities. At the same time, it is necessary to take into account the capabilities of vehicle manufacturers, national specifics and legislation, the physical and financial capabilities of cities for transformation, restrictions, the level of return on investment, the tendency to build the green transport systems.

The studies were conducted in 2017-2018 based on the information available at that time and, in many positions, they have not lost their relevance at the time of publication. Experimental and computational-theoretical studies were carried out, in the direction to improve the work of route passenger (urban) transport of cities (on the example of Polotsk and Novopolotsk). An assessment is made of the possibility of achieving planned indicators for reducing the greenhouse gas emissions from implementation of the pilot project measures aimed at improving the quality and efficiency of the route passenger transport in these cities. A comparative analysis of the possibility of developing various types of electric route passenger transport is carried out. A map has been developed for reducing emissions of pollutants from vehicles with a change in the structure of mobility of the population and an increase in the share of use of route passenger transport, an increase in the speed of movement of route passenger transport. These studies of authors allowed us to formulate a concept and propose specific comprehensive measures aimed at improving the quality and efficiency of the route passenger transport in Polotsk and Novopolotsk, including optimizing the existing route network of route passenger transport. A business model has been developed for implementation of the standard measures, aimed at improving the quality and efficiency of the route passenger transport, a set of measures has been proposed to increase the attractiveness and efficiency of urban passenger transport.

Turning to world research on these issues, it is worth noting that the importance of the issue of efficiency and the methodology of constructing a synthetic model for estimating the operating costs of the operation of route passenger transport are considered in [1]. The study [2] builds a model based on which the efficiency of Norwegian bus companies is evaluated. The paper [3] emphasizes that efficiency of a transport system depends on used technology, strategies and policies, planning process etc. The abundance of bibliographic references in [3] indicates the importance of this issue and attention paid to it in many countries of the world too. Researchers pay great attention to planning of the route network, the development of the timetable. Paper [4] presents a new approach to generating run-time values that is based on analytical development and micro simulations. This works based on the retroanalysis and selection of atypical trips using statistical and modelling methods. Similar approaches are reflected in the study where an optimization model, based on minimizing the operational and user costs of the system, is proposed [5]. An interesting approach is considered in the study [6], which notes the importance of a differentiated approach to peak and off-peak time. It is also noted that optimal bus passenger capacity lies in-between the capacities obtained when each period is independently optimized. This once again confirms that the research topics of Belarusian and world scientists are directed in the relevant direction.

It is worth noting that much attention is currently being paid to the issues of electric transport for passenger transportation by the research of well-known scientists. Gnap, Dockalik and Dydkowski in paper [7] say that the setting of minimum targets for EU member states to procure green vehicles within two reference periods ending in 2025 and 2030, should help to promote mobility with low, respectively zero emissions. Research results will find it very difficult to meet the set minimum targets for the share of ecological buses in the total number of buses, included in the sum of all contracts subject to EU Directive 2019/1161 concluded from 2 August 2021. The authors note that the crisis caused by the COVID-19 pandemic, which has and continues to affect bus demand across Europe, may have a significant impact on meeting the minimum targets, especially by the end of the first reference period. The methodology for assessing the economic efficiency of vehicles for the transportation of passengers with electric drive is developed and described in [8]. The paper presents possible models of electric buses purchase financing, taking into account that the purchase prices are higher now than for the case of traditional buses, it also allowed to include issues related to applicability and implications of formulated solutions for managerial practice. In t [9] authors present the possible solutions of daily circulations in terms of the transport ensuring the daily performance of vehicles and staffing. It appears that the analysis of the transport solution is the first step to determine the successful optimal solution of the transport performance volume. Authors of [10] present the methods of operational analysis and especially methods for solving the optimization problems, which were used in the draft of a novel system of lines of public bus transport in the city of Ceske Budejovice that showed benefits of the solutions for transport practice and scientific knowledge.

2 Methodology

The research was initiated in the form of studying the proposed technical solutions in the field of route passenger transport, affecting the issues of infrastructure and vehicles, their technical equipment. Methodologically, research is divided into three related groups: vehicles and technical issue, route network and organization of transportation.

2.1 Vehicles and technical issue

Currently, the Republic of Belarus has established its own production of trams, trolleybuses, trolleybuses-electric buses and electric buses. Various types of urban electric transport are known and widely used in world practice:

1. Tram is the oldest type of electric transport vehicles, which move on the track.
2. Trolleybus is a type of electric transport vehicles, which move on roads and are driven by electric motors that receive electrical energy from the laid contact wires. Trolleybuses, in the classic and known to the consumer representation, are vehicles with feeding in motion - IMF (in-Motion-Feeding). If, to obtain electricity on some parts of the route, contact network and autonomous on-board energy source are not used, such trolleybuses can be considered as trolleybuses-electric buses with dynamic charging - IMC (in-Motion-Charging).
3. Hybrid bus is a type of transport whose vehicles move on roads and are driven by the combined work of an internal combustion engine and an electric motor.
4. Electric bus - it is a type of electric transport, vehicles of which move on roads, driven by electric motors, which receive electric energy from an autonomous onboard source (charging of the onboard source occurs during the stay of an electric bus at special charging stations and requires a certain time).

Recent years have been characterized by the rapid development of electric transport, manufacturers of route vehicles with electric drive also continue to develop this direction and offer customers new solutions. The emergence of new models and modifications of vehicles have led to the fact that within the same scheme according to the existing classification there were vehicles with significant differences in parameters determining their operational properties and qualities, requirements for charging infrastructure and, as a consequence, characterizing the possibility of using vehicles on regular routes of a certain configuration and length [11].

Thus, the existing classification at the moment turned out to be very stingy and, in the opinion of the authors, there was a need to create an extended classification. In the extended classification proposed by the authors, in addition to the designation of the scheme, the concept of a category with a digital designation is introduced, while the higher the value of the category, the greater the margin of autonomous travel the vehicle has.

For trolleybuses, built according to the IMF scheme, two categories are provided:

- IMF-0 - no reserve of autonomous travel;
- IMF-1 - autonomous range up to 1 km (this is an emergency mode).

For trolleybuses, built according to the IMC scheme, three categories are provided:

- IMC-1 - autonomous range from 5 to 15 km;

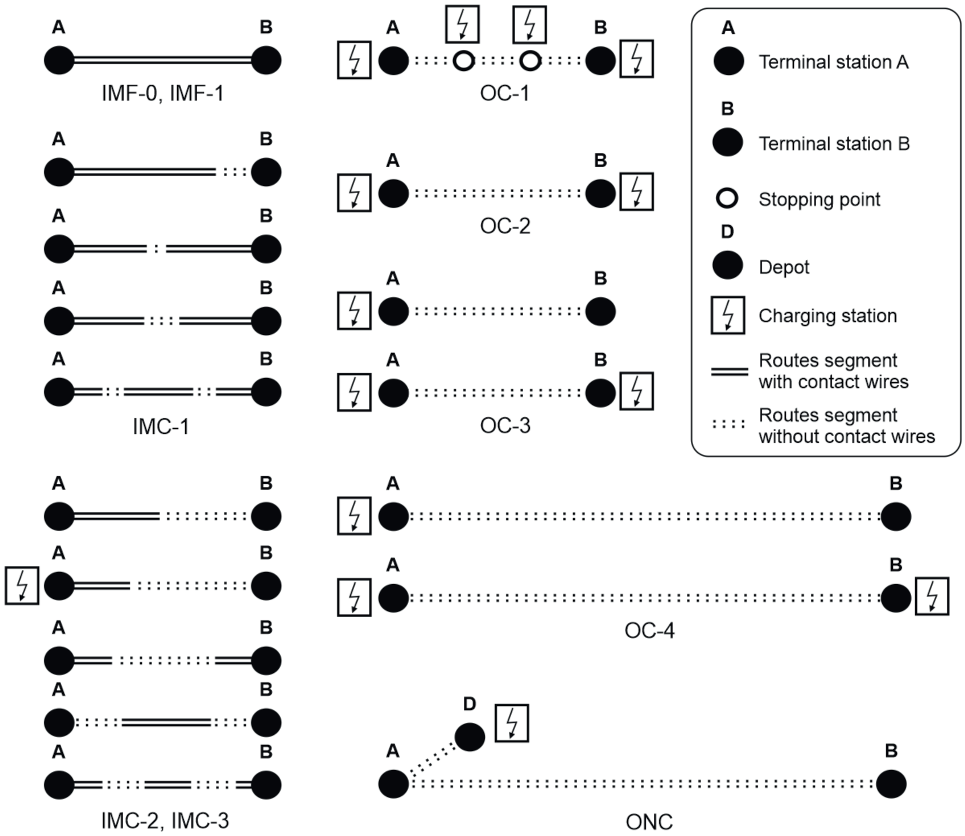

***Figure 1** Typical routes configurations for determining parameters of vehicle operation models*

Table 1 *Infrastructure required to provide traction for IMF trolleybuses, IMC trolleybuses, duobuses and charging electric buses of various versions*

Name, Value	IMF	IMC	Duobus	OC	ONC
Traction substation	+	+	+	+	+
Cable network	+	+	+	+	+
Contact wires	+	+/-	+/-	-	-
Charging stations on the line	-	-	-	+	-
Charging stations in the depot	-	-	-	+	+

- IMC-2 - autonomous range from 15 to 31 km;
- IMC-3 - autonomous range from 31 to 51 km.

For electric buses, built according to the OC scheme, four categories are provided:

- OC-1 - autonomous range from 3 to 5 km;
- OC-2 - autonomous range from 5 to 13 km;
- OC-3 - autonomous range from 13 to 21 km;
- OC-4 - autonomous range from 21 to 51 km.

For electric buses, built according to the ONC scheme, two categories are provided:

- ONC-1 - autonomous range up to 170 km (equal to the duration of one working shift);
- ONC-2 - autonomous range from 170 to 250 km (duration of one working day with restrictions);
- ONC-3 - autonomous range from 250 to 350 km (duration of one working day).

The proposed categories are formed based on the solutions offered by manufacturers and the established practice of using the route vehicles with electric drive on regular routes. The emergence of new solutions, which would require introduction of additional categories in the classification under consideration, is not excluded. Typical routes configurations for determining the parameters of vehicle operation models are shown in Figure 1.

The infrastructure elements, necessary to provide traction of trolleybuses and charging of electric buses of various versions, are given in Table 1.

2.2 Route network

In order to obtain reliable information about the route network, formed passenger flows and correspondence, various field studies and experiments were carried out. They were carried out by examining the operation of transport systems, objective and expert assessments, measurements, including using the analysis of video recordings and GPS tracks.

To perform an analysis of the route network, all the routes were classified according to geographical, topographic features, route topology and purpose. The areas of duplication of routes performed by vehicles of different capacity classes have been identified, the degree of duplication of routes has been established. Urban and suburban areas were zoned according to territorial and (or) functional characteristics.

During the survey of stopping points, the general planning parameters of the road network, planning parameters of elements and equipment of stopping points, approaches and pedestrian connections, the presence of systemic interference for the movement of route vehicles, the presence of interference and inclusive barriers, were studied. The main shortcomings identified include the absence of entry pockets on streets with the high traffic intensity, the absence of landing pads, the discrepancy between the level of the landing pad and the floor level of the vehicle, barriers when using vehicles of the M2 category (commercial minibuses). When conducting passenger traffic studies, a continuous and selective method was used. The places of gravity, passenger-forming points, places of intensive passenger exchange, were determined. In the selective method, a capacity score was used (with a differentiated scale from 1 to 6 points for vehicles of different capacity classes), the date, time, route number, vehicle registration plate, number of passengers entering and exiting, occupancy, were recorded. According to the results of the study, the volume of passenger traffic on certain sections of the route network was clarified, dependencies were established reflecting the unevenness by time of day, by directions and by days of the week.

2.3 Organization of transportation

All the routes were classified according to the purpose of the route, according to the frequency of movement (high-frequency with a frequency of more than 6 trips per hour, medium-frequency with a frequency of 3 to 6 trips per hour, low-frequency with a frequency of up to 3 trips per hour). The schedule has been studied for each route and graphical trips charts have been compiled. It was established by which capacity buses each route is served. Trends and dependencies were identified. In particular, it was found that passenger capacity does not always correlate with the frequency of traffic on the route, which is abnormal and should become a trigger for making decisions on reorganization of the route network. Separate studies were conducted to study the time of disembarkation and boarding of passengers. It is established that this time increases when the bus class does not match the capacity of passenger traffic, with an increase in the degree of

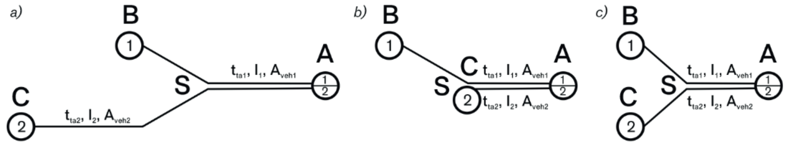

***Figure 2** Models of the RPT routes, the work of which is organized by the sectoral method*

filling of the vehicle, when using vehicles with a high floor level. A study of the speed of route vehicles with details on the stages was carried out. The factors that affect the speed of movement are established: the type of transport, the number of intersections with traffic light regulation, lack of coordination, green wave, the number of unregulated pedestrian crossings, artificial irregularities, the presence of level crossings, unregulated objects with high traffic intensity, the presence of a narrow carriageway, the presence of randomly parked cars in unauthorized places [12].

The following models were used to determine the parameters of the transport processes:

- passenger travel time t_{ptt}, which includes the time of approach to the stopping point t_{apr}, waiting time t_{wait}, time on the move t_{move}, transfer time $t_{transfer}$ (if applicable), t_{fin} final travel time from the stopping point to the destination:

$$t_{ptt} = t_{apr} + t_{wait} + t_{move} + t_{transfer} + t_{fin}\ , \tag{1}$$

- turnaround time T_{tt}, depending on the time for mandatory technological stopping T_{tsA} at the conditional station A of the route, time for stopping for the sanitary needs of the driver T_{ssA} at the conditional station A of the route, time for movement T_{mAB} from the conditional station A to the conditional station B, time for mandatory technological stopping T_{tsB} at the conditional station B of the route, time for stopping T_{ssB} for the sanitary needs of the driver at the conditional station B of the route, time for movement T_{mBA} from the conditional station B to the conditional station A:

$$T_{tt} = T_{tsA} + T_{ssA} + T_{mAB} + T_{tsB} + T_{ssB} + T_{mBA}, \tag{2}$$

- the number of vehicles on the route n, depending on the hourly capacity of passenger traffic Q in the most loaded stage, the passenger capacity q of the vehicles used, operating ratio of passenger capacity γ (sets the service level), turnaround time T_{tt}:

$$n = \frac{q\gamma T_{tt}}{60Q} = \frac{q\gamma\begin{pmatrix} T_{tsA} + T_{ssA} + T_{mAB} + \\ + T_{tsB} + T_{ssB} + T_{mBA} \end{pmatrix}}{60Q}. \tag{3}$$

The solution of the optimization problem from the point of view of the organization of transportation, as an objective function, should be used $n \rightarrow$ min. Solving in various ways, optimizing values Ttt, minimizing them, setting the level of service $\gamma \leq 0{,}80$.

Authors' sectoral methods can be used for service of the route network. The route technology of passenger service provides for the operation of the route passenger transport (RPT) vehicle, along the laid routes from terminal station A (hereinafter referred to as Station A) to terminal station B (hereinafter referred to as Station B) and back according to the timetable. For a detailed study of the work of the RPT vehicle on the route, a model was developed, characterized by division of their parking time into stations A and B for mandatory and additional. The possibility of using the sectoral method for organizing the work of the vehicle on the RPT routes is to allocate and combine the routes with common segments based on the rules of "switching" and combining routes within the sector, while maintaining the mandatory sequential alternation of work on them, rational distribution of driving and technical resources of the sector [13]. The implementation of the sectoral method for organizing the work of the vehicle on the RPT routes is considered using the model presented in:

$$\begin{cases} t_{ta1} = t_{lstmA} + t_{lstaA1} + t_{AB} + t_{lstmB} + t_{lstaB1} + t_{BA} \\ A_{veh1} = \dfrac{t_{ta1}}{I_1} \\ t_{ta2} = t_{lstmA} + t_{lstaA2} + t_{AC} + t_{lstmC} + t_{lstaC2} + t_{CA} \\ A_{veh2} = \dfrac{t_{ta2}}{I_2} \end{cases}. \tag{4}$$

It is carried out by allocating joint segments on the routes AB, AC (a section of the route AS), while route configurations are possible when AC is significantly larger than AB, when the route AC is a part of the route AB and is intended to strengthen it and in fact the common segment AS is the route AC as well as when AC = AB (Figure 2).

At the same time, the proposed scheme of sectoral service provides for the operation of the AB and AS routes in such a way that the AS segment on them is always serviced according to the principle of equality of the network interval I_1=I_2, with the guaranteed exception of the so-called Vernier effect, which entails not only an even distribution of the production load, but also reduces the economic losses of passengers, consisting in wasting their time on excessive waiting for the RPT vehicle at stopping points, while overloading the vehicle and complicating the work of drivers on routes is prevented. Such infrastructural combinations of routes (and even types of the RPT) are also a solution to increase the throughput and productivity of the sector by minimizing t_{lstaA1}, t_{lstaB1} and t_{lstaC2} when the assigned conditions are met for use of the sectoral method for organizing the work of the vehicle on RPT routes.

At the same time, the model in Equation (5) will already be applicable:

$$\begin{cases} t_{ta12} = t_{lstmA} + t_{lstaA12.1} + t_{AB} + t_{lstmB} + t_{lstaB12} + \\ + t_{BA} t_{lstmA} + t_{lstaA12.2} + t_{AC} + t_{lstmC} + t_{lstaC12} + t_{CA} \\ A_{veh2} = \dfrac{t_{ta12}}{I_{12}} \end{cases}. \quad (5)$$

3 Analysis and results

The possibilities of using different types of urban electric transport in the cities of Belarus is proposed to be evaluated on the example of the Polotsk agglomeration (cities of Polotsk and Novopolotsk). This route can be chosen bus route No. 4 "Marynenka-Baravukha-3" in the city of Polotsk. The main parameters of route No. 4 when using different types of urban electric transport are given in Table 2 and represented in Figures 3 and 4.

Route 4 runs along Marynenka street, Pyatrusya Brouka street, Yubileynaya street, Kastrychnickaya street, Hogal' street, Kammunistychnaya street, Efrosinnya Polotsk street, Kasmonautau street, Valagodskaya street. The length of the route is 25.19 km; the bus work time in the forward direction and in the reverse direction is 40 minutes. The Current schedule provides for 124 trips, including 62 trips in the forward and 62 trips in the reverse direction. The route works from 05:00 to 00:45. The highest frequency of traffic on the route from 6 AM to 8 AM and from 4 PM to 6 PM, when 9 vehicles are used for passenger service at the same time. In the consolidated calculations, it is assumed that the depot for electric transport will be located in the existing bus fleet No. 2 on Budaunichaya street.

The assessment of possibility of using different types of the urban electric transport in Novopolotsk

Table 2 *Comparison of parameters of route No. 4 in Polotsk at service by vehicles of various types of city electric transport*

Name, Value	Quantity of vehicles		Min. turnaround time, min.	Average operating speed, km/h	The length of sections, km	
	On the line	Total			with contact network	without contact network
Scenario 1. Service by single 12m length class vehicles						
IMF	12	15	90	16.79	25.19	0
IMC (LTO w/extra rapid charge)	12	15	90	16.79	3.20*	21.99
IMC (LFP)	12	15	90	16.79	12.00*	13.19
OC	14	18	100	15.11	0	25.19
Scenario 2. Service by articulated 15m length class vehicles						
IMF	9	11	90	16.79	25.19	0
IMC (LTO w/extra rapid charge)	9	11	90	16.79	3.20	21.99
IMC (LFP)	9	11	90	16.79	12.00*	13.19
OC	10	13	100	15.11	0	25.19

* It is necessary to build a contact wired

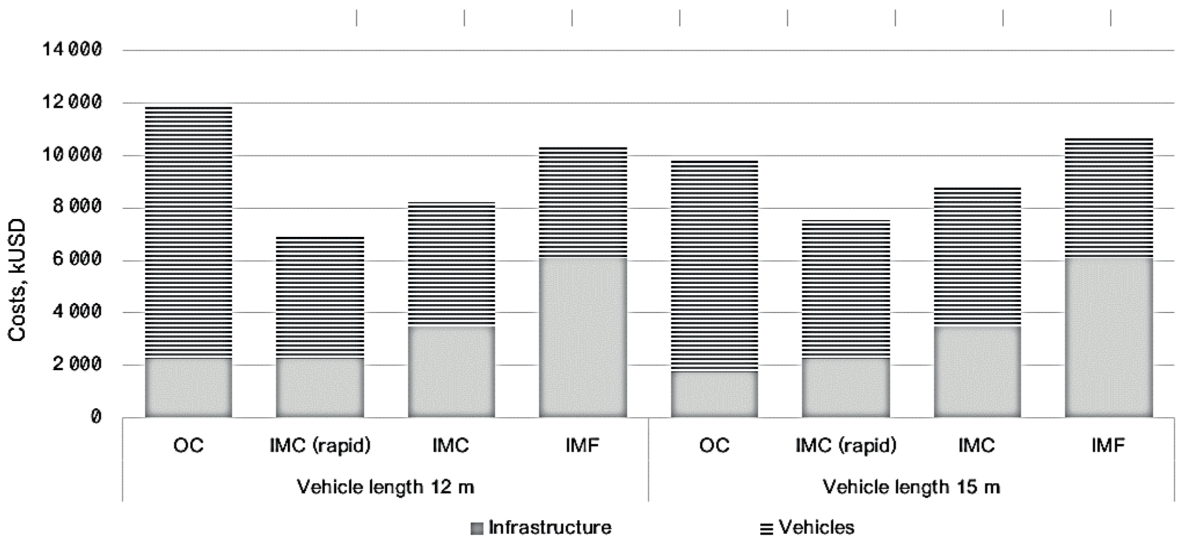

Figure 3 *Total investments for Route No. 4 in Polotsk*

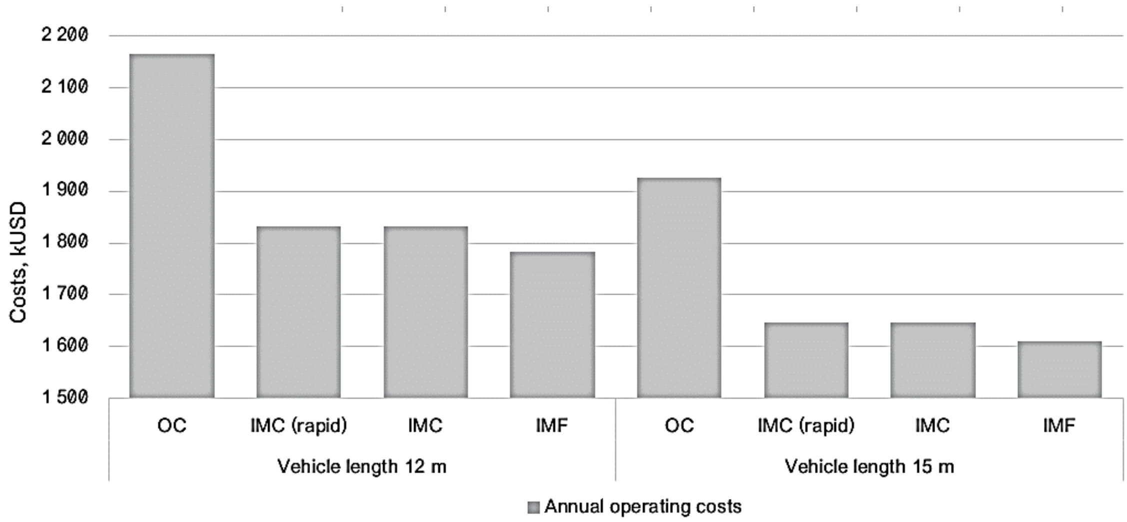

Figure 4 *Annual operating costs for Route No. 4 in Polotsk*

Table 3 *Comparison of parameters of route No. 4 in Novopolotsk at service by vehicles of various types of city electric transport*

Name, Value	Quantity of vehicles		Min. turnaround time, min.	Average operating speed, km/h	The length of sections, km	
	On the line	Total			with contact network	without contact network
IMF	5	7	54	16.58	14.92	0
IMC (LTO w/extra rapid charge)	5	7	54	16.58	2.53*	12.39
IMC (LFP)	5	7	54	16.58	7.00	7.92
OC	7	9	67	13.36	0	14.92

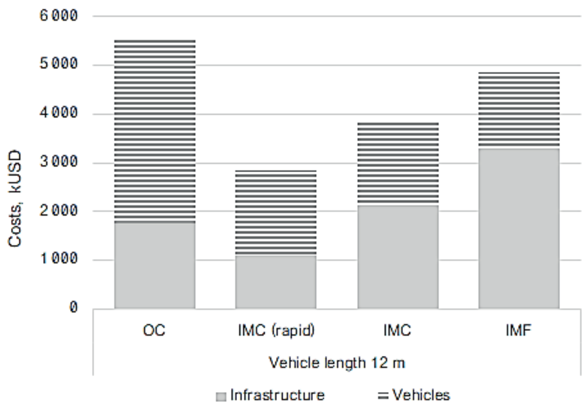

Figure 5 *Total investments for Route No. 4 in Novopolotsk*

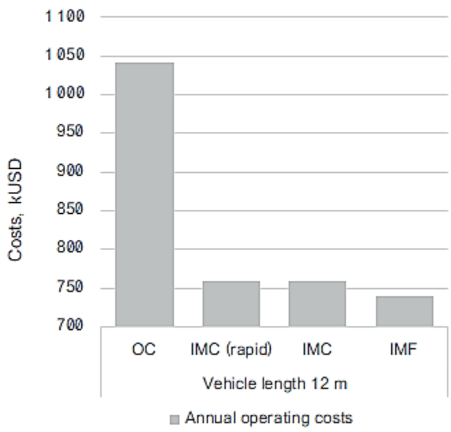

Figure 6 *Annual operating costs for Route No. 4 in Novopolotsk*

was carried out on the example of the bus route No. 4 “Padkasteltsy-Hospital town”.

The route No. 4 is for Moladzewa Street, Ktatarava Str., Slabadskaya Str., Haidara str. in forward direction and Haidar Str. and Moladzewa Street in the reverse direction. The length of the route is 14.92 km, the bus travel time in the forward direction is 25 minutes, in the reverse direction - 24 minutes. The current schedule provides for implementation of 106 trips (53 trips in the forward and reverse directions). The route works from 08:24 to 23:52. The highest frequency of traffic on the route from 5 PM to 7 PM, when 5 vehicles are used simultaneously for passenger service. In consolidated calculations it was accepted that the depot for electric vehicle will be located on the terminal station “Padkasteltsy” [14].

The main parameters of the route when using different types of urban electric transport are given in Table 3. The total investments are summarized in Figure 5. When calculating the total investments in infrastructure and vehicles, the costs of contact wires, traction substations, charging stations and the vehicles themselves, required for work on the route, are taken into account. The costs of design and the contract work

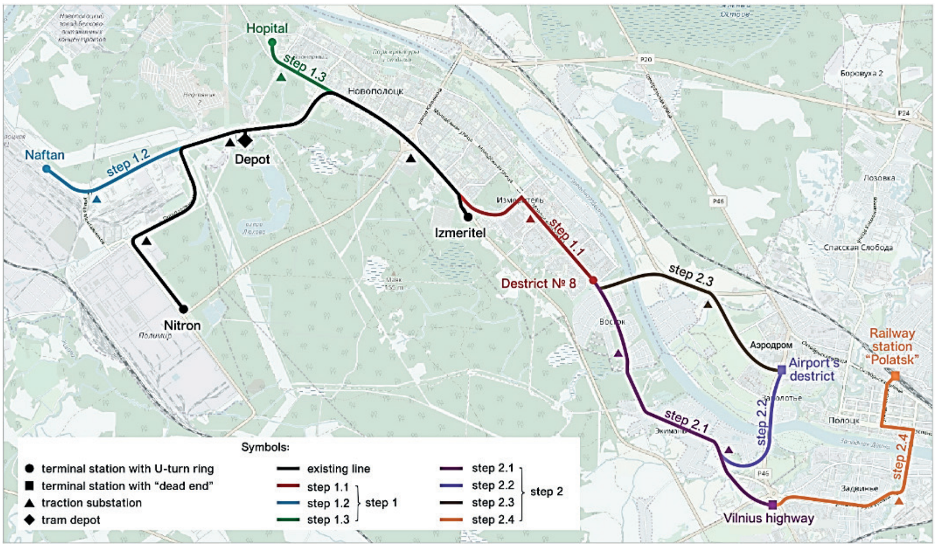

Figure 7 *Tram development scheme in the agglomeration of Polotsk-Novopolotsk*

to create a base for maintenance and repair of vehicles at the transport enterprise, were not taken into account.

An overview of annual operating costs is shown in Figure 6. Consider separately the problems of traffic organization, transportation organization and traffic safety arising from the operation of some types of non-rail electric transport. Trolleybuses IMC, IMF, duobuses favourably differ from electric buses OC, which have a limited working reserve and require periodic stops to charge the drives. This stop occurs at each terminal station and its duration is about 10 minutes.

This fact introduces a number of restrictions in the technology of organization of the electric buses movement and in the order of scheduling.

Moreover, from the standpoint of economic efficiency, the use of electric buses with a travel interval of less than 10 minutes requires the construction of not one, but two or more charging stations at the final station, which are necessary for the stable functioning of the route.

In addition, in case of delay, the stability of the system is violated. A delayed electric bus will occupy a slot in the schedule belonging to the next electric bus that operates on the same route. This will lead to it also starting late, as well. Then the “domino principle” will work. Each subsequent electric bus will be late.

From the point of view of the human factor and psychophysiology of the public transport driver, such violations of the traffic schedule will lead to the fact that drivers will begin to reduce delays by increasing the speed of traffic on routes. Experience shows that this will happen in those parts of the route where it is unsafe and will lead to an increase in number of accidents.

At the same time, an alternative scenario provides for the development of tram. At the same time, the tram depot already has the necessary base for the repair and maintenance of trams, as well as the trams themselves in the quantity necessary to work on the new lines. The step-by-step plan of tram transportation is shown in Figure 7 [15].

4 Discussion

Returning to the problems of the Polotsk agglomeration, it should be noted that Novopolotsk enterprises form the largest petrochemical complex in Belarus and this affects the environmental situation. Novopolotsk is one of the cities with the highest density of emissions of harmful substances. Mobile sources of emissions also play a negative role in the overall air pollution. In these circumstances, the increase in the share of environmentally friendly transport is particularly relevant [16].

The analysis of various variants of application of the non-rail electric transport is given in Table 4.

To organize the movement of the non-rail electric transport, it is necessary to purchase vehicles, create a base for their repair and maintenance in bus fleets, construction of traction (and charging) substations, cable networks, training of personnel. The construction of the contact wires along the entire length of the route is required for the IMF trolleybuses and partially for IMC trolleybuses and duobuses. To organize the movement of electric buses, it is necessary to build charging stations in the depot and at the end stations (for the OC electric buses).

Revealing the issues of complex optimization of costs for the maintenance of the route network by route passenger transport, it is necessary to return to the Equation (3).

It is now possible to simulate the operation of two routes leaving the same terminal station according to the scheme of Figure 1a, making the following assumptions: the preparatory and final time for the driver is not taken into account and the time of lunch breaks is not taken into account, the depot is considered adjacent to station A, zero mileage at the beginning and at the end of work is 5 km and 18 min. The simulation results show that as a result of organizing the work of routes 1 and 2 by the sectoral method, with the work of each vehicle with

Table 4 *Analysis of application possibilities of the non-rail electric transport*

Name, Value	Electric bus OC, ONC	Trolleybus IMC	Trolleybus IMF
Experience of operating in the cities	-	-	-
Place of storage of vehicles	+/- (can be placed in the bus depot)		
Operational base (maintenance, repair)	- (need to build)		
Degree of binding to the infrastructure	Binding to charging stations	Partial binding to the contact wires	Full binding to the contact wires
Needing for driver training	Driver‘s license for Cat. "D" is necessary	Driver‘s license for Cat. "I" is necessary	Driver‘s license for Cat. "I" is necessary
Ability to change the route	From charging stations within the range of the autonomous range	From any point of site with the contact wires within radius of autonomous range	Without construction of the contact wires it is impossible to change route
Needing for an one-time purchase of vehicles for open new routes	Necessary	Necessary	Necessary
Equivalent value of the vehicle (for 1 people of passenger capacity)	4.26-4.66	2.20-2.75	2.20-2.75
Period of operation of the vehicles base (extended)	10	10 (15)	10 (15)
Presented (to 1 person of passenger capacity and a basic 10-year service life) the cost of the vehicle	4.26-4.66	2.20-2.75	2.20-2.75
Specific electricity costs for transportation of 100 passengers per 1km in summer, USD / 100 pass.km	0.18	0.18	0.18
Specific fuel consumption for transportation of 100 passengers per 1km in winter, USD / 100 pass.km	0.42	0.29	0.29
Ecological issue	+/- - - (emissions of harmful substances during the operation of diesel heating, tires, rubber dust in the interaction of wheels with the road surface)	+/- (disposal of traction batteries, tires, rubber dust by interaction of wheels and the road surface)	+/- (recycling of tires, rubber dust by interaction of wheels and the road surface)

drivers on a sequential route 1+2, there is a daily gain in the number of vehicles on 1 unit, in the number of drivers on 2, in the number of zero trips on 2, reducing the time of additional parking (unproductive time) by 17 hours, machine hours by 17.60 hours, reduction of mileage in 10 hours, increase in operating speed by 1.17 km/h (+9%). At the same time, share of unproductive parking time decreases from 8% to 0% and the share of car hours in traffic increases from 84% to 91%.

The enlarged calculation of the economic effect of the sectoral method introduction was made according to the criterion of the costs of paying drivers and capital investment in the purchase of additional vehicles. Due to the circumstances described above, other indicators are simplified. The expected economic effect of servicing each two routes by the sectoral method, if the necessary conditions were met, is expressed for a bus for a 10-year period (the life cycle of one vehicle) at current prices of 665 000 EUR, for a trolleybus for a 15-year period 968 000 EUR, for a tram for a 30-year period 1895 000 EUR.

5 Conclusions

Thus, a further increase in the share of electric transport in the cities of Belarus is also possible due to the organization of the movement of IMC trolleybuses on some busy routes with the construction of a contact wires for charging energy storage in IMC trolleybuses on certain sections of the route outside the central part of the city. This solution from the point of view of traffic organization, transportation and traffic safety, is the optimal and attractive. The advantages of this solution are: distributed load on the electric network throughout the day, operation of autonomous onboard energy sources in a smooth mode, electric heating and air conditioning, charging of autonomous onboard energy sources during the route without the downtime of vehicles at end stations or depots. This combined solution makes it possible to significantly expand the geography of use of the IMC trolleybuses due to the possibility of including sections of the road network that are not equipped with contact wires in their routes.

A methodology for assessing the efficiency of urban passenger transport has been developed, including taking into account the development of electric vehicles, which made it possible to determine the need to purchase appropriate vehicles for organizing the movement of the non-rail electric vehicles; create a base for their repair and maintenance; construction of traction substations (new or additional); construction of cable networks; train staff. In addition, for the use of the IMF trolleybuses, it is necessary to build a contact network along the entire length of the route, for the IMC trolleybuses and duobuses - on some routes. To organize the movement of electric buses, it is necessary to build charging stations in parks (for the OC electric buses - and at terminal stations).

It should be noted that the development of a network of the tram lines will attract additional passengers and increase the annual volume of passenger traffic (according to preliminary expert estimates) by approximately 4.1 million passengers. during the implementation of all the stages of stage 1 (in Novopolotsk) and 6.7 million passengers. during the implementation of all the stages of stage 2 (in the agglomeration). The most efficient operation of the tram will become when it starts to be used for "agglomeration" transportation on the sections with the highest passenger traffic (for example, along the route of the existing bus route N°. 5 and route taxis N°. 5t). The "agglomeration" rail passenger system of Novopolotsk-Polotsk will be the only one in Belarus and may become one of the ways to develop the tourist potential of cities.

In addition, an algorithm has been developed for implementation of the least costly activities at the initial stage with limited funding. The studies performed allowed to formulate a concept and propose specific comprehensive measures aimed at improving the quality and efficiency of the route passenger transport in Polotsk and Novopolotsk, including optimizing the existing route network of route passenger transport.

Studies of the effectiveness of measures, aimed at reducing delays in route passenger transport, have been carried out, criteria and places of their application in Polotsk and Novopolotsk have been determined, as well as an assessment of the technical and economic indicators of the proposed options using the international Cost Benefit Analysis (CBA) methodology.

A business model has been developed for implementation of standard measures aimed at improving the quality and efficiency of the route passenger transport, a set of measures to increase the attractiveness and efficiency of urban passenger transport has been proposed.

The proposed expanded classification system for route vehicles with electric drive will allow classifying and categorizing various solutions offered by manufacturers of route vehicles with electric drive, which will facilitate the work when making decisions by both operating organizations and design bureaus, since the designation of the scheme, supplemented by the category number, will make it easy to determine the scope and capabilities of this vehicle, the need for charging infrastructure.

The IMC-2 and IMC-3 trolleybuses are of the greatest interest for cities with trolleybus traffic, which allow expanding the route network of an environmentally friendly trolleybus and replacing a number of bus routes with trolleybuses.

Improving the traffic safety by development of the route passenger transport will be achieved by deterring motorization. Statistics show that there are fewer road accidents per route vehicle than per vehicle for personal use. Drivers of the fixed-route vehicles are professional drivers; they are well prepared and trained. A further increase in the share of route passenger transport will contribute to an increase in the number of trips using route vehicles. This will contribute to further unloading of the road network, improving the traffic conditions on the streets of cities.

For a comprehensive assessment of the quality of decisions taken, a loss assessment methodology, based on accounting for the economic costs arising from the use of each type of transport, should be used [17]. Costs differ from expenses in that costs take into account all costs (explicit and implicit, which cannot be accounted for transparently). All such costs, which are losses, can be classified into accidents, environmental, economic, operating and social. Total losses by definition represent the sum of all the types of losses and are used for a comprehensive assessment of the quality of traffic.

The results of the study can be useful for developing the concept of electrification of the route network in cities that are beginning the transition from diesel buses to electric transport. Of particular interest is the information systematized in this study for cities that have a trolleybus network and can diversify it through the use of new types of trolleybuses. The organization of work on the route network, when drawing up a schedule using the sectoral method will reduce both operating costs and the costs of purchasing vehicles.

Grants and funding

The authors received no financial support for the research, authorship and/or publication of this article.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Nomenclature:

- IMF - in Motion Feeding - trolleybuses as vehicles with feeding in motion
- IMC - in Motion Charging - trolleybuses with autonomous on-board energy source (battery) as vehicles with dynamic (in motion) charging
- OC - opportunity charging - electric bus with a relatively small autonomous running resource, requiring frequent and fast charging
- ONC - overnight charging - an electric bus with a power reserve sufficient to operate during a shift, requiring a long, usually overnight charge
- LTO - Lithium Titanate Oxid battery
- LFP - Lithium Iron phosphate battery
- NMC - Nickel Manganese Cobalt battery
- RPT - route passenger transport

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TARIFF SYSTEMS AND DISTANCE MEASUREMENT OF PUBLIC PASSENGER TRANSPORT STOPS

Jozef Gnap[1,*], Grzegorz Dydkowski[2], Ján Ondruš[1], František Synák[1]

[1]Department of Road and Urban Transport, Faculty of Operation and Economics of Transport and Communications, University of Zilina, Zilina, Slovakia
[2]Department of Transport, University of Economics in Katowice, Katowice, Poland

*E-mail of corresponding author: jozef.gnap@fpedas.uniza.sk

Jozef Gnap 0000-0002-0833-7850,
Jan Ondrus 0000-0003-4379-4931,
Grzegorz Dydkowski 0000-0002-2780-2009,
Frantisek Synak 0000-0001-7998-8960

Resume

The development of IT technologies in the systems of tickets sales facilitates the charging and differentiating the fare amounts versus distance, as well as in the systems of public transport on short distances, in the urban, suburban and regional transport. The essence of the transport activity consists in covering a distance and a part of cost components and thereby the total costs, increase with the distance covered by means of transport. In a similar way the calculation of fares depending on distances may be considered as the most appropriate from the point of view of transport as a service. Inaccuracies and deviations during the distance measurements have various results, which further on may have effect on analyses, comparisons, correctness during the fare calculations, as well as settlements related to public financing of the public transport. An independent and precise distance measurement is indispensable to eliminate the impact of the measurement method on distances.

Available online: https://doi.org/10.26552/com.C.2023.009

Article info

Received 9 September 2022
Accepted 6 November 2022
Online 30 November 2022

Keywords:

public transport
tariff system
measuring
bus-stop distances

ISSN 1335-4205 (print version)
ISSN 2585-7878 (online version)

1 Introduction

An efficient urban and regional transport creates increasingly great challenges together with the increasing number of rides, commuting to cities from longer and longer distances, transport congestion, limitations of the land, which may be used for transport purposes and the necessity for environmental protection of cities. Hence the need for development of public transport systems, competitive for individual motorization. Apart from qualitative factors, prices are an extremely important element of the assessment and competitiveness of the urban and regional public transport. Their amounts are affected by very many factors, economic, social and political ones. The services of urban and regional public transport are a mass in nature and are widely available, hence a tariff method of price shaping is used. The public transport tariffs are expected to ensure the assumed income, however, on the other hand they are a significant part of the policy carried out by cities, not only in the field of urban mobility, but in the field of funds redistribution between various social groups, as well.

The occurring effects of suburbanization, city sprawl and localization of various functions and activities outside their boundaries, cause on the one hand that suburban areas are covered by the urban public transport services and on the other hand a share of regional nature transport, when serving daily commuting to work. The integration of such systems is a natural course of events and this also means the application of tariff regulations previously characteristic of regional transport, also in the urban transport and vice versa.

Various solutions may be encountered in the field of public financing of passenger public transport. The urban public transport is widely financed from the public funds, apart from tariff revenues. The financing is related to the interference of public authorities in the scope of provided services and prices, including entitlements to concessionary travelling. As a result, the services of urban public transport are provided within their scope, i.e. city areas and lines with low occupancy, in non-rush hours and on holidays on a level, which would not be possible, if the ticket revenues would entirely have to cover the costs. In the case of regional transport, the public interference is generally smaller and a share of market decisions higher, however, in this case various systems of public financing are used as well, starting from financing the income lost on the sales of concessionary tickets up to subsidies to the performed operational work.

Despite the fact that the tariff revenues obtained in the urban public transport are only a part of those needed to finance the provided services, the level of prices in the urban public transport and the rules of their differentiation are the subject of great interest of the public and of medial activity. Prices affect the image of public transport, the transport policy of cities is evaluated from their angle, as well. It is important, because the social perception and the image shaped by the media ultimately decides about the demand for services of the urban and regional public transport.

The adopted principles of differentiation, including the type of adopted tariff, the scope of persons entitled to concessionary and free travelling and the differentiation depending on the number of services, i.e. prices of multi-ride and season tickets, have a special place in discussions and assessments of prices in the public transport.

The paper is aimed at comparing the price differentiation rules in the urban and regional public transport and showing against this background theoretical and practical principles of section-based tariffs application, including the measurement of inter-stop distances. It is necessary to draw attention to the fact that distance tariffs, despite their numerous advantages and widespread use in the passenger transport on longer distances, as well as in the cargo transport, so far were not common in the urban public transport. This resulted from a mass nature of services and the necessity of simplifications in the sales systems. However, together with the dissemination of IT and systems of fare charging, it is now necessary to consider this method of price differentiation, because it best links not only increasing costs of transport with the increasing distance and fare, but the service measured by the covered distance with its price, as well. This does not mean switching only to this type of tariff in the tariff systems used in cities, but as an option to be chosen by the service users. The implementation of such a system requires, among other things, to perform properly the distance measurements, so as to avoid inaccuracies and thereby incorrectness in the fare charging. The methods of inter-stop distances measurement will be presented in the paper and the adoption of uniform rules in this field excludes situations, in which the performance of measurements by various methods can result in different results and related subsequent misunderstandings. In addition, the results of carried out measurements can also be used in other areas of the urban transport management, including the calculation of the remuneration, to which the carrier is entitled for the services provision.

2 The hitherto state of research

The public transport, including the urban public transport, has an important place in the research on cities functioning and development, in the economics of the public sector and transport. Hence, there are numerous studies on financing of the urban transport, including issues related to the demand for services and prices. In particular, the research and publications focus on issues related to the impact of various factors on the size of demand for urban transport services, including the relationships of the price elasticity of the demand [1-14]. A factor, which additionally intensifies the research now, is the use of IT and glocalization technologies in the transport management, including the sales of services; on the one hand they enable access to many data, e.g. the volume of transport, but also inter alia solutions in the field of price differentiation, which only a decade or two ago were not possible. It is also important that the public financing of urban transport, as well as appropriate price differentiation, causes changes in the share of transport work and limits the external effects of transport, including those related to road accidents [15]. The tariff systems are also expected to be effective, so that together with the public funds it would be possible to finance the purchases of ecological means of public transport [16]. Therefore, studies into the price differentiation are important [17-21], as well as the comparative studies on their amounts, which consider a diversified economic potential of cities [22]. Based on that it is visible that, in big cities in Europe, the study carried out altogether for 100 big cities in different countries, a uniform (fixed) or zone tariff prevails in the urban public transport [22]. With respect to single tickets a uniform tariff occurred in 57.3% of cases, a zone tariff in 33.3% and a section-based tariff in 9.4% of cases. The situation was quite similar for monthly tickets, 60.4%, 36.6% and 3% of cases, respectively [22]. The occurrence frequency of various tariff solutions in big cities in Europe and a widespread use, for many years, of uniform or zone tariffs, cause that publications focus on them, e.g. in the field of the very zones designing [23-24].

In publications on prices it is also possible to distinguish those which describe, in the form of algorithms, the selection procedures for fare collection systems [25], showing methods and models possible to use, including mathematical models to search for solutions of selected decision problems, e.g. comparisons of fare and revenues of entities in the case of distance or zone tariffs [26], or searching, at a known tariff structure and various proceeding strategies, for the cheapest connections [27]. The methodologies of procedure are important both for the service users and for carriers, for whom the fares paid by passengers are the revenues on sales of services.

However, it is necessary to consider that the developed models may frequently not contain parameters or relationships between variables, which makes their practical use under the current conditions difficult or impossible. It is necessary to be aware of many factors, e.g. economic, social and time, when the changes and implementations occur, which ultimately translates into various limitations, difficult to define in mathematical formulae as well as of neglecting certain factors and limitations in the developed models. Therefore, the heuristic methods, including the most popular Delphi and brainstorming method, are frequently advised for solutions searching. Hence, as a result, the searching for a solution requires knowledge, experience and skills to identify causalities, to analyze and assess a wide range of possible solution variants. Prices are not the only field of mathematical methods use in the public transport, their application in practice covers now most decision problems occurring in the organization itself and in the provision of urban public transport services [28].

Despite the multitude of publications, a shortage is still perceived in the field of studies on the relationships between prices and the travel distance in the urban transport. Making the fare dependent on the distance, hence section-based tariffs, were and are widely used only in the longer-distance transport due to carrying out in the past sales by carriers at their own points and now, with the development of IT technologies and with their use, they can be applied in a broader range. However, there are now no analyses on the use of section-based tariffs in the urban public transport, this gap is to be filled by this paper. As it has been stated [29]: "… rather less well-developed literature on the relationship between public transport prices and distance (…), there has to our knowledge been little practical work on bringing these two concepts together". Few papers can be mentioned among published and available results of studies [30-34].

The digitisation of payments is the main trend in the passenger transport and it is very frequently perceived as a condition for improving the effectiveness of provided services. The technology used for digital payments in the passenger transport is permanently developing [35-36]. It is also possible to add that the price differentiation depending on distances is not the only one; the differentiation e.g. depending on affiliation to various social groups, like children and youth, pupils and students, retired persons and persons above an indicated age, is widely applied, or on the number of services, like single tickets and multi-ride or season tickets. In this way the ticket prices of urban public transport take into account social elements and via low unit prices, in the case of season tickets converted to a ride, elements of motivation and shaping the share of transport tasks division [21-22, 37]. Tariffs can also be used to extract the consumer's surplus when there are a lot of connections supplied, so that a law of large number applies in the estimation of the consumer's willingness to pay [38].

In addition, understanding the expectations of price fairness and of accessibility of urban and regional public transport services, which also are appearing in publications related to the urban transport prices, it is possible to notice that the increase in services availability is achieved by public financing, subsidies to the cost of services provision and/or entitlements to concessionary travels and the price differentiation for various social groups. It is also possible to show certain doubts, whether by means of urban or regional transport prices the welfare and social policy should be carried out, or is it a task of other public institutions, while the public transport should focus primarily on the effective use of resources and provision of high quality services. The pursuit of justice, understanding at the same time various meanings of this term, is obtained just by application of tariffs, which on the one hand reflect the relationships in the costs of transport, consisting in increased costs at transport on longer distances and on the other hand, create a system, in which a person travelling a shorter distance would pay less than that who travels a longer distance.

3 Tariff types used in the urban and regional public transport

Adopting the method of considering the travel distance as the criterion, three basic types of tariffs may be mentioned [18-19, 37]:

- uniform,
- zone,
- distance.

In the uniform tariff the ticket price does not depend on the distance of a ride; the price is the same in a specific network, in which it is binding, in a city or in an indicated area. The advantage of this tariff consists in the price list simplification and thereby in facilitation of the tickets purchase and hence the use of public transport services. In addition, an easy determination of the fare amount enables passengers to make comparisons between costs related to various methods of movement. At the same time the tariff is relatively simple for the carriers themselves; the lack of differentiation depending on the distance reduces the number of sold ticket types, which is major facilitation, in particular when paper tickets are used and the sales are carried out using the rules of outsourcing, at external points of sales. In addition, the tickets inspection is easier, because it is not necessary to check if a zone or distance has been exceeded, as it is the case for other tariff types. Identical prices of tickets for all the passengers, irrespective of the travelled distance, are the basic drawback of this tariff system. That means that passengers travelling only a short distance, for example one or two stops, pay the same amount as passengers travelling a distance of a dozen or so stops, which causes that persons travelling a short distance have a feeling that the paid fare is too high. This tariff solution may be the reason for dodging, when travelling a short distance, hence the price is perceived as high and a probability of inspection low due to a short time of travel [39], or entirely giving up travel in favour of a walk. Apart from simplicity of this tariff system, an opinion may be encountered as well that its application in cities results from a limited impact of residents on spatial management and the location of places of residence and such activities as work, education and purchases, hence persons living at longer distances should not be burdened with high costs of commuting.

In its nature the uniform tariff is a solution, in which single tickets are binding, which next results in a pressure to create direct connections. Willing to avoid that, this system is modified, enabling transfers, thus, in the uniform tariff systems it is frequently possible to use various lines for a specified time, within the area covered by the uniform tariff. This allows avoiding situations in which many direct connections are created with a low frequency of journeys, at the same time characterised by a non-uniform occupancy on the entire route length [37].

The zone (area) tariff consists in dividing a given area into various zones, where their boundaries may be determined in various ways. Such solutions are used, where the zone boundaries are universally known, e.g. within a region or metropolitan area the zone boundaries

***Table 1** Comparison of various tariff types*

Tariff type	Advantages	Disadvantages
Uniform	- very simple and easy to use for passengers, - one face value of a normal single ticket facilitated the development of sales systems, in particular in the case of paper tickets, a possibility to use external points of sale, - easy tickets inspection, there is no problem of zone crossing,	- no differentiation depending on the travel distance, as a result rides on short distances are relatively expensive, which can encourage to travel without a valid ticket or to give up riding on short distances, - no price differentiation depending on the distance causes that it is not good to use as the only tariff in large metropolitan areas or in big cities, - the offered tickets are single tickets, in the case of multi-ride travels the necessity to buy the next tickets causes that direct connections are expected, which is unfavourable from the transport organization point of view,
Zone	- relatively simple and easy in use and allowing in areas with a large number of lines to link the amount of fare with the travelled distance, - a small number of tickets face values does not complicate the tariff information and sales systems, - the ease of defining and identifying the tariff zones in a situation, where these are boundaries of districts, cities, or other administrative units,	- the issue of a too high fare in the situation of starting a ride before the boundary of a tariff zone and finishing behind it, the necessity to apply an option with a time validity of the ticket, hence the ticket entitles to travel within the zone or during a certain time, - the necessity to apply zone exceptions in situations where the line route goes beyond the zone boundaries, but there are no stops there, or only one stop and the route returns, - in the case of a larger number of zones, the necessity to mark the ride start on the ticket, - the adoption of administrative units as zone boundaries can result in the diversification of zone areas; the adoption of notional boundaries can cause difficulties in the tariff zone identification, in particular for persons using the public transport occasionally, - in the case of time zone determination (time tariff), not the best link with the travel distance; depending on the line route, time of day, or day of a week, the travel time on the same distance can differ even a few times,
Section-based	- making the amount of fare dependent on the travel distance, for passengers a possibility of lower fares as compared to other tariff types during the rides on short distances, in the case of long distances the degression of tariff rates, - the tariff application even only as an option in the urban transport systems facilitates the integration of tariff solutions with the regional transport systems,	- multitude of ticket face values or paid fares requires passengers to determine the place of destination during the ticket purchase, or the carriers to apply systems for fares calculation, which use IT systems and solutions of check-in and check-out type, - more difficult ticket sales, in particular in external sales networks, multitude of face values can also increase the costs of sales for paper tickets, - a relatively more complex price list, in particular where there are many distance sections and the fare degression systems may discourage persons, who use the public transport occasionally, from the use of services, as well, - more difficult tickets inspection due to a possibility of exceeding a specific distance section.

may be determined by administrative boundaries of cities or other administrative units; there may also be a solution in which the area is divided into zones determined by administrative boundaries of the city - urban and suburban. In addition, district boundaries may be the zones or other spatial boundaries, e.g. rivers or express roads passing through cities and dividing them in this way, the crossing of a zone boundary occurs on bridges or flyovers. Another approach is also used, the city center is the central zone and the others are determined as rings that surround it, hence the next zone comprises districts surrounding the city center, then peripheral districts and suburban areas next. The zones can also have a honeycomb shape, i.e. the form of neighboring hexagons, as shapes filling the entire surface and having relatively short boundaries in relation to the surface. In such cases the size of zones may be freely changed and the price diversification achieved in this way. The advantage of zone systems is creation of a relatively simple system, in which even in a complicated network of lines and connections, the fare depends on the travelled distance. The situations, in which a ride starts before a zone boundary and ends on the stop after the boundary crossing, is a drawback of zone systems, which according to general rules may mean the necessity of a higher fare, due to the fact that the zone boundary was crossed during the ride. To avoid higher fares in such situations, the zone systems are modified by e.g. allowing alternative travelling with individual ticket types also for some time. As a result, passengers during a short ride can cross the zone boundary, which has been determined in space, however, they will not pass this boundary in the time dimension, hence they will not have to pay an increased fare. The zones are determined in space, as indicated areas, however, it is also possible to consider that time tickets belong to zone solutions, where zones, for which they are valid, are determined by the ticket validity period since validation. In addition, other approaches may be encountered, in which the differentiation depending on time is classified as section-based tariffs.

Zone tariffs make the fare dependent on the distance, which results in a fare growing with the increasing travelled distance, but for simplification it is not the distance of e.g. each covered kilometer, but the amount of fare is determined for certain distance ranges, given in meters or in kilometers, or measured by the number of stops. The adopted distance ranges may be identical or diversified, in a similar way the fares versus distance may be proportional, albeit degressive fares are frequently applied. The adopted distance ranges, i.e. the length of sections, are conditioned locally, by the expanse of the area and the length of the transport line routes; however, it is necessary to consider that the adoption of overly long distance ranges results in reduced differentiation depending on the distance, for example within the range of 10 to 20 km the person travelling 11 km pays the same fare, as the person travelling 19 km. Table 1 presents a comparison of uniform, zone and section-based tariffs.

The actual distances are determined by measurements between consecutive stops and arithmetical rounding should be performed only after summing up distances between stops on a given route. It is also necessary to emphasize situations, where between the same two stops one can travel by various lines on various routes, hence also distances, which can result in a different amount of fare. Thus, there may appear situations where the distance, according to which the fare is calculated, is not a real distance, but a tariff distance. It is worth considering, to what extent the additional cases of entering should be taken into account, e.g. to serve a housing estate, for persons, who do not get on or off; this is an additional elongation of the route, which also increases the amount of fare. The applied prices can be aimed at competing with moving by private cars, hence it is worth considering the tariff setting on as short as possible route, on which private cars move.

4 Section-based tariffs in the system of urban, regional and national tariffs

The section-based tariffs in the systems of urban transport were not often used in the past. This resulted from the mass nature of such transport, ticket sales at various external points, where the possibilities of information provision as well as sales of a significant tickets range were limited and also difficulties for passengers to determine the distance, on which they are travelling and hence what face value of the ticket should be bought. Therefore, in systems of paper tickets in the urban public transport, the situations, where the section-based tariff was used, were rare. It is necessary to consider that in the urban public transport there is only a part of persons, who use the services systematically and who have knowledge about the system. Part of passengers use the services occasionally, thus for them prices, with a large range of differentiation, are a problem. The implementation of solutions using the IT, including systems with the localization of means of transport on a current basis, took off from passengers the necessity of acquiring the information independently; this is carried out using algorithms in various sales programs and applications. The situation was and is different in the systems of longer-distance public transport, where the sales were carried out at own points of sales, ticket windows or by vehicle drivers, hence the use of section-based tariff was widespread.

It is indisputable that the section-based tariff in the best way, among the tariffs used, reflects the costs of the service provision, because the costs of transport services depend in a major part on the mileage of means of transport. In addition, in the section-based tariff ticket prices are not averaged, those for short distances are cheaper than those for longer distances. Hence, in the case of travelling a distance of one or two stops prices are low, or at least lower than those for longer distances, which eliminates the very feeling on injustice, which appears in such situations in the uniform or zone tariffs and it does not motivate to walk or to travel without paying the fare as well, assuming that the risk is then relatively low, since the lack of ticket or paying the fare in another way may be justified that the inspection started too early from the moment of entering the vehicle by the passenger and due to that he/she has not paid a relevant fare. In addition, the risk of inspection during a ride on a short distance is smaller due to a shorter travel time, than if distances are longer. Hence in the section-based tariff systems, by making the ticket price dependent on the distance, a feeling of fair prices is experienced and there is no field for losing passengers or revenues on sales of these services on short distances, as well.

The tariff, which makes the fare directly dependent on the distance, by its congruence with tariffs used in the transport provided on longer distances, both bus and railway transport, creates a good starting point for the introduction of integrated tariff systems in the urban and regional transport. This is important especially in the processes of suburbanization and daily commuting from suburban areas to city centers.

The implementation of a section-based tariff requires measuring distances between the consecutive stops on the routes and adopting the so-called tariff distances between them. It should be emphasized that the tariff distances for various reasons not necessarily must correspond to the actual distances; there may be situations, where for a number of reasons a means of transport covers a longer distance, e.g. diversions due to road repairs or temporary difficulties and closures and the price is calculated according to the original distance. Moreover, the service users expect the route to be as short as possible, while there may be situations, where the route of a given line for a number of reasons not necessarily reflects the shortest one.

5 Request and methods of measuring the bus-stop distances of mass passenger transport lines

5.1 Request for measuring in Slovakia

The need for measuring the real bus-stop distances of mass passenger transport lines is a result of Act No. 56/2012 Coll. of the National Council of the Slovak Republic on Road Transport as amended and the Decree of the Ministry of Transport and Construction of the Slovak Republic No. 124/2012 Coll. as amended, which implements related provisions of the above-mentioned act. The transport regulation of bus service for the regular bus transport, except for the city bus transport, includes the list of all the bus stops of the bus service with their tariff numbers and tariff distance from the departure bus stop. The tariff distance serves as a basis for calculation of the basic passenger fare, payment for carriage of luggage, domestic animals and bus consignments. The bus-stop tariff distance of the bus service is determined by a real distance of a bus stop from the departure bus stop in kilometres rounded up. The real distance is measured by a specific measuring instrument under Art. 7 Sec. 4 of the Decree No. 124/2012 Coll. according to the road passport or digital maps.

From the given options, measuring in the real road network with a bus is the most accurate way of determining the real bus-stop distance. The measurement must be performed in compliance with Act No. 157/2018 Coll. of the National Council of the Slovak Republic on Metrology and amendment to some acts (Art. 28 Sec. 2). The results from measuring are the basis for establishing the tariff distances of each bus stop of respective mass passenger transport lines, for processing the transport regulations of bus service, the whole network of City Public mass transport or suburban bus services.

The Department of Road and Urban Transport at the University of Zilina in Zilina is an intellectual property owner of measurement methodology for distances called "Measuring methodology for distances by the measurement and reporting instrument Correvit" (Number of methodology: 01/2002/KCMD). This methodology was validated and approved by the Slovak Metrological Institute Bratislava and it is recommended to be used for a specified purpose.

The methodology gives a general procedure for ***measurement of distances*** via the Correvit system. Based on the fact that its text is generally formulated, it can also be used in the other types of measurement (as for the road vehicle driving performances) that are realized on the same principle with using the Correvit system [40]. In accordance with its version, the speed, time, acceleration, deceleration, track or any dynamical vehicle driving tests can be measured without problems. The second methodology of the Department of Road and Urban Transport is called "The measuring methodology for real bus-stop distances of mass passenger transport lines" (Number of methodology: 02/2002/KCMD). This methodology was validated and approved by the Ministry of Transport, Posts and Telecommunications and it is recommended to be used for a specified purpose. It gives the principles and procedures for measurement of ***real distances***, the results of which constitute the basis for determination of tariff distances between the bus stops on the transport lines. Both methodologies are used for measurements in the Slovak Republic.

5.2 Research methods

The following measurement instruments and metres, or some of their similar character, are used for measurements of the bus-stop distances in compliance with texts of the above-mentioned methodologies. These are used for measuring the required quantities while providing necessary accuracy of measurement:

- Measuring and reporting instrument CORREVIT (s. no. of the microwave sensor: 21.0336); Manufacturer: CORRSYS DATRON, Sensorsysteme GmbH, P.O. Box 1349, 35523 Wetzlar, Germany
- Tape measure 50 m (STN 25 1150.2) - *specified measuring instrument;* Manufacturer KINEX, a.s., Bytca.
- Multimeter METEX INSTRUMENTS M 3860D.
- Level.

CORREVIT from Corrsys Datron (Figure 1 and 2) was used as a measuring and reporting instrument for measuring the real bus-stop distances. The operating principle of Correvit is a method of optical correlation. It does not require a strictly defined structure (such as a measuring grid located on the surface measured).

It operates with a random stochastic structure of a monitored object's surface (road surface, rail, belt of rolled steel, textile, paper and the like). Random non-repetitive distribution of lighter and darker points of the surface monitored means that the light signal reflected from the surface must be processed and assessed on the basis of statistical methods.

The system is used most frequently for measuring the driving dynamic performances of road vehicles since the measurement is contactless and it means that the results are not burdened by a drive slip and abrasion of tyres. For these reasons, the measurement can be performed on different surfaces (asphalt, concrete, snow, ice etc.) and in any terrain.

Depending on a type of sensor used (the so-called measuring head), the system makes it possible to determine the speed, track, acceleration, deceleration, vehicle performance while coasting and to monitor the angles of vehicle rolling and drifting.

This instrument consists of three basic components: a microwave optical sensor (Figure 1), an evaluation and control unit and a control panel of service and display unit (Figure 2). By means of the level and measure tape, the horizontal plane and prescribed height of the optoelectronic sensor were set, which are necessary for the instrument to function properly.

The main part of the CORREVIT system is developed by an efficient and precise optoelectronic sensor, not only designed for tasks solutions at measurement of dynamic characteristics of the road transport, but it has greater applications as well, such as measuring the distances, driving time and the like. It enables touch-less scanning of the vehicle's speed in the longitudinal direction from 0.5 to 400 km.h^{-1} with accuracy of ± 0.5 % and is confirmed by the calibration protocol.

A microwave optical sensor provides accurate, reliable and contactless measurement of the speed and length via using technology based on the Doppler effect. The unit detects relative motion between the unit itself and the testing surface by a planar antenna, which emits two radio beams in an angle of 45 °. After reaching the surface, the beams are reflected back to the antenna. The resulting dual frequency (equal to difference of received and transmitted frequencies) is directly related to the speed.

This dual beam planar system enhances the accuracy by automatic compensation of errors caused by the surface unevenness. The signal received is converted to required quantity via RISC - a board central processing unit and then sent to relevant outputs. Thanks to effective working range from 300 mm to 1200 mm, the microwave optical sensor may be used in applications demanding greater distances without the loss of accuracy. The basic data on the measuring instrument used are given in Table 2.

Prior to measurement of the bus-stop distances, the measuring and reporting instrument CORREVIT from

Figure 1 *Attachment of the microwave optical sensor*

Figure 2 *Evaluation and control unit (left) and control panel (right)*

***Table 2** Basic specific data on Correvit*

Measuring range	
Test range	0,5 - 400 km/h
Location	300 - 1200 mm from the Earth's surface
Speed accuracy	< 1% of the test value
Distance accuracy	< 0.5% (>2 00 m)
Reproducibility	< 0.25% (the test distance 200 m)
Inputs/outputs	
Pulse output	compatible with TTL
Analogue output	0 ... 10 V, proportional to the speed
Serial interface	compatible with PC, RS 232
Pulse input	compatible with TTL
Transmission frequency	24.125 GHz (± 50 MHz)
Transmission power	< + 25 dBm, (source 5mW)
Light beam angle	2 x 45° ± 10° lengthwise
Light beam angle	90° ± 7.5° transverse
Power supply	9 - 32 V DC, 10 W
Operating parameters	
Operating temperature	- 20 °C to + 60 °C
Protection	Sensor head IP65
Shocks	6 ms
Vibrations	10 ... 150 Hz
Dimensions	
Sensor	166 mm x 44 mm x 108 mm
Evaluation unit	170 mm x 45 mm x 125 mm
Weight	
Sensor	550 g
Evaluation unit	800 g
Length of cables	5 m

***Table 3** Distances measured and deviations of the measuring instrument on the standard and calibrated track of 1,000 m*

Order number	Distance measured by Correvit [m]	Deviation from the standard track [%]
1	1,002.16	0.216
2	1,001.96	0.196
3	1,002.58	0.258
4	1,004.21	0.421
5	1,003.71	0.371
6	1,003.46	0.346
7	1,002.87	0.287
8	1,003.18	0.318
		0.302

Corrsys Datron was verified in a certified and accredited calibration laboratory, resulting in a calibration certificate, which provides information on the speed of the sensor guaranteeing the quality and measurement accuracy of the device.

The calibration also involved verification of measurement for distances by Correvit. ZTS Elektronika SKS, s.r.o. Accreditation - Calibration Laboratory is an owner of certified measuring track 1 000 m long, which was measured by laser and geodetically by GEO3 Trencin, s.r.o. company. On this track, there were 8 measurements for distances performed and their results are shown in Table 3. The percentage deviation of each measurement from the standard (certified measuring section) and the overall average deviation of the measuring instrument Correvit of 0.302% were further calculated.

Based on the fact that in the most cases of measurements for distances by the CORREVIT system (especially when measuring the distances between the bus-stops of mass passenger transport lines) the conclusion of measurement results is based only on the sole independent measurement (from the economic reasons and after the client's agreement), the measurement uncertainty is expressed by a limit error of the CORREVIT system declared by the manufacturer, i.e. < 0.5% (see Table 1).

The manufacturer guarantees the measurement accuracy in terms of technical parameters of the measuring instrument CORREVIT, specified by calibration measurement.

5.3 Measuring the reals bus-stop distances - case study

The measurement itself for real bus-stop distances of mass passenger transport lines was performed *incrementally* for a certain journey section. It means that the beginning of measurement is in the departure bus stop (starting point) and the end is in the following, pre-determined measuring point of a transport line.

The vehicle started after being commanded by the head of measurement and was driving straightforwardly, if possible, on the track surveyed. The speed, driving mode and measurement conditions within measuring the bus-stop distances of mass passenger transport lines are compatible with operating conditions and are agreed prior to measurement itself. The driver ran and stopped the vehicle always at the pre-determined and agreed place, which was still at the same place of each bus stop, for example at the bus stop sign as in the real service.

After the vehicle was stopped in the respective measuring point by a control panel, the values measured, i.e. the distances between individual measuring points (bus stops), were stored in the measuring instrument's memory for further processing.

The measurement for the real bus-stop distances of mass passenger transport lines is usually performed by one measuring on the client's determined transport road, one-way from the departure bus stop to the end bus stop of the bus service and vice versa, due to different arrangement of the bus stops in the opposite way.

***Table 4** Examples of measurement results regarding the bus-stop distances*

O.N.	Note	Bus stop 1	Bus stop 2	Number of measurements by Correvit	Journey length (m)
1		SAD	Prievidza, tehelna	236	676.3
2		Prievidza, tehelna	Prievidza, Nestle	237	426.9
3		Prievidza, Nestle	Prievidza, aut.st.	238	1,115.4
4		Prievidza, aut.st.	Prievidza, L.Ondrejova	239	1,509.2
5	transition	Prievidza, L.Ondrejova	Prievidza, hotel Magura	240	2,566.1
6		Prievidza, hotel Magura	Prievidza, L.Ondrejova	241	1,857.7
7		Prievidza, L.Ondrejova	Prievidza, aut.st.	242	1,592.9
8		Prievidza, aut.st.	Prievidza, Prior	243	907.1
9		Prievidza, Prior	Prievidza, Necpalska	244	753.9
10	transition	Prievidza, Necpalska	Okruzna krizovatka - Prievidza, Necpalska	245	1,704.6
11		Prievidza, Necpalska	Prievidza, Prior	246	809.6
12		Prievidza, Prior	Prievidza, aut.st.	247	891.9
13		Prievidza, aut.st.	Prievidza, Necpalska	248	833.9
14		Prievidza, Necpalska	Nedozery-Brezany, zel.st.	249	4,764.0
15		Nedozery-Brezany, zel.st.	Nedozery-Brezany, Brezany, Jednota	250	560.7

For the data processing and evaluation, the software CeCallWinPro 1.09.001 was used. Here, the microwave system works as an all-inclusive system for the data collection and evaluation. Software's functions can store the testing parameters and corresponding description permanently, together with online display and evaluation (e.g. creation of graphs, tables). All the data measured may be stored and evaluated later in the off-line mode, as well. The data are given clearly in the form of a table with required parameters and these can be further handled meaningfully. The data being exported to the XLS were time, track, speed, acceleration or deceleration in a time period of each 0.1 second.

Within one of the real measurements of selected suburban transport lines in the area of the Self-governing Region of Trencin, there were 141 measurements performed. According to the methodology approved, the Protocol from the measurement results is being issued. The measurement results are given in a tabular form including all the selected bus-stop distances (sections) of mass passenger transport lines (Table 4).

When required by a client, the tariff distances for suburban or urban public passenger transport lines under Slovak legislation are defined, as well.

6 Discussion and summary

The transport services consist in changing place; hence, it is natural for the service users to pay for the covered distance. Moreover, part of costs depends on the distance, on which the transport is provided. Time tariffs are used in the urban transport practice, their advantage is the ease of use; in addition, to some extent they reflect the involvement of resources of the service provider, because some costs depend on time. It is possible to mention depreciation calculated based on the time and personnel costs, payroll, including the vehicle drivers, as well. The premises for their use resulted from the ease of price differentiation in that respect, however, for the service users it is the changing of location that is important and not being in a means of transport; the service users would prefer the service to be as short as possible. Contrary to other services or purchased products, in which processes of their creation are not attended, the movement consumes the time of service users, during the ride it is difficult to utilize this time in another way. Albeit in a situation, when during the travel the distance is covered all the time, the feeling of lost time is weaker than if people are waiting at stops or lose time during transfers. It should be added that in many cases the value of time for travelling and assessing it as lost, is many times higher, than the ticket price. Hence, considering the relationship between the costs and travel distances as well as the very subject of work in the transport services, which consists in the change of location, it is advisable to use tariffs making the fare dependant on the distance.

In the case of transport entities, the creation and updating on a current basis of a stop distances database is necessary and indispensable during the business running. These are the data necessary for timetables themselves, settlements of costs and various payments, if they depend on the distance. As a result of measurements, a database is obtained with actual distances; these figures should be updated, e.g. if a stop location is changed, if the traffic organization changes, or routes are corrected and changed. The actual distances may be used in price lists, containing information on the applied rates and may be the basis to calculate the fare. However, in some cases it is also possible to adopt the tariff distances, hence distances, which were intentionally corrected, so that as a result, the amount of fare for covering a specific section would change, as well. In particular this can be applied in situations where:

- between indicated stops various route variants exist, or various lines run along different routes, then different prices would be illogical, the more so if the route for a given line is chosen by the carrier,
- vehicles travel between stops on a longer distance, despite the fact that also a shorter one is possible, however, for various reasons the latter has not been chosen, for example it runs via dense development and there is no stop on the route, so the minimization of vehicles environmental impact is pursued,
- temporary diversions result from road closures due to repairs or other reasons.

Attention is drawn to the fact that measurements should be carried out precisely, in accordance with the adopted rules, because the obtained values are the basis for price calculation and deviations, if any, may be treated as a breach of consumer interests. It is also good to make measurements for possible routes, if any, so that at changes it would be not necessary to make measurements each time. As a result of measurements sufficient and known, accuracy is obtained, which would not necessarily be possible using maps.

The systems of e-tickets create great possibilities in the field of more innovative and flexible price differentiation and concessions defining, as well as promotions management. The use of IT technologies results in possibilities to introduce distance charging, i.e. section-based tariffs, without any difficulties for passengers. Various solutions can be used in this case, including also charging based on localization systems and defining the travel routes and distances from maps. This can be an alternative tariff for their calculation and its advantage consists in making the price dependent on the travelled distances, which may be important, in particular for the short-distance travels.

In recent times, there has been a higher demand for the measurements of tariff bus-stop distances of suburban bus transport in the Slovak Republic from the ordering parties of public transport services, namely the self-governing regions. This especially includes preparation of documents for procurement procedures for the next 10 years and the ordering party usually requires the real kilometres on the bus transport lines in the self-governing region or town. So, it is not only a tariff distance issue, which is very important for the passengers, but it is necessary to specify the transport performances, which enter the reimbursement of the economically substantiated costs and the adequate profit.

The distances of the bus stops were measured and determined by the Slovak state until 1990 through the Road Transport Institute. After 1990, the Slovak Republic did not appoint an independent organisation to take patronage over this professional activity. When building the new bus stops, determination of the tariff distances has been given to the hands of transport services suppliers, i.e. to the carriers. Here, it has led continuously to some disproportions and the measurement independence has lost. For instance, the transport performance for one carrier in the Self-governing Region of Kosice in the Slovak Republic is more than 12 million km per year and for the second one it is more than 14 million km. If the measurement accuracy of a properly determined transport performance is only 0.5 %, it is 140,000 km per year and 1,400,000 km per 10 years. When the economic price of performance is for example 1.6 EUR/km, it equals to a sum of EUR 2,240,000, which may not correspond to the transport performances provided.

In relation to the zone tariffs in the integrated transport systems, there is no problem with a correct tariff distance, if the zone tariff is used (in the Bratislava region for example), however, the integrated transport's organizer interests in the measurement for the real bus-stop distances of the bus transport lines due to fair funding for public passenger transport over the real performances realised. Given the size of the Slovak Republic, it could be effective that the Ministry of Transport and Construction of the Slovak Republic establish and fund one single information system of the bus stops of public passenger transport including the bus-stop distances with its regular update.

7 Conclusions

The essence of the transport activity consists in covering a distance and a part of costs components and thereby the total costs, increase with the distance covered by means of transport. In a similar way the calculation of fares depending on distances may be considered most appropriate from the point of view of transport as a service. Inaccuracies and deviations during the distance measurements have various results, which further on may have effect on analyses, comparisons, correctness during the fare calculations, as well as settlements related to public financing of the public transport. An independent and precise distance measurement is indispensable to eliminate the impact of the measurement method on distances.

In the urban and regional transport there are different approaches in differentiating the prices and considering the travel distances. In the case of uniform tariffs the distance does not differentiate the fare, in the zone tariff the fare goes up only after a tariff zone boundary crossing and for section-based tariffs the amount of fare increases with the increase in the covered distance. The development of systems, which enable automated calculation of fares, using e.g. automatic localisation, enables the application of section-based tariffs on a larger scale. In comparison to the uniform or zone tariffs their advantage consists in a lower fare at short-distance rides and a higher fare when travelling long distances. This is a premise of increasing the transport volume, because the feeling of overly high fare at short-distance rides is less strong, but on the other hand it is possible to apply higher prices at longer-distance travels, hence in a situation when the sensitivity to them is lowered. Obviously, in the systems, in which the uniform or zone tariffs have been used for many years, the section-based tariff may be one of tariff options, to be chosen by passengers.

Acknowledgment

This research was funded by the project of institutional research of the Faculty of Operation and Economics of Transport and Communications, University of Zilina no. 2/KCMD/2021 Research on the impact of urban logistics on the environment.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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ANALYSIS OF THE LENGTH OF HIGHWAYS AND THE NUMBER OF MOTOR VEHICLES IMPACT ON THE INTENSITY OF ROAD ACCIDENTS IN SELECTED EUROPEAN COUNTRIES IN 2010-2020

Damian Frej, Emilia Szumska*

Department of Automotive Engineering and Transport, Kielce University of Technology, Kielce, Poland

*E-mail of corresponding author: eszumska@tu.kielce.pl

Damian Frej 0000-0003-1899-4712, Emilia Szumska 0000-0001-6024-6748

Resume

The main purpose of this study was to compare the frequency of road fatalities in selected European countries, including Poland. Moreover, based on statistical data, the determination index R2 was determined for both the total number of road accidents and fatalities in road accidents in terms of the number of registered vehicles and the length of motorways in selected European countries. Results show the dependence of factors, such as road infrastructure and the number of registered motor vehicles, influence on the level of road safety in selected European countries.

Article info

Received 8 September 2022
Accepted 22 November 2022
Online 13 December 2022

Keywords:

road accidents
collisions
road safety
passenger vehicle

Available online: https://doi.org/10.26552/com.C.2023.012

ISSN 1335-4205 (print version)
ISSN 2585-7878 (online version)

1 Introduction

The behavior and driving style are individual for each driver. Although the driving process is largely supported by electronic safety systems (ADAS), the attention and behavior of the driver have a decisive impact on the road safety. While driving the vehicle, the actions of driver also influence other road users. The dynamically changing road situation forces the driver to quickly assess events and make precise decisions. The amount of information and signals reaching the driver may cause them to misjudge the situation and to react incorrectly, which may lead to a dangerous traffic incident. When analyzing all the risks in road traffic, three categories of accident causes can be listed [1-2]:

- man-made hazards, in all the situations and events, which arise as a result of the driver or another participant in an accident (pedestrian, cyclist) behavior;
- threats caused by natural forces, such as fog, blizzards;
- threats resulting from infrastructure defects, e.g. defects in the road surface.

The human factor is one of the most common causes of the road accidents and collisions. The former may occur as a result of the psychophysical features of drivers, non-compliance with the road traffic regulations, or the lack of driving skills [3]. Advanced research on influence of a person’s psychophysical predisposition on their behavior in the road traffic was carried out in the 1980s [4-7]. Since then, there have been numerous studies and projects focused on determining the influence of the personality, character and emotional state of the driver as well as their skills and individual habits on their driving behavior.

How a driver’s personality influences their driving style is of interest to the transport psychology specialists and road safety scientists. The results of the research presented, among others, in the works [8-10], confirm that the personality of the driver can influence the behavior while driving. Certain personality traits may more define a specific driver behavior on the road. Likewise, individual driving skills and experience contribute to it, as well. The research results presented in the works [11-13] show that the age of the driver and experience in driving have a significant impact on the road safety. The authors showed that older drivers with more driving experience have a higher awareness of the risk of road incidents and are less likely to perform dangerous maneuvers. The surprising research results presented, among others, in the works [14-16], show that drivers characterized by a high level of perceptual and motor skills show a riskier driving style. This is evidenced by the number of accidents committed by them and received fines.

The emotional state of the driver can also influence the driving behavior. Emotions that accompany the vehicle driver, e.g. fatigue, drowsiness, depression, worry, nervousness or anger affect the manner of driving and performing road maneuvers. The research results included, inter alia, in works [17-20], show that when a driver is tired, sleepy, sick or bored while driving, they incline to a more careful driving style. Conversely, if the driver is depressed, worried, nervous or angry, they drive the vehicle more aggressively.

Due to the individual characteristics and skills of the driver influencing driving behavior, the term "driving style" has been developed. Driving style refers to the way the driver habitually drives the vehicle. It is based on a combination of the driver's cognitive, emotional, sensory and motor factors [21]. Driving style is generally believed to determine the manner in which the road maneuvers are performed. In the work [22], two groups of factors influencing the driving style were distinguished: subjective factors and objective factors. The subjective factors are: psychological characteristics, physiological characteristics (age, gender), social characteristic (occupation, income). The objective factors included: road conditions, road type, driving resistance situation (air resistance coefficient, rolling resistance coefficient, acceleration characteristics).

Although each driver has their own individual driving style, there are behaviors that are common to multiple drivers. Thanks to this, common driving style categories were distinguished, characterized by a specific behavior and attitude while driving. There are many classifications in the literature, but the following driving styles are mainly observed [23-26]:

- reckless and careless driving style, characterized by a tendency to drive at high speed and to ill-considered and risky maneuvers;
- anxious driving style, characterized by uncertainty and indecision when maneuvering;
- aggressive driving style, which reflects hostile and aggressive behavior towards other drivers, as well as violent performance of the road maneuvers and non-compliance with the road rules;
- patient and attentive driving style, which shows a tendency to be polite towards other drivers and to behave rationally on the road;
- dissociative driving style, which describes the tendency to be distracted and inattentive while driving and to make driving mistakes related to a lack of concentration.

Much work and projects have been devoted to development of algorithms which recognize and determine the driver's driving style for the purposes of the ADAS systems. Based on selected parameters, e.g. acceleration, engine speed, position of the accelerator and brake pedals, the algorithm determines the driving style of the driver. The driving style category information is then used to determine how the assistance systems are adjusted to the driver's characteristics. This solution increases the safety and comfort of driving - especially if the driving style is defined as aggressive (dangerous). Examples can be found, among others, in works [27-29].

The phenomenon of road accidents and fatalities in road accidents has been an interesting issue for many researchers around the world for years. Road accidents in the works [30-33] are considered as an individual case of the driver's behavior. In the work [34-35] the intensity of the road accidents is comparable to the European Union countries. In the works [36-37], road accidents are subject to statistical analysis in order to divide the European Union countries in terms of the road safety. In the works [38-39], the number of road accidents and the number of fatalities in road accidents is analyzed in the assumed period of time in order to better understand their intensity. It should be noted that in the works [40-42] the intensity of road accidents in selected European Union countries is analyzed with help of forecasts in order to show the problem of road accidents.

As mentioned before, many factors can affect the road safety. There are still a large number of accidents and collisions on the roads, with a significant number of casualties. The aim of this study was to present the number of road accidents which involve fatalities, in Poland and European Union countries. The study analyzed the number of accident victims in terms of a specific day of the week and time of day.

2 Methodology

Social and economic losses of road accidents in Poland and in EU Member States indicate the need to develop the road safety programs. Due to the long-term activities of the adopted programs heading to the improvement of road safety, it is necessary to develop the low-cost projects to eliminate dangerous places of occurrence of the road accidents occurrence. It is also important to determine in statistical terms the impact of parameters such as the number of vehicles, the age of vehicles, the length of motorways and expressways, the number of electric vehicles, or the age of the driver affects the intensity of road accidents and the intensity of fatal road accidents.

This study uses a methodology for analyzing the historical data on road accidents in Poland and selected European countries in order to analyze the impact of the length of motorways, the number of vehicles registered on the intensity of road accidents and the intensity of fatal road accidents.

The coefficient of determination R^2 was used to analyze the relationships between the previously mentioned variables. The coefficient of determination takes values between 0 and 1. The coefficient of determination R^2 in the article explains to what extent the change in the length of motorways and the number of registered vehicles affect the change in the number of road accidents and the number of fatalities in road accidents. The coefficient of determination was obtained as, [43]:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_l)^2}{\sum_{i=1}^{n}(\dot{y}_l - \bar{y}_l)^2}. \quad (1)$$

The coefficient of determination R^2 in this publication is treated as the first parameter determining the impact of selected parameters on the number of road accidents and the number of fatalities. Based on the R^2 determination index and the use of multiple regression, European countries can be classified in terms of the road safety.

3 Road infrastructure

The total length of highways in the European Union and the Schengen area is over 82,000 kilometers. Nowadays, the system of interconnected motorways allows free passage from the border of one state to the border of another state without having to leave the motorway routes even for a moment. Unfortunately, for economic reasons, the motorway networks in individual Member States of the European Union differ significantly in terms of size and degree of advancement. The most extensive network of express roads can be found in the western countries of the European continent. Spain has the longest motorway network, over 17,228 km. In 2020, the total length of highways in Germany exceeded 13,190 km. In Poland, the length of motorways in 2020 was over 1,712 km. Figure 1 presents the characteristics of the motorway length of the European countries in 2010 and 2020. Figure 2 presents the characteristics of the percentage changes in the length of the motorway in European countries. Comparing the condition of motorways from 2020 to 2010, Romania recorded the largest increase of 177%. In Romania, in 2010, the total length of motorways was 332 km and in 2020, the total length of motorways was 920. Poland is the second largest European country in terms of motorway growth in 2010-2020. In the period under consideration, Poland doubled the number of motorways. In 2010, there were 857 km of highways in Poland, while in 2020 there were 1,712 km. Bulgaria is in the third place with an increase of 84% by motorway. Figure 3 presents the characteristics of the length of motorways for selected European Union countries. To compare the length of motorways in 2010-2020, countries, such as France, Germany, Poland, Spain, Slovakia and Romania, were selected. It should be noted that despite the doubling of the length of motorways in Poland in 2010-2020, the length of motorways in Poland is still much shorter than in France, Spain or Germany. It is similar with Slovakia and Romania.

In Poland, in 2010, the total length of highways was 857.4 km and of expressways - only 674.7 km. Figure 4 shows the length of highways and expressways in Poland in 2010-2020. In 2020, the total length of highways in Poland was 1712.2 km and express roads 2548.5 km. In 2020, the length of motorways increased

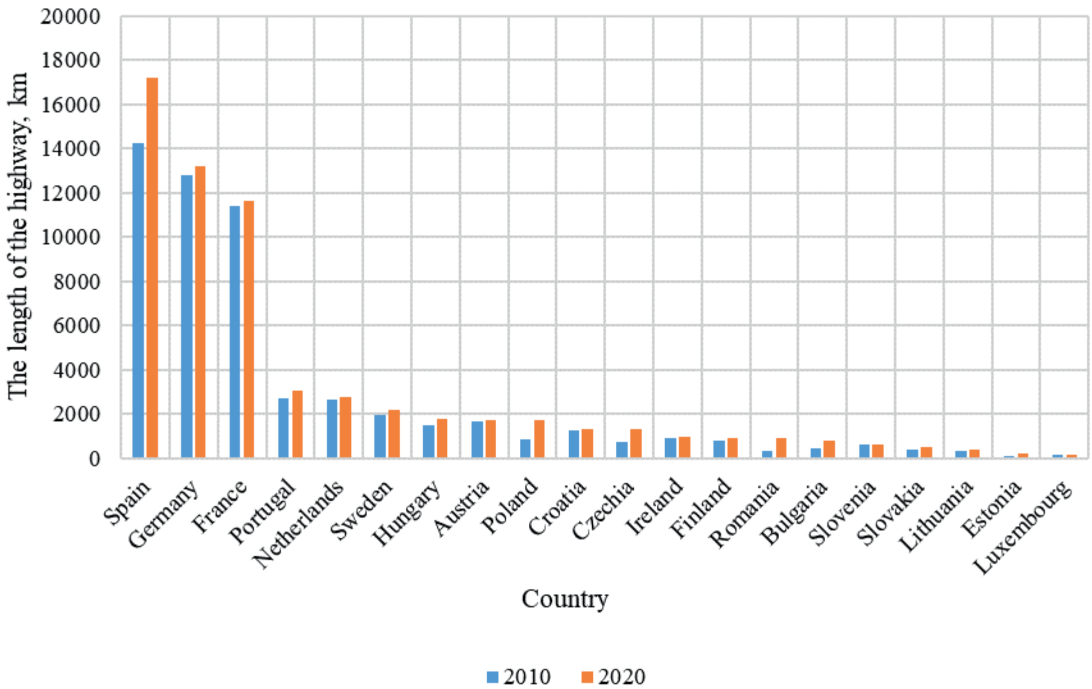

Figure 1 *Characteristics of the motorway length in European countries in 2010 and 2020*

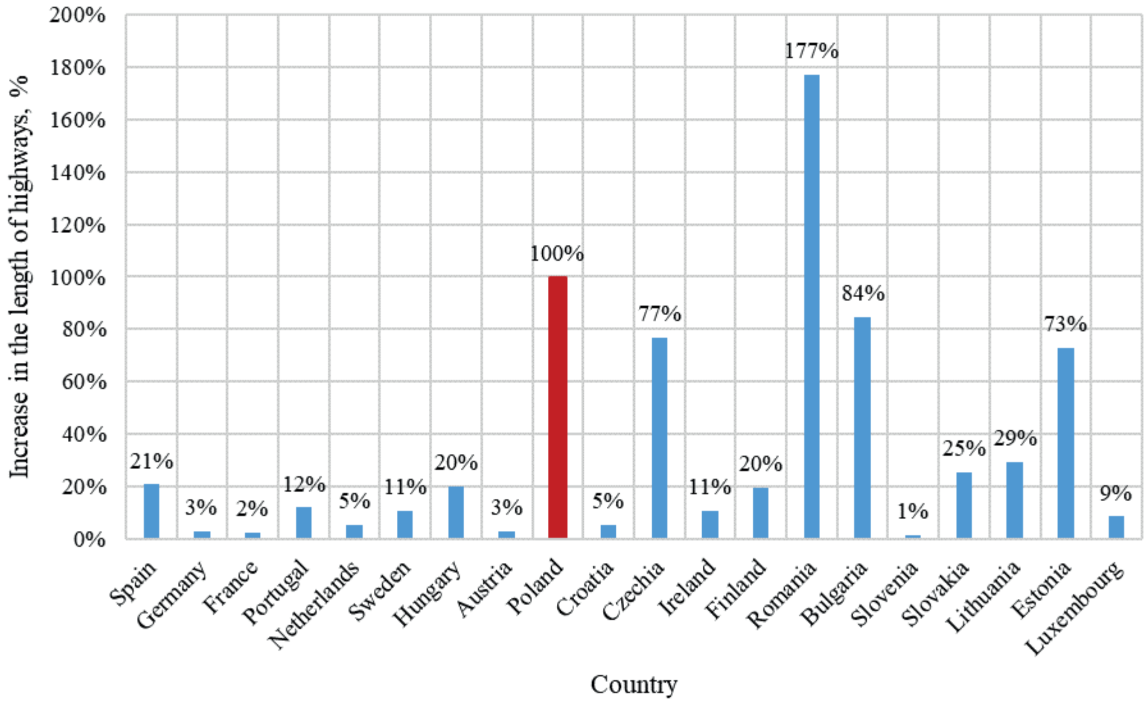

Figure 2 *Characteristics of the increase in the length of highways in European countries in 2020 compared to 2010*

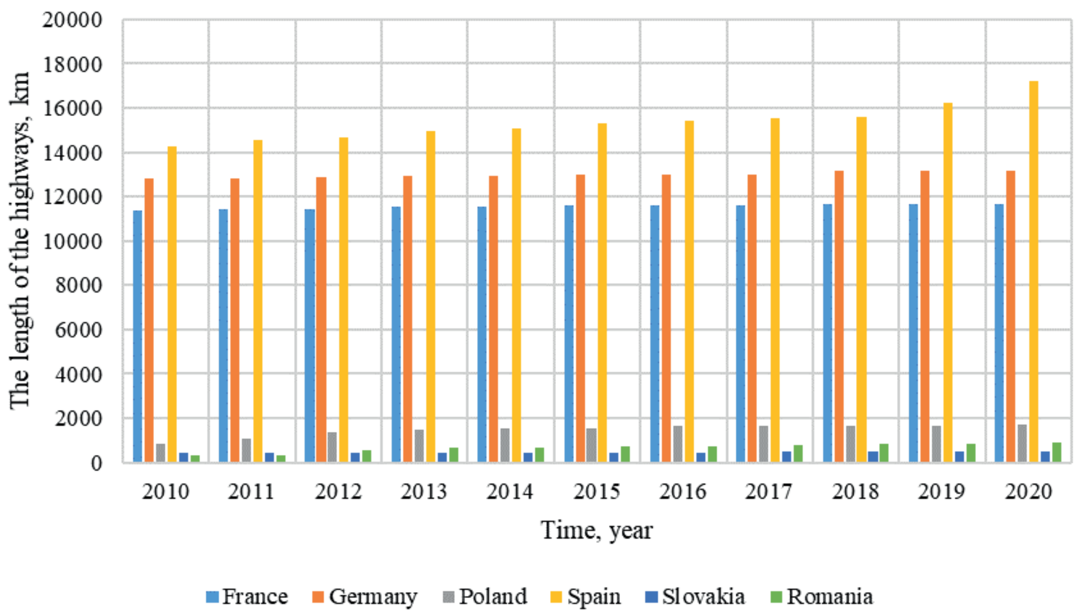

Figure 3 *Comparison of the length of highways in selected EU countries in 2010-2020*

by approximately 100% compared to 2010. The length of expressways in 2020 increased by 297% compared to 2010. Despite the fact that Poland differs significantly in terms of the length of motorways from Spain or Germany, it is pleasing that within 10 years the road infrastructure is subject to continuous development and extension of expressways [44-47].

The number of registered motor vehicles in Poland in 2010-2020 has changed significantly. Figure 5 shows the number of registered motor vehicles in Poland in 2010-2020. This number increased from 23 million (2010) to 33 million (2020) [44-47]. On average, the number of motor vehicles in Poland increases by 3% each year.

The number of vehicles registered in European countries is increasing every year. Most motor vehicles in 2020 were registered in Germany (53,651,934 units) and Italy (44,980,390 units). Figure 6 presents the characteristics of the change in the number of registered vehicles in European countries in 2010 and 2020. Figure 7 shows the percentage change of registered vehicles in

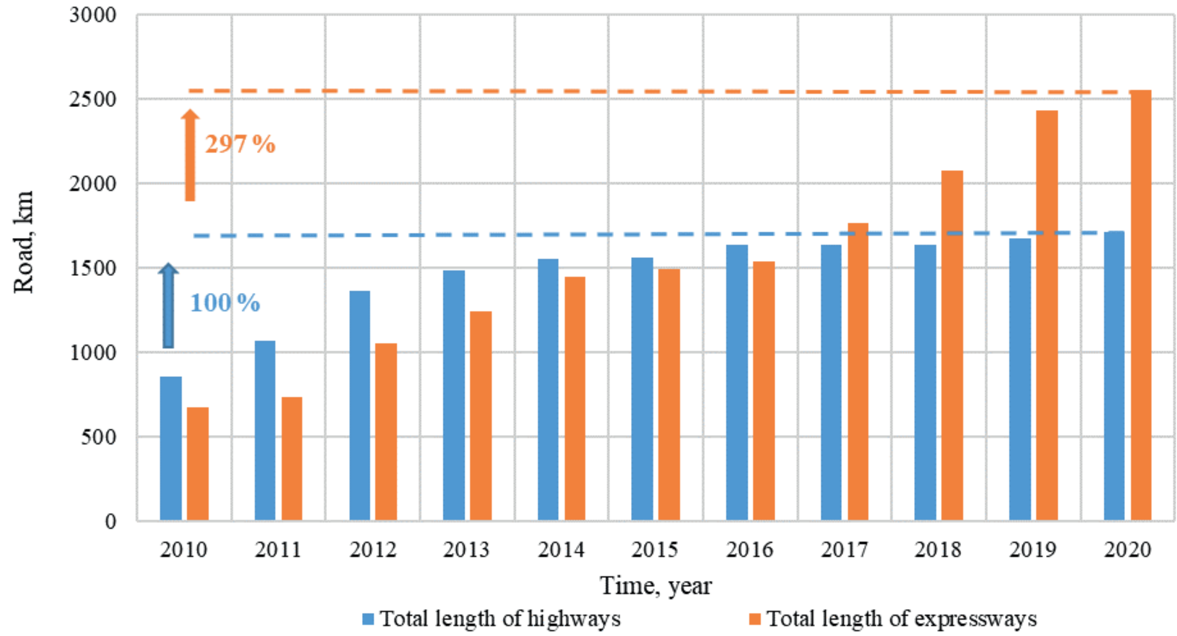

Figure 4 *The length of highways and expressways in Poland in 2010-2020*

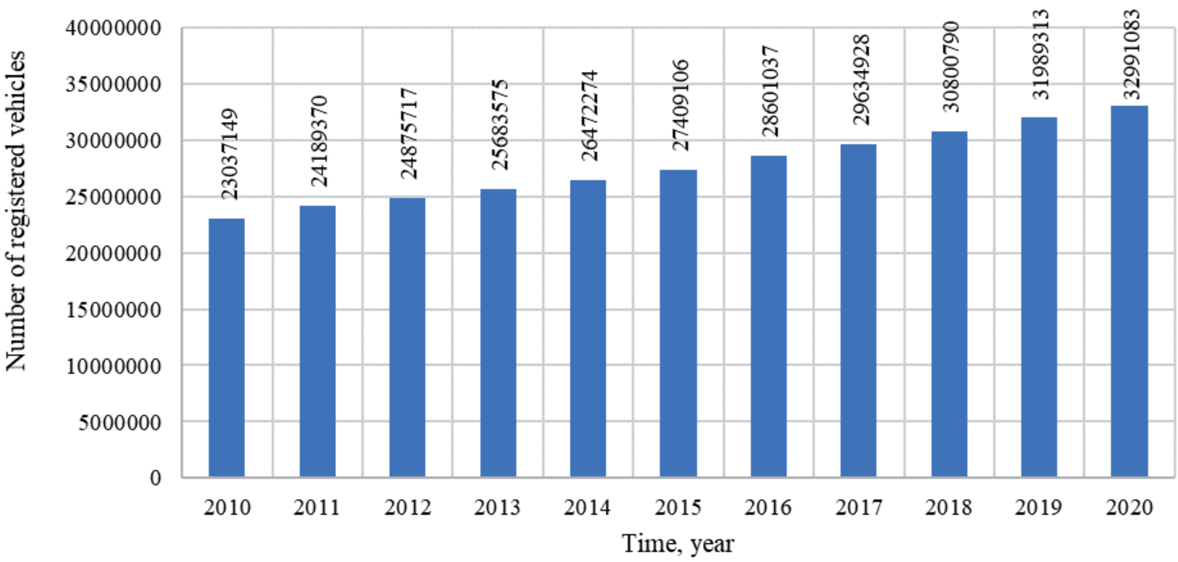

Figure 5 *Number of motor vehicles in Poland in 2010-2020*

European countries in 2020 compared to 2010. It should be noted that in the period under consideration, from 2010 to 2020, the highest increase in motor vehicles was recorded in Romania and amounted to 68%. During that period, the number of motor vehicles in Romania increased from 5,058,500 to 8,518,166. In Germany, during the period under consideration, the number of motor vehicles increased by 16% and in Italy by 8%. In Poland, the number of motor vehicles in the years 2010-2020 increased by 44%. In Poland, in 2010, the number of registered motor vehicles was 20,458,100, while in 2020 it was 29,466,460.

Compared to 2010, in 2020 the number of registered passenger cars in Poland increased by 29%, motorcycles by 36% and trucks by 19% [44-47]. Figure 8 shows the growth characteristics of registered passenger cars in Poland in 2010-2020, while Figure 9 shows the growth characteristics of registered motorcycles and trucks in Poland in 2010-2020.

4 Road accidents in Poland

The road traffic poses a risk of collisions and road accidents. Unfortunately, those events still constitute a serious social problem. Despite many measures taken in Poland and in the EU, it was not possible to reduce the number of fatalities by 50% compared to 2010. The number of road accidents in Poland in 2010-2020 decreased from 38,832 to 23,540 (-39.4 %), while the

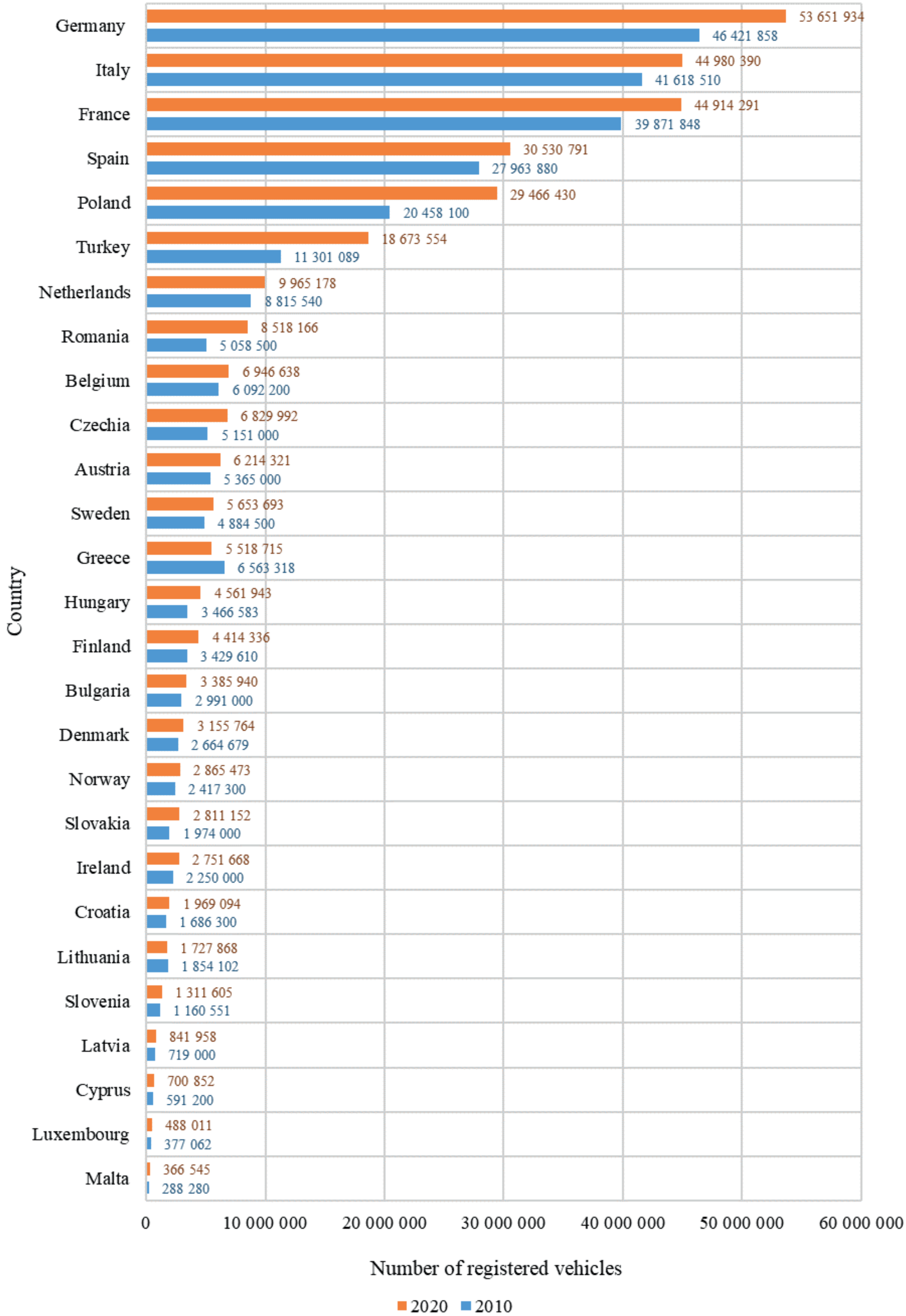

Figure 6 *Characteristics of the change in the number of registered vehicles in European countries in 2010 and 2020*

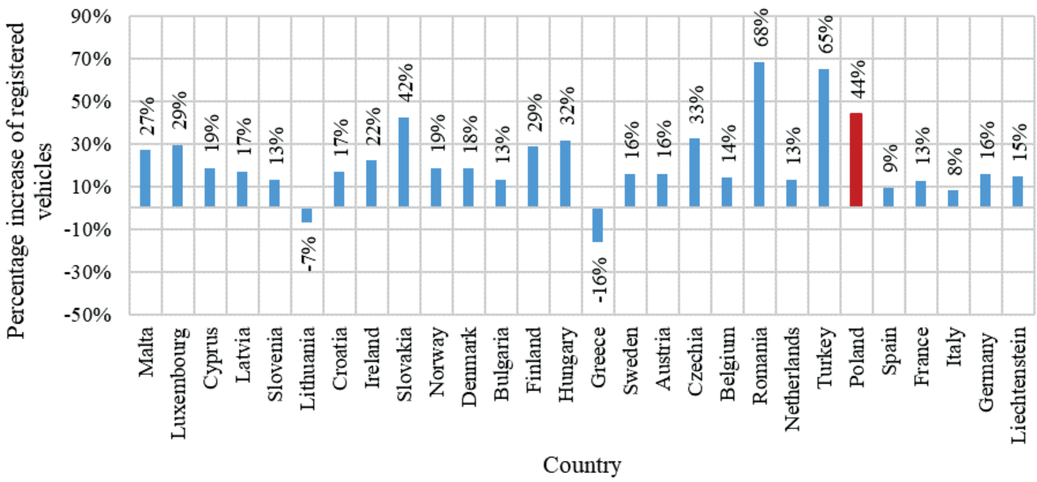

Figure 7 *Percentage change of registered vehicles in European countries in 2020 compared to 2010*

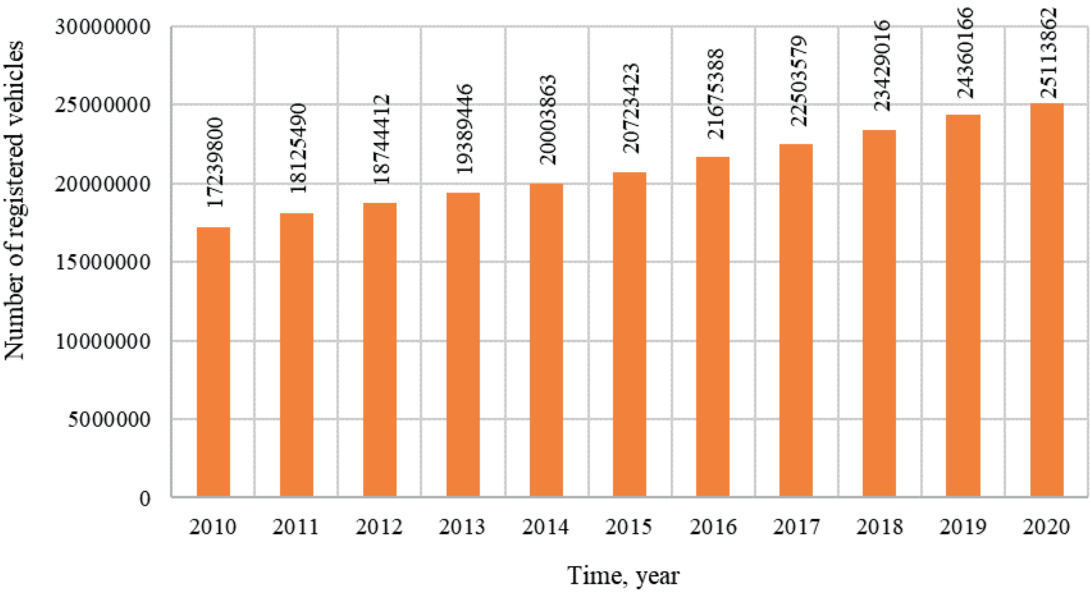

Figure 8 *Variation of the registered passenger cars growth in Poland in 2010-2020*

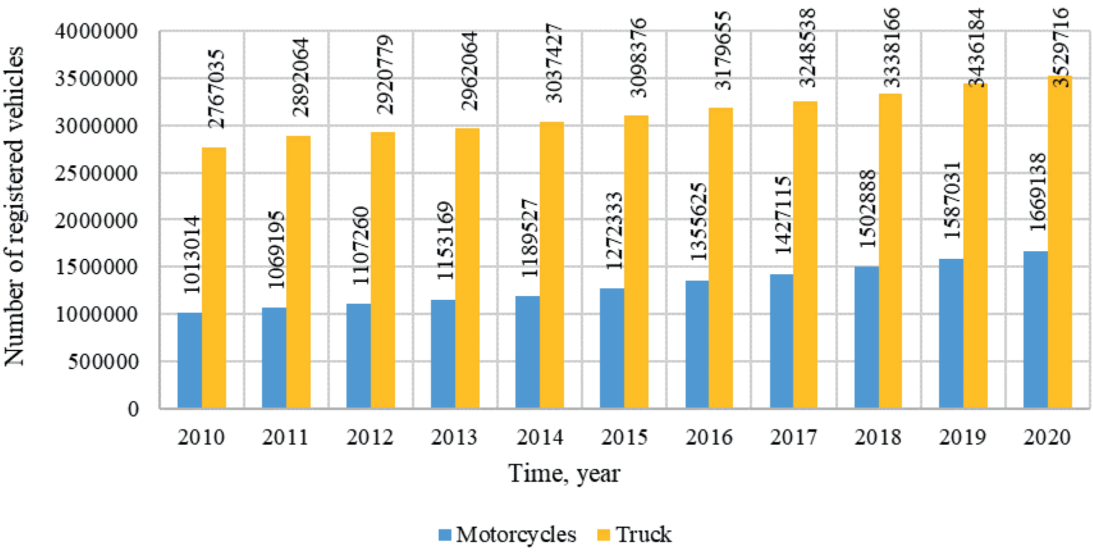

Figure 9 *Characteristics of the registered motorcycles and trucks growth in Poland in 2010-2020*

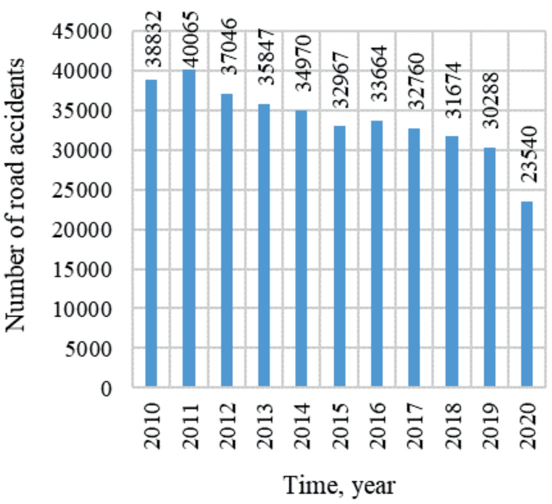

Figure 10 *Number of road accidents in 2010-2020*

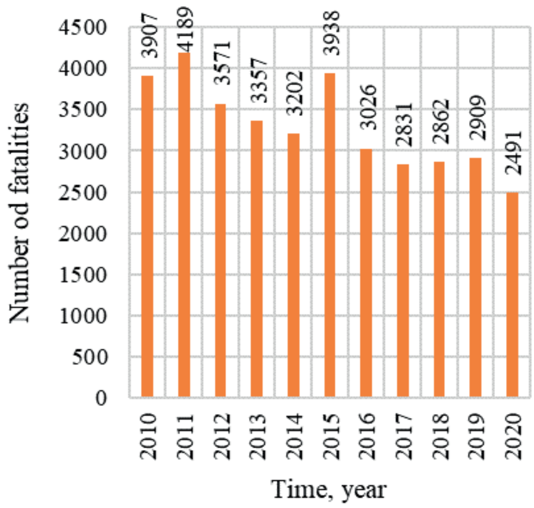

Figure 11 *Number of fatalities in road accidents in 2010-2020*

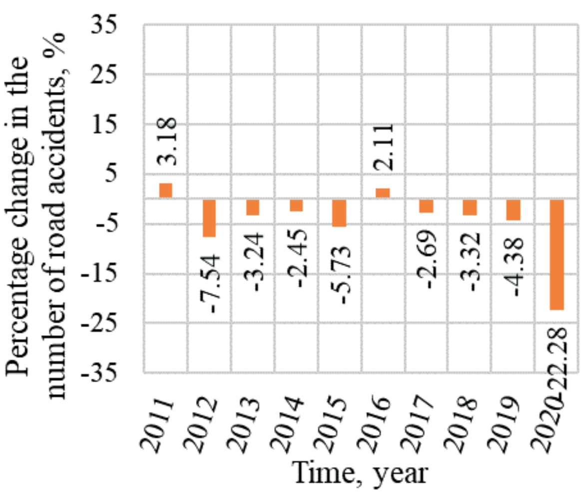

Figure 12 *Annual change in the number of road accidents in Poland in 2010-2020*

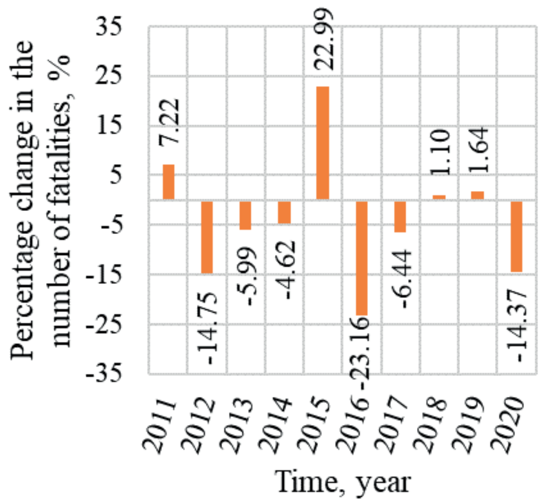

Figure 13 *Annual change in the number of road fatalities in Poland in 2010-2020*

number of fatalities decreased from 3,907 to 2,491 (-36.3 %). Poland, like the EU member states, assumed a 50% reduction in the number of fatalities in the analyzed period. The assumed number of fatalities in road accidents in Poland in 2020 should be 1954. Unfortunately, the real number was higher by as many as 538 fatalities [44-47]. Figure 10 presents the characteristics of the number of road accidents and Figure 11 shows the number of fatalities in road accidents in 2010-2020.

In the analyzed period, the largest decrease in the number of road accidents took place in 2020 compared to 2019 and amounted to -22.3%. Over the last 10 years, only in 2011 and 2016 there was an increase in the number of accidents compared to the previous year. The number of fatalities in 2015 increased in fatalities by as much as 22.9% compared to 2014. In addition, there was an increase in death toll in 2011, 2018 and 2019 [44-47]. Figure 12 shows the annual change in the number of road accidents in Poland in 2010-2020. Figure 13 shows the annual change in the number of road fatalities in Poland in 2010-2020.

5 Road accidents and their consequences

The approach to improvement of the road safety is primarily aimed at ensuring a safe transport system for all the road users. The cornerstone of the road safety improvement system is elimination of the fatal accidents and reduction of serious injuries, as a result of the safe roads and roadsides and the determination of a safe speed for traveling on certain types of roads. At the same time, safety systems in vehicles are under constant development [3, 47]. Every year, road accidents generate huge costs for society. The total number of road fatalities per 1 million inhabitants in the EU decreased by 37% in 2020 compared to 2010. Unfortunately, the number

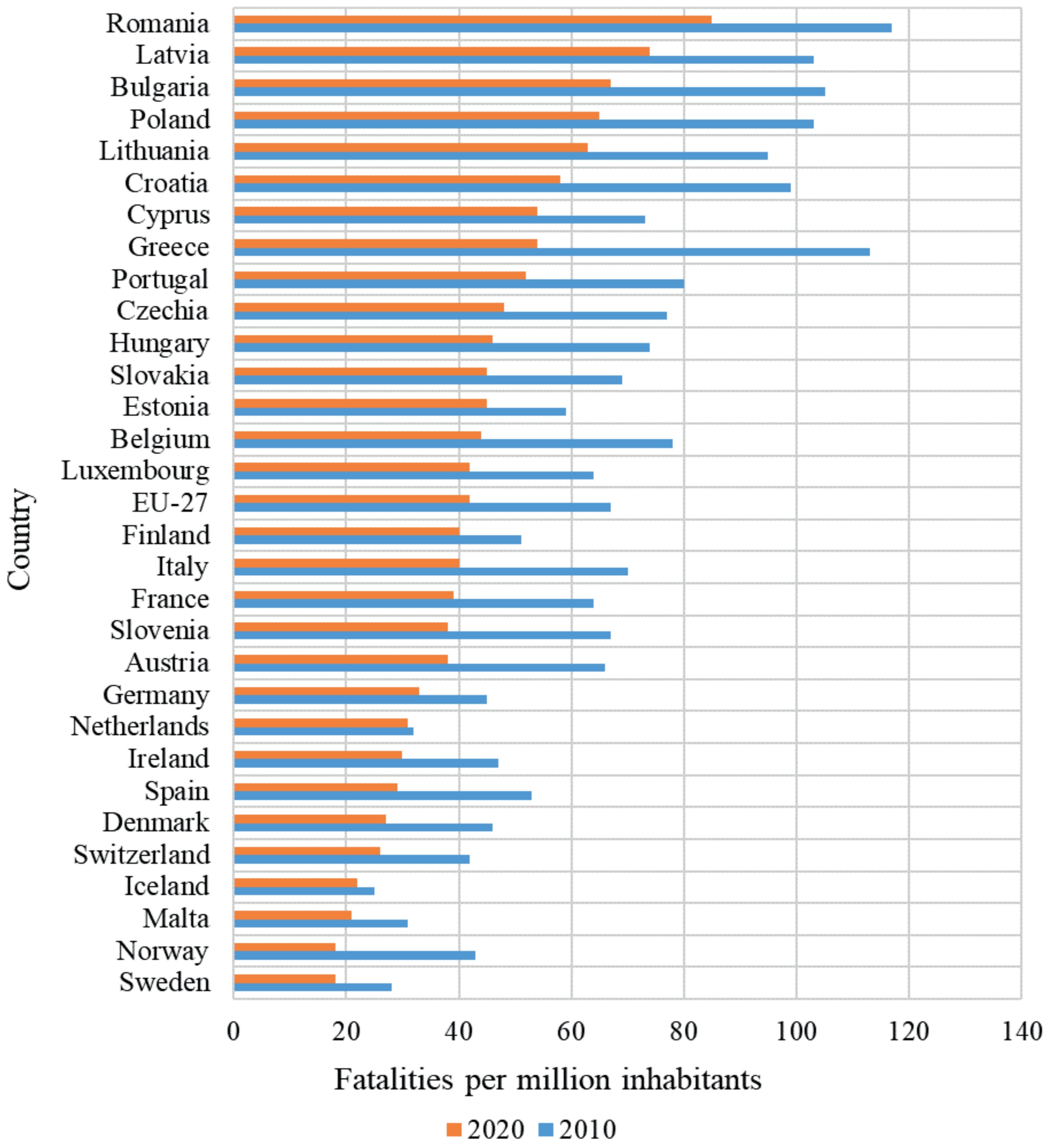

Figure 14 *Number of road fatalities per million inhabitants in individual EU member states*

of deaths per 1 million inhabitants has not decreased in the last decade in all the EU Member States. Among the European Union countries, the lowest number of fatalities in road accidents is noted in Sweden (18 deaths per million inhabitants), while the highest occurred in Romania (85 deaths per million inhabitants). The European Union fatality rate in 2020 was 42 deaths per 1 million inhabitants; this result is almost 5 times lower than the world average, which in 2020 was 180 deaths in road accidents per million inhabitants [44-47]. Figure 14 presents the characteristics of the number of road fatalities per million inhabitants in individual EU member states.

It should be noted that within a decade, Greece and Norway achieved a 50% reduction in the number of road fatalities. Countries such as Belgium, Bulgaria, Spain, Croatia, Italy, Lithuania, Portugal and Slovakia recorded a decline of more than 40%. In Poland, in 2010, the number of fatalities in road accidents per million inhabitants was 103 people, while in 2020 it was 65 people, so there was a decrease by 37% [-44-47]. The percentage change in the number of road fatalities per million inhabitants in individual EU member states in the period 2010-2020 is presented in Figure 15.

The annual change in the number of fatalities in accidents on EU roads shows a downward trend in the period 2010-2019 (Figure 16). The largest annual decrease took place in 2013 and amounted to 8.6% compared to 2012. Only in 2015, the number of fatalities on EU roads increased by 0.9% compared to 2014. The annual downward trend in the number of fatalities in the Member States varies significantly. In Germany, in 2011, 2014, 2015 and 2018, there was an increase in the number of fatalities compared to the previous year (Figure 17). In France, the increase in the number of fatalities occurred in 2014, 2015 and 2016 (Figure 19). In contrast, in Spain, the annual rise in the number of fatalities was recorded from 2014 to 2017 (Figure 18). In Slovakia, the increase in the number of fatalities occurred in 2012, 2014, 2015, 2017, 2019 (Figure 20); on the other hand, in Romania in 2012, 2015, 2016, 2017 (Figure 21) [-44-47].

The number of road fatalities in the EU in 2019 is presented in Figure 22. The highest number of road fatalities in the EU as a whole occurs during the holiday period between June and August. In these months in 2019, the total number of fatalities on EU roads amounted to 6,653 people. The lowest number of road fatalities in the EU in 2019 was recorded in February and amounted to 1,560 people. It can be noted that in Germany, France, Italy, Portugal, Spain, Poland, the highest number of fatalities in road accidents during the year is recorded in the period from July to September. In Romania, on the other hand, the record number of fatalities occurs from October to December (Figure 23) [44-47].

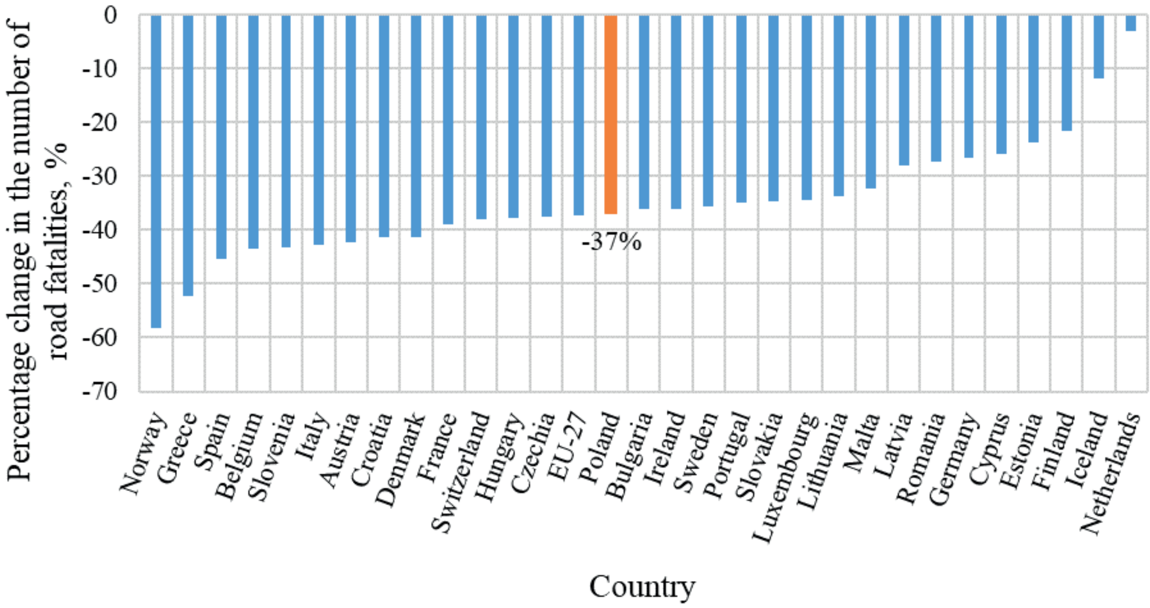

Figure 15 *Percentage change in the number of road fatalities per million inhabitants in individual EU Member States in 2010-2020*

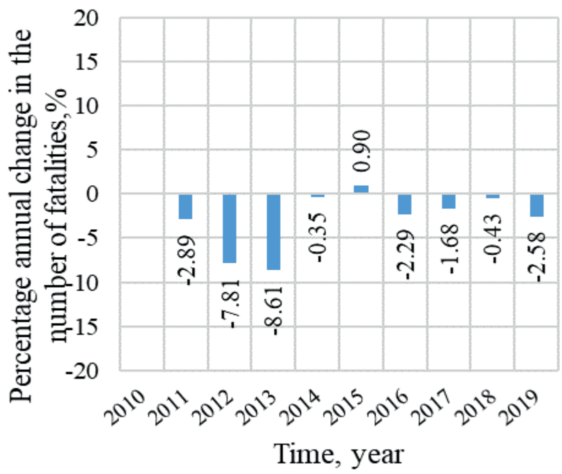

Figure 16 *Annual change in the number of fatalities in accidents on EU roads in 2010-2019*

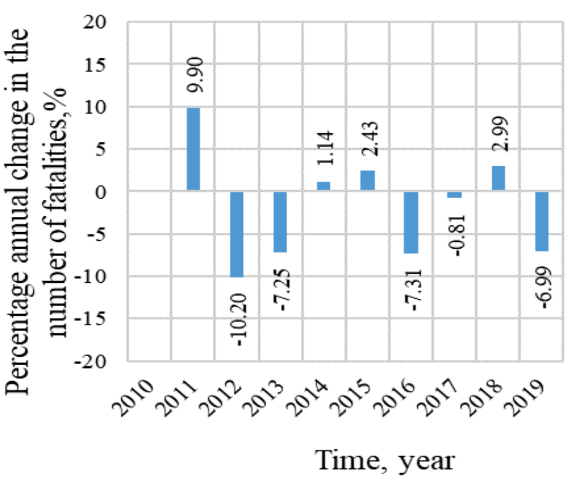

Figure 17 *Annual change in the number of fatalities in road accidents in Germany in 2010-2019*

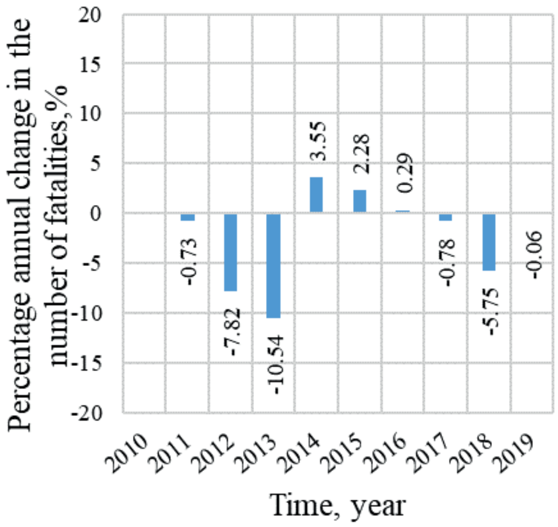

Figure 18 *Annual change in the number of road fatalities in accidents on Spain's roads 2010-2019*

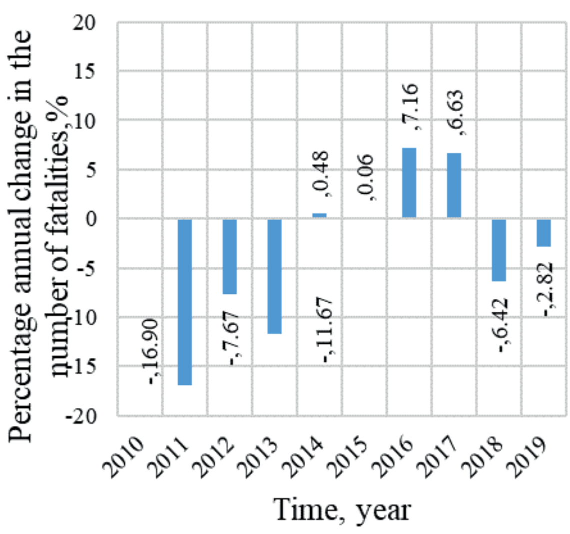

Figure 19 *Annual change in the number of fatalities in road accidents in France in 2010-2019*

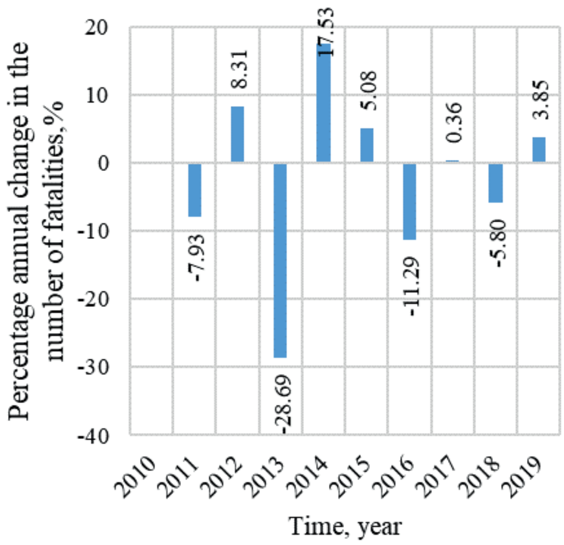

Figure 20 *Annual change in the number of road fatalities in accidents on Slovakia roads 2010-2019*

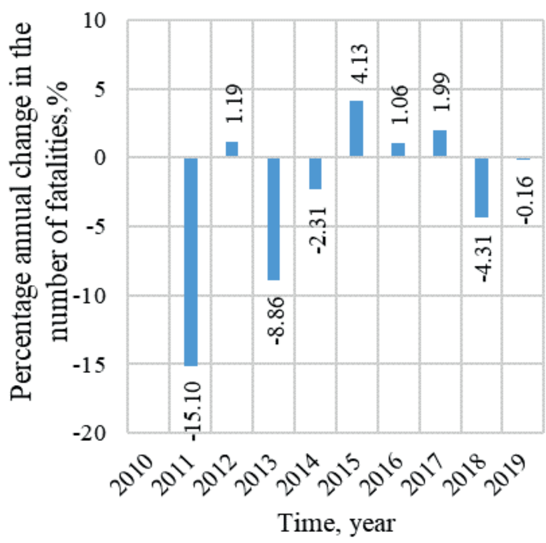

Figure 21 *Annual change in the number of fatalities in road accidents in Romania in 2010-2019*

The number of road fatalities in the EU and selected Member States on specific days of the week is presented in Figure 24. When analyzing accidents in 2019 in the EU, the lowest number of fatalities was recorded on Tuesdays (2,906 victims), while the highest number was recorded on Saturdays (3,782 victims). Similarly, in Poland, in 2019 the most fatalities were noted on Saturdays, 485 victims. In Germany, the highest number of deaths in road accidents in 2019 was recorded on Sundays (464 victims) and the lowest on Thursdays (394 victims). In the case of France and Italy, the highest number of road fatalities was observed on Saturdays [44-47].

The number of fatalities in road accidents by time, in the EU and selected Member States, is shown in Figure 25. It should be noted that the most fatalities in road accidents in the EU in 2019 occurred between 3 PM and 5 PM, while the lowest was at night. A similar situation occurs in Poland, France and Germany. In Italy, the highest number of road fatalities occurred between 6 PM and 8 PM [44-47].

6 Statistical analysis

The number of road fatalities in the European Union and in the Member States is getting smaller every year. Some countries experience an increase in the number of road fatalities in one year, but the overall downward trend is maintained. The "Zero Accident

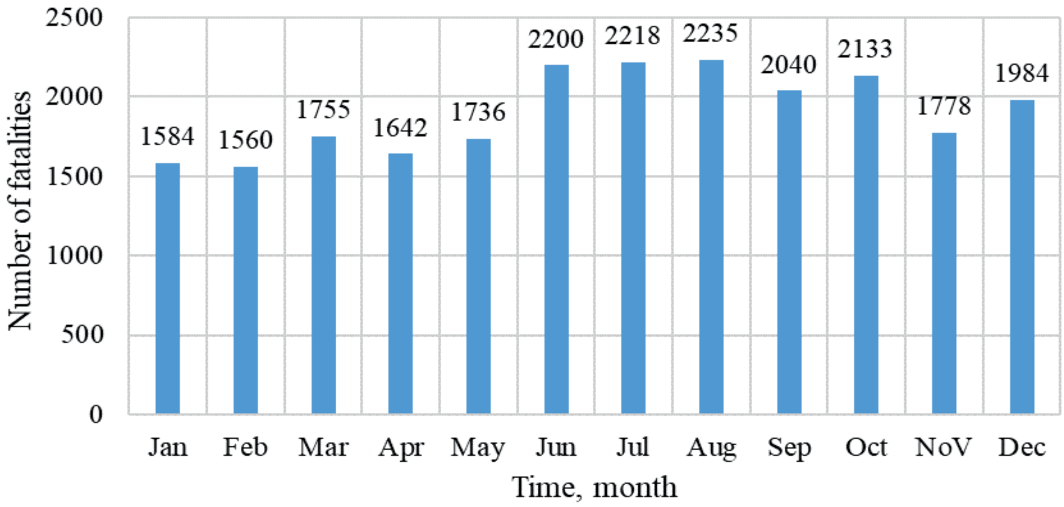

Figure 22 *Number of road fatalities in the EU in 2019*

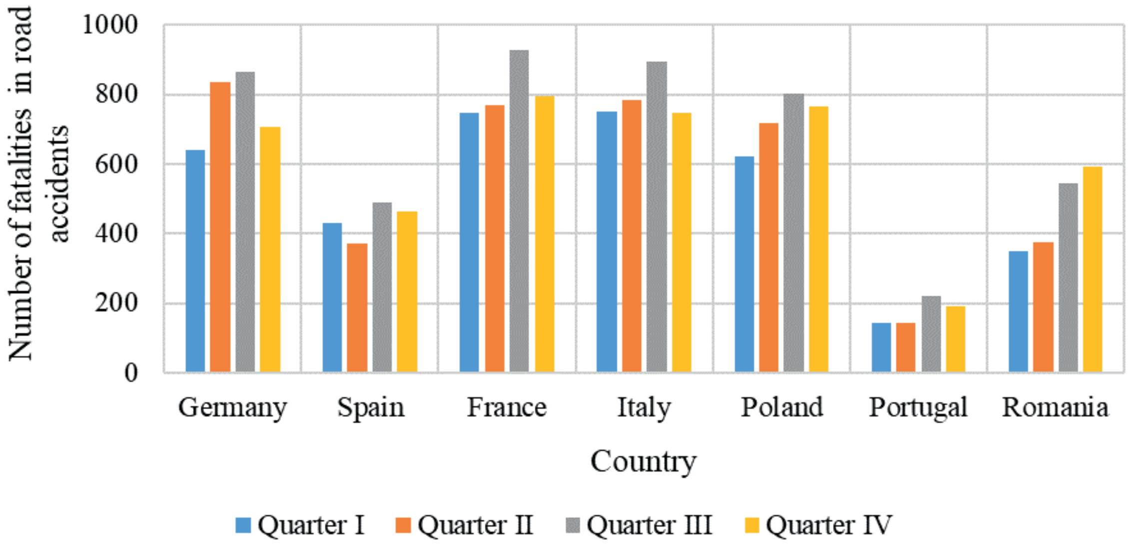

Figure 23 *Number of fatalities in road accidents in individual quarters of 2019 in selected EU Member States*

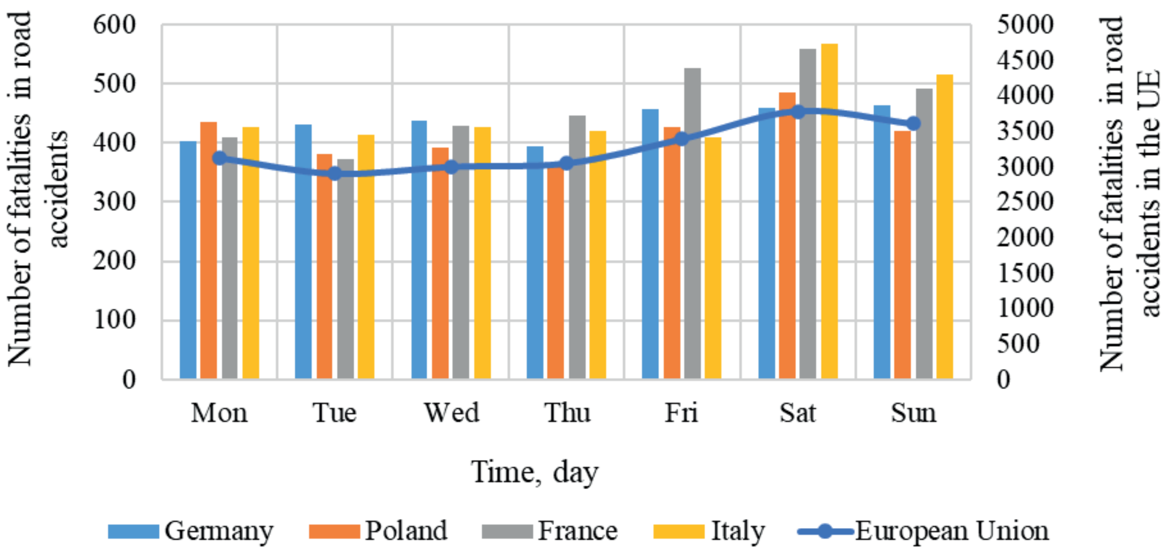

Figure 24 *Number of fatalities in road accidents in the EU and selected Member States on specific days of the week in 2019*

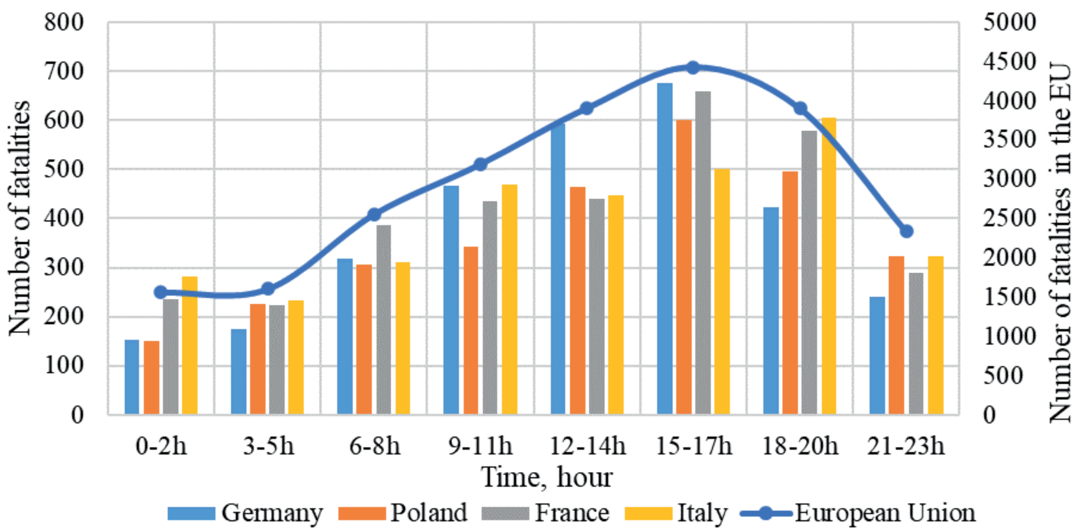

Figure 25 *Number of fatalities in road accidents in the EU and selected Member States at different times of the day in 2019*

Table 1 *The coefficient of determination R^2 for data on the number of fatalities in selected EU countries*

Country	R^2 coefficient	Country	R2 coefficient
Poland	0.6705	Ireland	0.2279
Austria	0.1866	Italy	0.9614
Belgium	0.9131	Latvia	0.0941
Bulgaria	0.4676	Lithuania	0.6234
Croatia	0.9285	Luxembourg	0.0194
Czech Republic	0.0236	Malta	0.0013
Denmark	0.4769	Netherlands	0.0478
Estonia	0.0475	Portugal	0.0522
Finland	0.6945	Romania	0.0802
France	0.9690	Slovak Republic	0.3967
Germany	0.2421	Slovenia	0.8537
Greece	0.9663	Spain	0.0976
Hungary	0.505	Sweden	0.3441

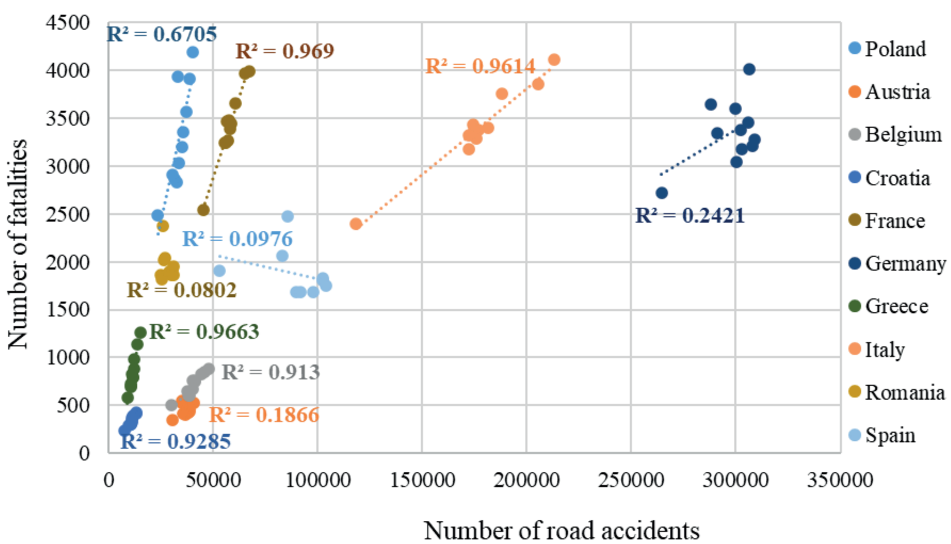

Figure 26 *Number of road accidents versus number of fatalities for selected EU Member States*

Vision" policy, pursued in the Member States of the European Union, contributes to increasing the safety of the newly manufactured motor vehicles, improving the road infrastructure and tightening the provisions of the Highway Code. Apart from the driver's fault, the above factors are the most often mentioned as the cause of a road accident. By determining the R^2 coefficient, which is a measure of the quality of the model fit. The authors wanted to check which of the above factors (the number of registered motor vehicles, the total number of road accidents, the length of highways) has the greatest impact on the drop in the number of fatalities in selected European countries

Analyzing the available statistical data on the number of fatalities, attention should be paid to the relationship between the number of road accidents and the number of fatalities. The coefficient of determination R^2 for data on the number of fatalities, taking into account the total number of road accidents, in selected European countries, is presented in Table 1.

The R^2 coefficient of determination for data on the number of fatalities in selected European countries is presented in Table 1. The value of the R^2 coefficient of determination for France (R^2 = 0.9690), Greece (R^2 = 0.9663), Italy (R^2 = 0.9614), Croatia (R^2 = 0.9285), Belgium (R^2 = 0.9285) and Slovenia (R^2 = 0.8537), proves that the number of fatalities is closely related to the number of road accidents. This is an obvious statement, but it should be borne in mind that in countries where the value of the R^2 coefficient is close to 1, it indicates

Table 2 *The coefficient of determination R2 for data on the number of road accidents in terms of the number of registered motor vehicles in selected European countries*

Country	R^2	Country	R^2
Belgium	0.878	Spain	0.484
Austria	0.844	Ireland	0.449
Latvia	0.808	Netherlands	0.279
Slovakia	0.781	Greece	0.250
Poland	0.743	Sweden	0.205
France	0.730	Denmark	0.160
Italy	0.704	Luxembourg	0.120
Germany	0.702	Slovenia	0.106
Czechia	0.687	Lithuania	0.077
Hungary	0.676	Estonia	0.025
Finland	0.637	Portugal	0.025
Romania	0.545	Malta	0.020
Croatia	0.492	Bulgaria	0.004

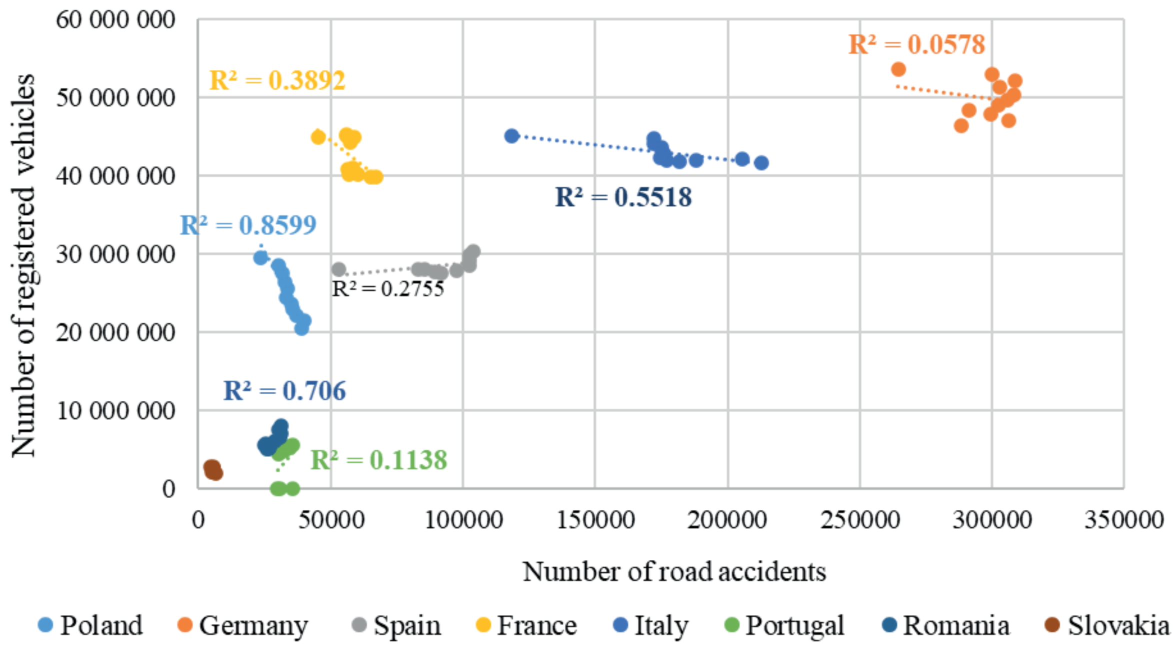

Figure 27 *The number of road accidents versus the number of registered motor vehicles for selected EU Member States*

a large number of accidents with fatalities in the total number of accidents. Therefore, in order to reduce the number of fatalities in these countries, the overall number of road accidents should be reduced. The lowest values of the determination indicator R^2 occurred in the Czech Republic (R^2 = 0.0236), Luxembourg (R2 = 0.0194) and Malta (0.0013) (Figure 26). In these countries, the number of fatalities is not closely related to the total number of road accidents. The coefficient of determination R^2 for Poland is 0.6705 in the period in question. This proves a moderate dependence of the number of fatalities on the total number of road accidents.

When analyzing the available statistical data on the number of road accidents, attention should be paid to the relationship between the number of road accidents and the number of registered motor vehicles. The determined coefficient of determination R2 for data on the number of road accidents, in terms of the number of registered motor vehicles in selected European countries, is presented in Table 2.

The results of the coefficient of determination R^2, for Belgium (R^2 = 0.878), Austria (R^2 = 0.844), Latvia (R^2 = 0.808), Slovakia (R^2 = 0.781), Poland (R^2 = 0.743) and France (R^2 = 0.730), show that the number of road accidents is related to the number of registered motor vehicles. Therefore, in order to reduce the number of road accidents in these countries, the total number of registered motor vehicles should be reduced. In addition, it should be noted that in Germany and Italy,

Table 3 *The coefficient of determination R^2 for data on the number of fatalities in terms of the number of registered motor vehicles in selected European countries*

Country	R^2	Country	R^2
Finland	0.9608	Croatia	0.495
Malta	0.9149	Spain	0.450
Poland	0.8599	Slovenia	0.400
Belgium	0.7807	Italy	0.343
Slovakia	0.7765	Netherlands	0.324
Germany	0.7013	Romania	0.265
Greece	0.6942	France	0.231
Hungary	0.6915	Bulgaria	0.222
Portugal	0.6770	Austria	0.176
Latvia	0.6621	Estonia	0.029
Denmark	0.5291	Lithuania	0.019
Luxembourg	0.5231	Ireland	0.011
Sweden	0.5102	Czechia	0.001

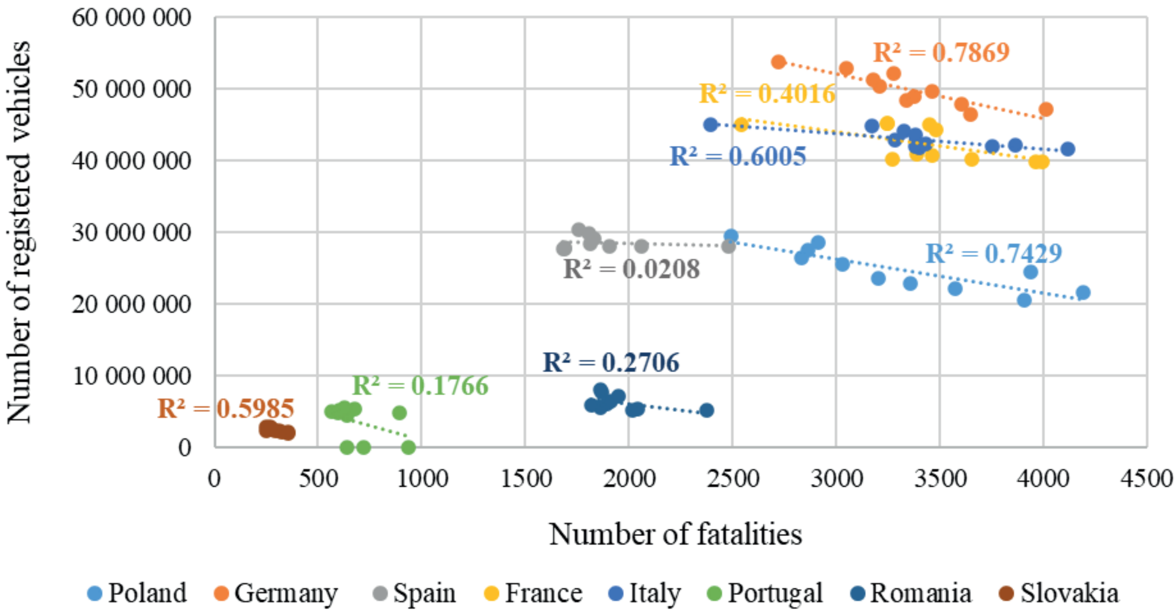

Figure 28 *Number of road fatalities versus the number of registered motor vehicles for selected EU Member States*

***Table 4** The coefficient of determination R^2 for data on the number of road accidents in terms of the length of motorways in selected European countries*

Country	R^2	Country	R^2
Spain	0.8700	Slovenia	0.3592
Finland	0.8337	Netherlands	0.2447
Slovakia	0.6960	France	0.2286
Germany	0.6834	Portugal	0.2189
Sweden	0.6455	Austria	0.1940
Poland	0.6079	Ireland	0.1013
Croatia	0.6071	Denmark	0.0281
Luxembourg	0.5829	Estonia	0.0218
Italy	0.4828	Bulgaria	0.0037
Romania	0.4461	Czechia	0.0021
Hungary	0.4310	Lithuania	0.0001

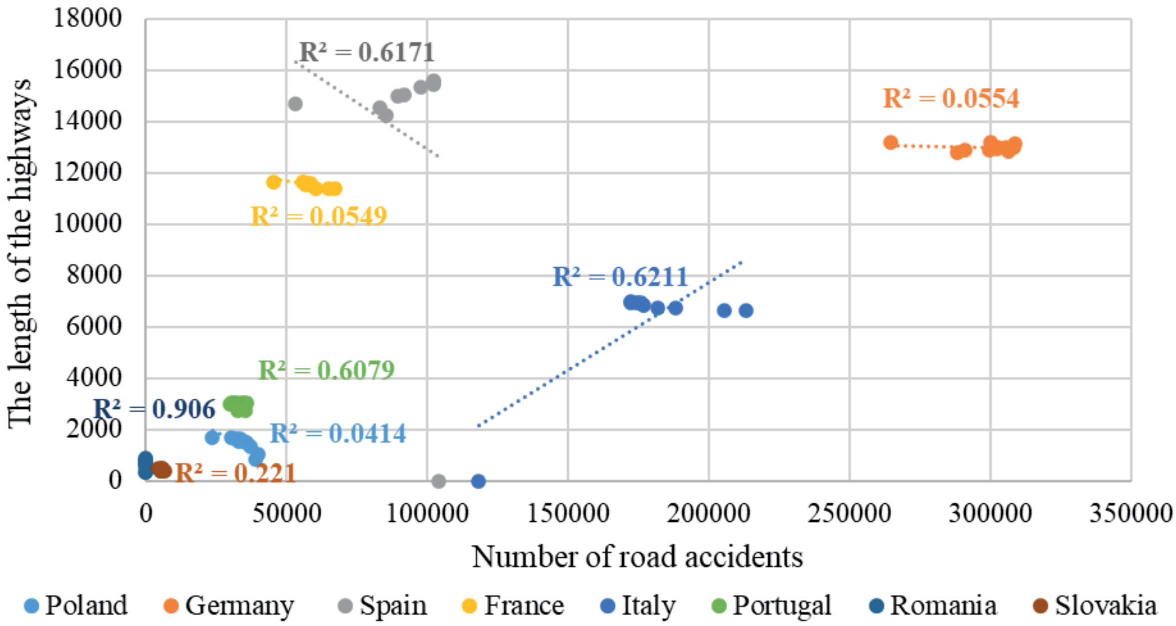

***Figure 29** The number of road accidents versus the length of motorways for selected EU Member States*

where the most registered motor vehicles are present, the coefficient of determination R^2 is 0.7, this result is much lower than for Belgium or Austria, where the number of registered motor vehicles is almost 10 times lower. The lowest values of the determination indicator R^2 were recorded in Lithuania, Estonia, Portugal, Malta and Bulgaria. For those countries, the value of the determination index R^2 did not exceed 0.1 (Figure 27); in those countries, the number of road accidents is not related to the total number of registered motor vehicles.

However, attention should be paid to the relationship between the number of road fatalities and the number of registered motor vehicles. The determined coefficient of determination R^2 for data on the number of fatalities in road accidents and the number of registered motor vehicles in selected European countries is presented in Table 3.

The results of the coefficient of determination R^2 for Finland (R^2 = 0.9608), Malta (R^2 = 0.9149), Poland (R^2 = 0.8599), Belgium (R^2 = 0.7807) and Slovakia (R^2 = 0.7765), show that the number of road fatalities is related to the number of registered motor vehicles. Therefore, in order to reduce the number of road fatalities in these countries, the total number of registered motor vehicles should be reduced. The lowest values of the determination indicator R^2 are for Estonia, Lithuania, Ireland and the Czech Republic. For these countries, the value of the determination index R^2 did not exceed 0.1 (Figure 28). In those countries, the number of road fatalities is not linked to the total number of registered motor vehicles.

When analyzing the available statistical data on the number of road accidents, attention should be paid to the relationship between the number of road accidents and the length of motorways. The determined coefficient of determination R2 for data on the number of road

***Table 5** The coefficient of determination R^2 for data on the number of road fatalities in terms of the length of motorways in selected European countries*

Country	R^2	Country	R^2
Spain	0.8561	Italy	0.5263
Czechia	0.7175	Hungary	0.5263
Croatia	0.7090	Netherlands	0.4797
Germany	0.6921	France	0.4779
Slovakia	0.6714	Ireland	0.4068
Portugal	0.6457	Sweden	0.2824
Romania	0.6409	Denmark	0.2304
Poland	0.6334	Luxembourg	0.1802
Austria	0.6234	Bulgaria	0.1763
Finland	0.5628	Slovenia	0.0741
Estonia	0.5410	Lithuania	0.0032

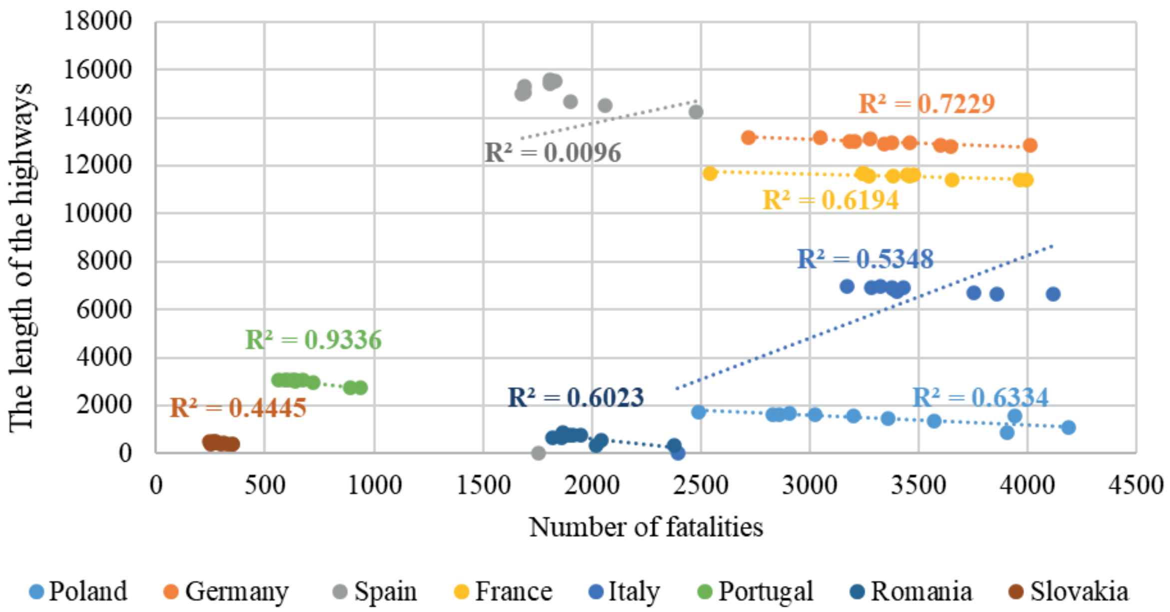

***Figure 30** Number of fatalities in road accidents versus the length of motorways for selected EU Member States*

accidents in terms of the length of motorways in selected European countries is presented in Table 4.

The results of the coefficient of determination R^2 for Spain (R^2 = 0.870), Finland (R^2 = 0.8337) and Slovakia (R^2 = 0.6960) show that the number of road accidents is related to the length of motorways. Therefore, in order to reduce the number of road accidents in these countries, the length of motorways should be increased. Moreover, it should be noted that in Germany (R^2 = 0.6834), Sweden (R^2 = 0.6455), Poland (R^2 = 0.6079) the coefficient of determination R2 indicates a significant relationship between the number of road accidents and the length of motorways. The lowest values of the determination indicator R^2 were recorded in Bulgaria, the Czech Republic and Lithuania. For these countries, the value of the determination index R^2 did not exceed 0.001 (Figure 29). In these countries, the number of road accidents is not related to the length of motorways.

However, attention should be paid to the relationship between the number of road fatalities and the length of motorways. The determined coefficient of determination R^2 for data on the number of fatalities in road accidents and the length of motorways in selected European countries is presented in Table 5.

Results of the coefficient of determination R^2 for Spain (R^2 = 0.8561), Czechia (R^2 = 0.7175), Croatia (R^2 = 0.7090), Germany (R^2 = 0.6921) and Slovakia (R^2 = 0.6714), show that the number of road fatalities is related to the length of motorways. Therefore, in order to reduce the number of road fatalities in these countries, the length of motorways should be increased. The lowest values of the determination index R^2 are for Slovenia and Lithuania. For these countries, the value of the determination index R^2 did not exceed 0.1 (Figure 30).

In these countries, the number of road fatalities is not linked to the length of the motorways.

7 Conclusions

The policy of the European Union is aimed at improving the road safety. A number of changes introduced by the member states of the European Union are aimed at reducing the number of fatalities in road accidents. The introduced changes are directed at improving the safety of motor vehicles, therefore new vehicles are equipped with a series of passive systems contributing to increasing safety, additionally the road infrastructure is developed, thanks to which the collision-free roads (highways, expressways) are created, in which all the participants travel in one direction.

The number of road accidents in the last decade has slightly decreased. Compared to 2010, the number of people who died as a result of a road accident decreased, as well. The overall number of fatalities in the EU in 2020 was lower by about 40% than in 2010. In Greece and Norway, the number of fatalities in road accidents in 2020 was 50% lower than in 2010. In Poland, in 2010, the number of fatalities in road accidents in 2020 was 37% lower than in 2010.

Analyzing the impact of the number of road accidents on the number of fatalities, it was confirmed that in some EU countries, the only way to reduce the number of fatalities is to reduce the total number of road accidents. Such countries include, for example, France, Greece and Italy. At the same time, these member states have very good road infrastructure.

When considering the number of fatalities, certain trends, specific to the EU and individual member states, were noticed. It was noted that the number of fatal accidents was highest in the summer months. It may be related to vacation and holiday trips. When analyzing the days of the week, most accidents with fatalities occur on Saturdays and the least on Tuesdays. Due to the time of day, most accidents take place in the afternoon. These are the so-called transport summit, which occur in most European countries between 3 PM and 5 PM The lowest number of accidents with fatalities is recorded at night.

In the analyzes presented in the paper, the R^2 index was used to assess the relationship between the number of accidents and the number of fatal accidents in individual EU countries. The high value of the index, oscillating around 1, indicates a large number of accidents with fatalities in the total number of accidents. When analyzing individual EU countries, Italy, France and Greece have the highest R^2 ratio. For these countries, the index is 0.97. Countries with the lowest rates are Malta, Luxembourg and the Czech Republic. The R^2 index for these countries is below 0.03.

Analyzing the impact of the number of road accidents on the number of registered motor vehicles, it was confirmed that in some EU countries, the only way to reduce the number of the road accidents is to reduce the total number of registered motor vehicles. Such countries include, for example, Belgium and Austria. At the same time, analyzing the impact of the number of road fatalities on the number of registered motor vehicles, it was confirmed that in some EU countries, the only way to reduce the number of road fatalities is to reduce the total number of registered motor vehicles. Such countries include Finland, Malta and Poland. Analyzing the impact of the number of road accidents on the length of motorways, it was confirmed that in some EU countries, the only way to reduce road accidents is to increase the length of motorways. Such countries include, for example, Spain, Finland and Slovakia. At the same time, when analyzing the impact of the number of road fatalities along the length of motorways, it was confirmed that in some EU countries, the only way to reduce the number of road fatalities is to increase the length of motorways. Such countries include the Spaniards and the Czech Republic. It should be noted that the number of road accidents is influenced by the infrastructure and to a large extent by the motorway network and the number of vehicles moving on the roads.

The R^2 coefficient of determination is used to analyze the impact of road accidents or victims in the road accidents in terms of Infrastructure or the number of registered motor vehicles. It may prove to be a useful indicator comparing the road safety for selected countries. In addition, the indicator can be used as one of the criteria for assessing the danger on the roads of European countries.

Perhaps the only effective measure to reduce the number of road fatalities is to educate road users. Social campaigns on television and social media can help to make drivers and other the road users aware of the consequences of accidents. One of the ways to influence drivers are high financial penalties for breaking the traffic regulations. An important issue for lawmakers and road managers is to ensure the safety of the road infrastructure, e.g. through appropriate marking, lighting, or the introduction of less collision-related intersections and road connections. Continuous development of passive and active safety systems for vehicles is also important, which can contribute to increasing safety for both vehicle users and other road users.

Grants and funding

The authors received no financial support for the research, authorship and/or publication of this article.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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COMPARISON OF OPERATIONAL COSTS FOR FIXED-ROUTE BUS SERVICE AND DEMAND RESPONSIVE TRANSPORT SYSTEMS. THE CASE OF KOSICE REGION - SLOVAKIA

Tomáš Štofa, Peter Džupka, Radovan Dráb*

Faculty of Economics, Technical University of Kosice, Kosice, Slovakia
*E-mail of corresponding author: radovan.drab@tuke.sk

Tomáš Štofa 0000-0002-9824-3531, Peter Džupka 0000-0001-8947-6555, Radovan Dráb 0000-0002-6022-5995

Resume

The issue of sustainability of public transport is constantly receiving attention from both government and research. One possible solution, demand responsive transport (DRT), can increase accessibility in rural areas, improve the quality of service as well as reduce the costs. This paper estimates the operational costs for different types of vehicles in DRT in person-kilometers and compares it to the current costs of standard bus transport for year 2021 and analyses the capacity, occupancy and ticket prices of fixed-route bus transport. As the results indicate, in many cases the costs of DRT are higher compared to standard bus transport, but by increasing the occupancy of vehicles the DRT can provide savings up to 66%. The use of cars, as well as car-sharing, show higher costs, which is mainly related to a low transport capacity. As the most appropriate vehicles of DRT have been identified micro buses and minibuses.

Article info

Received 8 September 2022
Accepted 28 November 2022
Online 9 January 2023

Keywords:

costs
standard bus transport
demand responsive transport

Available online: https://doi.org/10.26552/com.C.2023.015

ISSN 1335-4205 (print version)
ISSN 2585-7878 (online version)

1 Introduction

Many countries and regions face problems of the public transport cost-efficiency especially in remote rural region. Current issues with their origins in Covid pandemic, caused dramatical drop in public transport usage. Together with the new increase in petrol prices are the former problems in rural areas transport accessibility articulated even to a higher extent.

The purpose of the paper was to compare the operational costs for providing bus transport in rural areas of Kosice region in Slovakia. Currently the bus transport in Kosice region is organized as a standard bus transport. Based on publicly available data, regarding the costs of bus transport in rural areas of the region is becoming less economically sustainable from year to year. The expenditures of all the public transport providers increased between 2009 and 2019 by 32%, operated milage stayed nearly consistent but the number of passengers decreased from 27.8 million In 2009 to 20.5 million in 2019. This is nearly 30% decrease in number of passengers compared to the level before pandemic. When the first pandemic year 2020 is considered, the decrease in number of passengers is more than 50%.

One of the possible solutions to improve the accessibility of people living in rural areas in Kosice region is to introduce some type of Demand responsive transport system, which could substitute or complement existing standard bus transport system in the region. These types of systems can increase the accessibility especially for disadvantaged people (older of disabled) living in rural areas. On the other hand, these types of systems come usually with higher operational costs.

The first part of the paper summarizes the literature about the DRT systems with aim to identify basic types of DRT system based on their flexibility. The second part describes the methodology used for estimation of operational costs for both transportation systems and the last part provides discussion of the results.

This paper is prepared as a part of the wider project dealing with Economic and social aspects of accessibility in rural areas using demand-oriented transport and flexible transport systems, which aims to explore the possibilities of improving the accessibility of rural regions by applying new "smart" solutions based on demand-oriented transport and flexible transport systems.

2 Literature review

According to Demand Responsive Transport (DRT) is partly a form of public transport, bearing the marks of fully flexible use of taxis and regular public transport. According to a study [1], DRT is partly a form of private or quasi-public transport, where routes are changed according to passengers' demand without the use of fixed timetables. However, as pointed out by [2], even the use of timetabled schedules is possible in DRT.

Within the literature review, a total of 454 articles dealing with the topic of DRT have been identified using the bibliographic platform SCOPUS, which provided the most articles from the search request. Three main types of DRT have been identified, categorized according to the level of flexibility offered by the service. More flexible services adapt better to customer requirements, but on the other hand they generate much higher costs than the less flexible services. It is the degree of flexibility that represents an important issue in planning the implementation of this service.

2.1 Forms of DRT

Based on the level of flexibility of the service, the following types of DRT have been identified:

Fully flexible DOD (door-to-door service)

Demand-oriented transport with all the components flexible, is usually referred as door-to-door service. These services pick up the customer in front of their own house door and take them to the door of the destination place. Such a service is primarily intended for passengers who cannot, or do not wish to, walk to the bus stop for various reasons. This form of DRT is also characterized by its full-time flexibility, which means that the pick-up time is fully dependent on the actual demand. It is mostly served by the low-capacity vehicles, such as cars with up to 6 passenger seats, or minibuses with a seating capacity of around 12. The type of a vehicle, used by the service, usually depends on the option of sharing the journey with other passengers. For such services, it is advantageous to have the highest possible occupancy of the vehicle, however, on the other, it also creates negative effect for passengers, where duration of the journey is longer due to multiple stops of the vehicle. Therefore, the real-time tracking and the optimization of the routes is necessary for such a service. Services, that do not allow ride sharing are closest to conventional taxi services and usually use smaller cars. This form of service is more expensive than a shared service where passengers with similar origins and destinations have the option of using a single vehicle [2-6].

Semi-flexible DOD (service serving stops/ points of interest)

In contrast to fully flexible demand-responsive transport, semi-flexible systems are characterized by limitation of transport flexibility. In the literature, it is usually referred to as "stop-based service", or service serving stops or specific points of interest. The limited flexibility may also apply to the changes of the route itself. Unlike the fully flexible transport systems, where car sharing is optional, the sharing of the vehicle is the basis of these services. Semi-flexible transport systems are also characterized by different time flexibility of the service. They can be fully dependent on the actual demand of the passengers, or have a fixed schedule with vehicle departures, which is mostly used by systems with defined stops. A third option is a combination of the two previous ones, where, for example, only the departure time of the vehicle from the starting stop is determined and subsequent arrivals are dependent on the number of intermediate stops on the route [2-8].

Car-sharing

A third, slightly different form of flexible transport systems is the car-sharing service. This form of service does not directly provide transport, but only a vehicle for short-term transfer to the destination. The system can be considered fully flexible within the area served, but the passenger must physically come to the vehicle. The service usually provides a capacity of 2 to 4 seats. The original idea of car sharing has several alternatives already, such as shared motorcycles, bicycles or scooters [2, 9].

2.2 Costs and ticket price in DRT

The objective of this paper was to estimate the operational costs of different types of Demand responsive transport in person-kilometers (personkm) and to compare them to the current costs of standard bus transport in Kosice region Slovakia. The paper also compares potential sales volume of these two different services and subsequently analyzes whether it would be possible to replace the standard fixed timetable bus transport with the DRT. Since we are only trying to reduce the costs of existing fixed-route bus transport, we do not deal with the transportation of vulnerable groups of passengers, such as children, disabled persons, pensioners. In the study [10], the main reason for the DRT failures have been identified higher costs. In addition, simpler services have higher chance for survival, as the higher flexibility is linked with higher costs. Therefore, this paper´s aim was to analyze the possibility to replace the fixed-route buses with the DRT on the same or similar routes as buses, especially for low demand areas and off-peak hours, as suggested by [11].

As [12] stated, the accepted price represents the satisfaction with ticket price and the travelling time to the station had have significant impact on usage of urban transport in this study. The lower the price, the higher the usage of public transport should follow. However, as study [13] stated, willignes to pay (WTP) of DRT can be higher than regular bus transport, because of other benefits of DRT transport, such as shorter waiting times, shorter travel times, higher comfort and flexibility. Those assumptions have been confirmed by [14], where they stated that the perceived costs, in the form of reasonable ticket prices, are positively related with travel satisfaction. This paper also suggested that the accessibility and the societal and environmental importance of the public transport are significant, as well. All these attributes are higher in the DRT transport and thus despite the fact, that the DRT is linked with higher ticket prices, the other positive attributes can overcome the higher fares. Application of the DRT can improve the transport serviceability of an area, as well [15].

3 Methodology and data

The first step was the estimation of operational costs of the different types of the DRT systems. Although the direct identification of such costs is not possible, these costs have been traced down and simplified to the types of vehicles used to transport people in the region by available commercial services. Therefore, market survey was conducted and 20 transport options have been analyzed for the region of Kosice. The results of this survey are shown in Tables 8, 9 and 10 in the Appendix. Data were also obtained from the largest standard bus operators in Kosice self-governing region (KSK), Arriva and Eurobus. These contain information about all the bus lines that operated during 2019 in the region of KSK, related to transported passengers, travelled kilometers, annual sales and costs of the bus lines.

We assume that the pricing strategy of the commercial services covers all the operating costs, vehicles´ wear and tear, as well as generates a reasonable profit. When a real DRT service is implemented, additional costs, related to the information system development and operation to organize the DRT system, will be required. However, we assume that these costs will not be significant from a long-term point of view and, therefore, we abstract them in our analysis. Based on the literature review the DRT systems usually operate with standard cars (with or without the share of the journey) [3, 5, 9]; microbuses [3, 8, 16]; minibuses [16]; buses [6]; shared cars [2, 9] and shared motorcycles [17].

The maximum number of seats in each vehicle was determined based on a study of [18]. As stated in the case study [19], DRT aims to maximize vehicle occupancy through various trip optimization techniques, such as adjusting service times to the busiest times and locations. This is due to the high costs of the drivers themselves, which represents up to 50% of the total costs of the service, as stated in [20]. On the other hand, standard bus transport operates buses and microbuses with an average capacity of 49.5 seats, however occupancy can be also higher due to standing passengers. Therefore, standard bus transport is preferable in the areas with large travel demand. In addition, the problem of congestions is a rising issue for all but especially larger cities [21,22]. However, the main objective of this paper is to analyse operational costs and sales for DRT vehicles. These DRT vehicles could replace existing fixed-route bus services, where the lower capacity of the DRT is acceptable and application of DRT would lead to savings because of lower costs or higher sales volume.

Based on these assumptions research of private operators of different transports services in Kosice region was done in November 2021. The aim was to identify the price policy of these operators. The structure of the analysed transport operators is described in Table 1.

From these inputs the operational costs in person-kilometer for different vehicles possibly used for demand responsive transport and for different expected vehicle occupancy were estimated.

Table 1 *Structure of the analysed operators and costs with Value-Added Tax (VAT)*

	DRT Vehicles				Sharing services		
Operators	Cars	Microbus	Minibus	Bus	Carsharing	Motorbike sharing	Standard bus transport
Number of operators	6	4	5	3	1	1	2
Max number of seats	4	8	15-25	52-55	2	1	49.5
Costs per kilometer [€]	Cars	Microbus	Minibus	Bus	Carsharing	Motorbike sharing	Standard bus transport
Average	0.69 €	0.74 €	0.83 €	1.50 €	0.42 €	0.22 €	1.5495 €
Std. Dev.	0.2735	0.2945	0.1775	0.0849	N/A	N/A	0.0740 €
Min	0.35 €	0.40 €	0.60 €	1.38 €	N/A	N/A	1.4612 €
Max	1.00 €	1.20 €	1.02 €	1.56 €	N/A	N/A	1.6141 €

Table 2 *Statistics of regular standard bus transport*

	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Operation milage [in 000 km]	26493	26777	26323	26455	26155	25881	26173	26182	26342	26520	26852	25542
Number of passengers per year (in 000)	27839	26953	25336	24498	23921	23050	22352	21466	20930	20627	20523	12876
Operational costs of operators per year [in 000 €]	27025	27781	29663	30756	31337	31575	31514	31373	33458	34643	35744	33481
Subsidies from Regional budget per year [in 000 €]	10863	12346	13720	15015	15858	16663	17138	17138	19939	21231	22288	29980

Source: [23]

Table 3 *Costs of DRT for different types of vehicles with VAT*

Operators	Cars	Microbus	Minibus	Bus	Carsharing	Motorbike sharing
Seats 50% - 100%	2 - 4	4 - 8	10 - 20	27 - 54	1 - 2	1
Costs per kilometer [€]	Cars	Microbus	Minibus	Bus	Carsharing	Motorbike sharing
Costs for personkm (1 traveler)	0.69	0.74	0.83	1.50	0.42	0.22
Costs for personkm (50% occupancy)	0.34	0.18	0.08	0.06	0.42	N/A
Costs for personkm (100% occupancy)	0.17	0.09	0.04	0.03	0.21	N/A

The second step represented the analysis of the operational costs for providing a regular standard bus transport in rural area in the Kosice region. Two private companies provide suburban bus transport based on a contract for the provision of services in the public interest with the Kosice self-governing region. Based on this contract, Kosice self-governing region provides subsidies to these two companies to provide suburban bus transport on agreed fares. These subsidies cover the loss from operation and a reasonable profit for private operators. Table 2 provides collected information from 2009 to 2020.

Using these inputs, the operational costs in person-kilometer for actual standard bus transport in the Kosice region were estimated.

4 Results and discussion

Based on the above-described data and methodology, the market costs of personkm (number of persons transported per 1 kilometer) were estimated for different types of vehicles that can be of a potentially use for DRT systems in the Kosice region. These costs reflect the actual market regionally specific prices. Table 3 describes costs for all the types of vehicles of DRT based in three levels of their occupancy during a trip: 1 passenger (also costs of vehicle per kilometer); 50% occupancy and full occupancy.

Before performing the costs for personkm calculation in the traditional standard bus transport in rural areas, an analysis of the development of several indicators for suburban bus transport in Kosice region was carried out. Figure 1 shows development of four indicators between 2009 and 2020. We consider the year 2019 as the last standard year not impacted by the COVID -19 pandemic restrictions. The year 2020 is the first and probably most impacted pandemic year, when most of the restriction in connection to COVID - 19 pandemics were introduced.

As can be seed from Figure 1 the increase of the operational costs indicator of all the private transport operators per one operated kilometer is rather moderate. The operated milage was stable, so the increase probably reflects the increase in direct costs (fuel, salaries etc.). Due to the sharp decrease of passengers in this period the operational costs of operators per passengers increased in time (blue line) especially during the pandemic impacted year 2020.

When considering the same indicators from the Kosice self-governing region point of view, the situation is also very interesting. Subsidies from regional budget for operators raised sharply especially when considering subsidies per one passenger. This situation can also be described by the share of regional budget subsidies in total operational costs. While in 2009 subsidies covered 40% of all the costs, in 2019 it was already 62% and in pandemic year 2020 more than 90% of total costs.

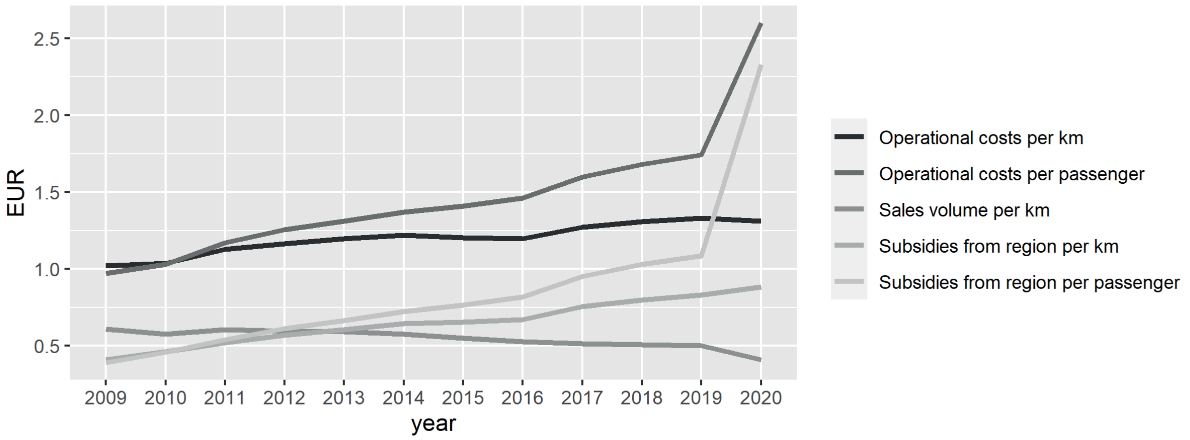

Figure 1 *Costs of traditional standard bus transport without VAT*

Table 4 *Operational costs and Subsidies per personkm with VAT*

	2019	2020
Operational costs/personkm [€]	0.06	0.10
Subsidies/personkm [€]	0.04	0.09

Source: Own calculations based on Annual reports of Kosice self-governing region

Table 5 *Standard market prices lower than subsidies*

Operators	Cars	Microbus	Minibus	Bus	Carsharing	Motorbike sharing
Seats 50% - 100%	2 - 4	4 - 8	10 - 20	27 - 54	1 - 2	1
Price per kilometer [€]	Cars	Microbus	Minibus	Bus	Carsharing	Motorbike sharing
Price for personkm (1 traveler)	0.69	0.74	0.83	1.50	0.42	0.22
Price for personkm (50% occupancy)	0.34	0.18	‡0.08 ‡	0.06	0.42	N/A
Price for personkm (100% occupancy)	0.17	‡0.09 ‡	‡0.04 ‡	0.03	0.21	N/A

From the cost-effectiveness point of view, this situation is not sustainable. In the light of increasing costs and subsidies we, therefore, tried to compare the costs and subsidies for person km in traditional standard sub-urban bus transport to the market prices for personkm. Table 4 shows the operational costs per personkm and subsidies from regional budget for personkm for both before pandemic (2019) and the first pandemic (2020) years.

We compared the subsidies for personkm for pandemic year - 0.09 € and the prices of the analyzed public transportation options. Cells highlighted by symbol ‡ in Table 5 represent the situation when the standard market prices for the use of Microbus and Minibus are equal or lower than the subsidies from the regional budget for personkm in pandemic year. Naturally, this is possible only when the DRT system could reach at least 50% occupancy in the case of Minibuses and full occupancy in the case of Microbuses. We have not considered the traditional buses as a DRT vehicle, since 50% occupancy of vehicles is not reachable in remoted rural areas in Kosice region during the analyzed period and the WTP was calculated as a price for services with a higher standard than regular bus transport, as well.

The DRT systems are usually related to the higher accessibility or/and comfort for passengers. This means that this type of services should increase the passengers perceived value of the service. In thesis [13] a small pilot primary research based on the WTP methodology with the aim to estimate the willingness to pay for the DRT service in three villages in Kosice region was carried out. The research sample was rather small - 100 households, but the results showed that the median value of the willingness to pay for DRT service was 0.09 € per travelled kilometer for a person.

In this context, we subtracted the median of willingness to pay per kilometer from the original market price and again compared the results to the self-governing region's subsidy per person-km. Cells highlighted by symbol ‡ now represent the situation when the passenger payments - market prices are lower or equal than the subsidies. This situation is present in the case of at least 50% occupancy, when

***Table 6** Standard market prices lower than subsidies considering willingness to pay*

Operators	Cars	Microbus	Minibus	Bus	Carsharing	Motorbike sharing
Seats 50% - 100%	2 - 4	4 - 8	10 - 20	27 - 54	1 - 2	1
Price per kilometer [€]	Cars	Microbus	Minibus	Bus	Carsharing	Motorbike sharing
Average	0.69	0.74	0.83	1.50	0.42	0.22
Price for personkm (1 traveler)	0.60	0.65	0.74	1.41	0.33	0.13
Price for personkm (50% occupancy)	0.25	‡0.09 ‡	‡-0.01 ‡	-0.03	0.33	N/A
Price for personkm (100% occupancy)	‡0.08 ‡	‡0.00 ‡	‡-0.05 ‡	-0.06	0.12	N/A

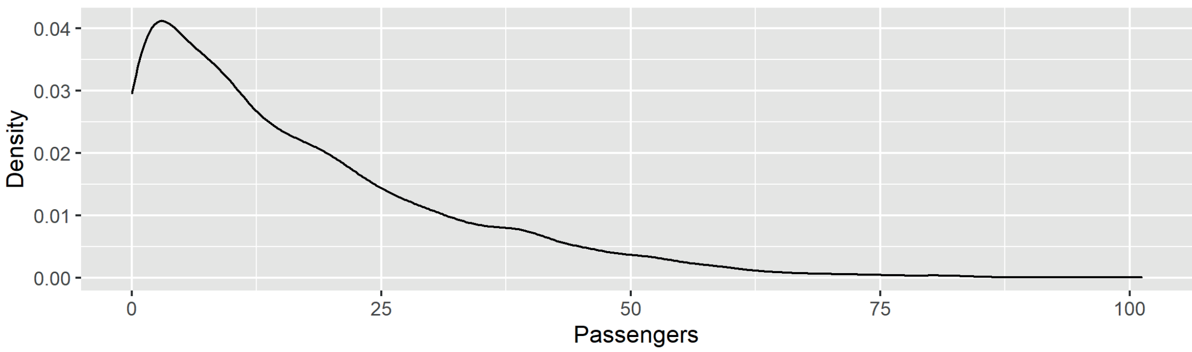

***Figure 2** Density chart of average occupancy of standard bus transport for year 2019*

***Table 7** Options for replacing fixed-route bus transport by DRT*

Average	Rides needed during year	Fixed routes replaceable by one DRT vehicle	Fixed routes replaceable by one DRT vehicle in %	Potential savings for selected routes %
Standard bus lines	6086			
Cars	28492	1341	22.03	55.47
Microbuses	15935	2239	36.79	52.24
minibuses	8624	4108	67.50	46.43
buses	6154	5918	97.24	3.19

Source: Own calculations based on Annual reports Kosice self-governing region

using minibuses and microbuses and in the case of full occupancy of cars, as well. Here, again, the traditional buses were not considered for the same reason described above. All these results are presented in Table 6.

As can be seen, car and motorbike sharing services represent a more expensive way to assess the accessibility problem, therefore we do not consider them as an alternative to standard bus transport. On the other hand, large buses as the DRT vehicles have multiple disadvantages, as limited comfort, limited flexibility and lower transport speed considering the high number of passengers that bus have to serve, although the higher seat capacity leads to higher savings when all the seats are occupied. Cars as the main vehicles of the DRT fleet are associated with the highest comfort and the fastest travel times, but their costs are high and even at full occupancy the savings would be too low. Therefore, the two main alternatives remain as the most appropriate ones for standard bus transport, microbuses and minibuses.

This paper analyzed the average occupancy of the fixed-route bus transport during the year 2019. As can be seen on Figure 2.78% of all the bus lines had the occupancy lower than 50% of the maximum seat capacity.

Therefore, we have analyzed the potential substitutability of the standard bus transport by different DRT vehicles. If we would like to replace all standard bus lines by DRT with one type of vehicle, the number of rides would grow, especially in category of cars and microbuses. However, we suggest replacing only the fixed routes, where one vehicle would be enough. As the minibuses and microbuses have been selected, the potential savings are up to 52.24% for replaced routes, as can be seen in Table 7.

Then we compared the calculated WTP to the

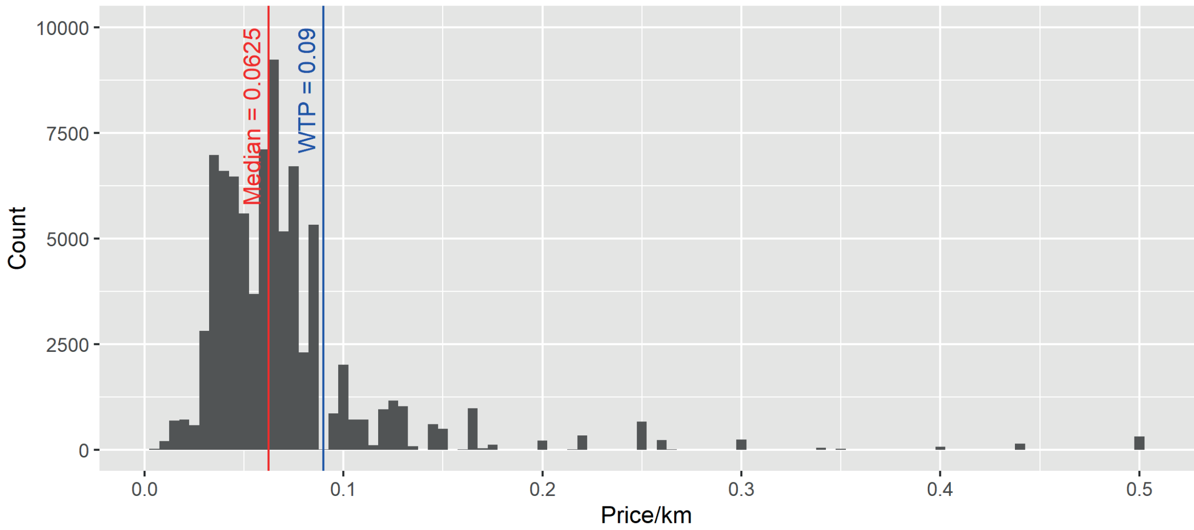

Figure 3 *Ticket price in EUR of standard bus transport (Grey histogram and red as median) and WTP for DRT (blue) per kilometer*

prices of standard transport tickets purchased during one normal working day in the Kosice region. Price of one personkm for one bought ticket was calculated as follows:

$$P_{km} = \frac{P_t}{KM}, \qquad (1)$$

where:
P_t is ticket price,
KM is number of kilometers.

Figure 3 shows the histogram of calculated prices per personkm for a given day. Even though we took only intercity transport into account, some bus connections may also serve as urban transport in smaller cities. In addition, standard bus transport use tariff prices, depending on the distance range. Transports over the short distances is for customers much more expensive than transport over the long distances. Due to these facts, it is possible to see clusters of prices over 0.2 €km. Since extreme values can significantly affect the calculated average price, we used the median for comparing to calculated WTP.

The median price per personkm was calculated at the level of € 0.0625, while the determined WTP price was € 0.09. Considering this difference, we can assume that there is a room for an increase in transport prices for the use of DRT, because people are willing to pay extra for the higher quality of services offered by the DRT. However, this difference is not enough to completely switch to DRT transport for this region.

According to [10], despite the 40 years of experience with the DRT, its higher costs are the main factor of DRT failure. Reducing the risk of high costs could be achieved by a combination of standard bus transport and the DRT, where these forms of transport alternate depending on demand. Outside the peak hours, the DRT would improve the quality of the transport service and during the peak hours, standard bus transport would maintain sufficient availability, as analysed by [21].

5 Conclusions

A total of three groups of the DRTs were identified within demand-responsive transport literature, categorized based on flexibility and services provided. Fully flexible DRT services can be seen as an alternative to taxi services as pointed out by [7]. Therefore, [22] emphasizes the creation of a regulated environment and the co-operation of different forms of transport. Partially flexible services, as the most widespread form of DRT, allow a higher degree of flexibility than the public transport, but with the aim of reducing costs compared to fully flexible services.

In this paper we have analysed four types of DRT vehicles and two sharing services as an alternative for the fixed-route bus transport. Due to the high costs of sharing services, the DRT represents a better alternative. There were four types of DRT vehicles analysed, cars, microbuses, minibuses and buses. Due to low capacity of cars and relatively high costs when the cars are running not fully occupied, personal cars have been marked as unsuitable for long-term operations. On the other hand, buses have the lowest costs when considering the full capacity of the vehicles; however, this assumption is not feasible when analysing the available data or considering the real occupancy. In addition, longer times, lower flexibility and comfort of this vehicle cannot be associated with the higher WTP identified for smaller vehicles.

Therefore, within the DRT, vehicles with lower transport capacity have been identified as the most used vehicles, namely minibuses and minicabs. The costs' survey confirmed that the higher the vehicle capacity, the higher the costs per vehicle km. However, due to the possibility of sharing the journey with other customers, the costs at the maximum vehicle utilization are approximately twice as low, when using minicabs compared to cars, or approximately four times lower when comparing to minibuses and cars. In many cases the DRT can be much more expensive than the standard bus transport, however, the real-time planning and route optimization can increase occupancy and thus reduce costs up to 70 % compared to standard transport.

On the other hand, the fixed-route transport cannot be fully replaced by the DRT, because of high travel demand in peak hours and for busy places. Such a substitution would lead to congestion when multiple DRT vehicles would need to replace higher capacity buses. However, this paper considers replacing only bus lines with low demand and by which the higher flexibility of DRT would lead to higher accessibility of rural areas, especially in off-peak hours.

At the same time, the willingness to pay has been analyzed and determined at the level of 0.09 € personkm, while the total operating costs of standard bus transport are 0.10 €. Such values were possible to achieve at a higher vehicle occupancy. Following these results, a real-time optimization of the route and the appropriate choice of vehicles according to the demand have a decisive influence on the success of the DRT. Thus, as stated in [10], there is a strong link between the DRT higher costs and its failure, while the simpler services have better chances to survive than the complex ones.

Acknowledgement

This research was carried within the project VEGA grant number 1/0455/20.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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APPENDIX

Table 8 *List of all operators analyzed - part 1*

Operator	Company	Vehicle type	Maximum passengers	Price per km €	Price per personkm with 50% occupancy €	Price per personkm with 100% occupancy €	Price for 1 hour waiting €	Starting fee €	Minimum fee €	Pollution fee €	Note	Web
YellowTaxi	Yellow Kosice s.r.o	car	4	0.90	0.45	0.23	12.00	1.00	3.00	30.00	Price when driving from the street 1.10 €/km	https://yellowtaxikosice.sk/cennik/
CTCTaxi	CAB s.r.o.	car	4	1.00	0.50	0.25	12.00	1.00	3.50	25.00		https://www.ctctaxi.sk/sk/cennik
EasyTaxi	easytaxi	car	4	0.50	0.25	0.13	12.00			20.00	Price in KE 3 €/ per address	http://easytaxi.sk/kosice/?sid=2
Hopin	HOPIN, s. r. o.	car	4	0.40	0.20	0.10	6.00	1.20	3.00		Price in the city is 0.40 €/km	https://hopintaxi.com/
T-Taxi	Zumark s.r.o.	car	4	0.96	0.48	0.24	15.00	0.80	3.50	40.00	The rate of 0.96/km is valid when ordering by phone. otherwise 1.10/km	https://www.t-taxi.sk/
Transport Taxi s.r.o.	EASY TAXI s.r.o.	car	4	0.35	0.18	0.09	10.00			40.00	Note: Standard fee in KE 5 €	https://transporttaxi.sk/referencie
CTCTaxi	CAB s.r.o.	microbus	8	1.20	0.30	0.15	12.00	0.00	15.00	25.00		https://www.ctctaxi.sk/sk/cennik
SLAVOMÍR PÁSZTOR	Slavomír Pásztor	microbus	8	0.75	0.19	0.09	10.00		50.00	20.00	Price depends on distance. from 0.60 € to 0.90 €/km. Flat fee for trips up to 100 km is 50 €	http://www.taxi-.sk/cennik/
Transport Taxi	Transporttaxi s.r.o.	microbus	8	0.40	0.10	0.05	10.00			40.00		https://transporttaxi.sk/referencie
TaxiBus	Ivan Bodnar, Serhiy Lashkay, Vitaliy Bodnar	microbus	8	0.60	0.15	0.08			10.00		Price depends on distance. 0.80 €/km from 1 to 99 km. 0.70 €/km from 100 to 299. 0.60 €/km from 300 to 1000 km.	https://www.taxibus.sk/preprava-.com-kosice/

Table 9 *List of all operators analyzed - part 2*

Operator	Company	Vehicle type	Maximum passengers	Price per km €	Price per personkm with 50% occupancy €	Price per personkm with 100% occupancy €	Price for 1 hour waiting €	Starting fee	Minimum fee	Pollution fee	Note	Web
Citybus	Ing. Radovan Stefko	minibus	15	0.65	0.09	0.04	10.00				Price up to 50 km out of town 60 €. price in town round trip 50 €.	http://www.city-bus.sk/
Minibuseuropa	Minibuseuropa s.r.o.	minibus	15	0.60	0.08	0.04	7.20				Price based on calculator	http://www.minibuseuropa.sk/#snami
Minibuseuropa	Minibuseuropa s.r.o.	minibus	20	0.84	0.08	0.04	7.20				Price based on calculator	http://www.minibuseuropa.sk/#snami
Minibuseuropa	Minibuseuropa s.r.o.	minibus	27	1.02	0.08	0.04	7.20				Price based on calculator	http://www.minibuseuropa.sk/#snami
Fevel	FEVEL s.r.o.	minibus	25	1.02	0.08	0.04	10.80				Minimum price 150 €	https://www.fevel.sk/
Minibuseuropa	Minibuseuropa s.r.o.	bus	52	1.38	0.05	0.03	7.20				Price based on calculator	http://www.minibuseuropa.sk/#snami
Fevel	FEVEL s.r.o.	bus	49	1.56	0.06	0.03	10.80				Minimum price 150 €	https://www.fevel.sk/
Fevel	FEVEL s.r.o.	bus	55	1.56	0.06	0.03	10.80				Minimum price 150 €	https://www.fevel.sk/

Table 10 List of car-sharing services

Operator	Company	Vehicle type	Maximum passengers	Price per km €	Price per personkm with 50% occupancy €	Price per personkm with 100% occupancy €	Starting fee	Minimum fee	Price per 1 minute	Note	Web
Sharengo	CARSHARING s.r.o.	Shared cars	2	0.42	0.42	0.21			0.29	The price per km was calculated based on a base rate of 0.29 €/min and an average vehicle speed in the city of 41 km/h based on the European Road Safety Observatory 2016 survey	https://site.sharengo.sk/
Antik SmartWay	ANTIK Telecom s.r.o.	Shared motorcycles	1	0.22	0.22	0.22			0.15	The price for Antik customers is 0.10/min, the price per km has been calculated based on a base rate of 0.15 €/h and on the average speed of vehicles in the city of 41 km/h based on the European Road Safety Observatory 2016 survey	https://www.antiksmartway.sk/sk/motorbike-sharing

REVIEW OF GLOBAL RESEARCH ON E-MOBILITY: A BIBLIOMETRIC ANALYSIS

Apurvkumar Desai*, Chetan R. Patel

Sardar Vallabhbhai National Institute of Technology, Surat, Gujarat, India

*E-mail of corresponding author: apurvadesaisurat@gmail.com, crp@ced.svnit.ac.in

Apurvkumar Desai 0000-0003-4920-420X, Chetan R. Patel 0000-0003-3395-7856

Resume

The present article portrays the bibliometric analysis of research conducted on E-mobility worldwide. The study aimed to understand research characteristics, evolution, challenges and potential research trends. Research articles published on E-mobility have been compiled from the Scopus database, resulting in 1737 articles published between 2001 and 2021. The software R Studio has been used for subsequent bibliometric analysis. The analysis examines the research trend in the field of E-mobility. In addition, it identifies the most productive contributors in terms of author, country and sources. Thematic analysis has been performed, as well, to reveal E-mobility research trends, including the most influential articles and authors. The study concludes that very few studies have been conducted on E-mobility and that there is much potential in E-mobility. The present paper can help the researcher pave the research path in E-mobility.

Article info

Received 1 November 2022
Accepted 4 December 2022
Online 21 December 2022

Keywords:

e-mobility
EV
bibliometric analysis
research trend analysis
charging infrastructure
environment

Available online: https://doi.org/10.26552/com.C.2023.016

ISSN 1335-4205 (print version)
ISSN 2585-7878 (online version)

1 Introduction

E-mobility being an emerging field, many research studies are being conducted worldwide in this field. Many pieces of research have been carried out that focus on different aspects of E-mobility. For a new researcher entering the field, the review articles provide a comprehensive overview of achievements in the field. Researchers have also published many review papers with varied objectives. For example, the review paper by Hawkins et. al. [1] discusses the environmental impact of Electric Vehicles (EVs). The article by Yong et al. [2] reviews development of the latest technologies, effects and opportunities due to EV deployment. The publication by Adnan and Nordin [3] examines EV adoption in Malaysia. Publication by Requia et al. [4] provides insights into the impact of E-mobility on GHG emissions and air pollutants. The publication by Viola [5] reviews the impact of human psychology on the adoption of EVs. Such traditional reviews adopted by many researchers help understand the cross-section of the topic and the latest facts. Still, they are not always helping researchers from developing and underdeveloped nations keep up with research publications, especially in emerging fields like E-mobility [6]. Despite the high growth rate in scientific research publications, very few attempts have analyzed worldwide publications on EVs [7]. Bibliometric studies help the researchers get insights into the global research in the field and find the research direction for future research. Bibliometric analysis is one of the most used approaches for analyzing published research [8]. The present study provides the researchers in the field with a bibliometric analysis of global research in the field of e-mobility to understand research trends and find the research gaps.

2 Literature background

Bibliometric methods are applied to analyze the output of scientific research quantitatively [9]. It uses bibliographic data from online scientific databases [10]. The number of bibliographic reviews has increased in different research areas, with increasing accessibility to bibliographic data [10]. In 2021 only, researchers like Sharifi et al. [6], Antony et al. [11], Gao et al. [12] and Sonkar et al. [13] have used bibliometric analysis for their respective research domains. The articles reported show the broad applicability of bibliometrics in different research fields.

Besides the above, bibliometric studies have also been performed in E-mobility domains. Secinaro et al. [10] have conducted a bibliometric analysis to identify a suitable business model for the EVs. Andres Barreto Ramirez et al. [14] have done bibliometric analysis for research published from 2007 to 2016. Recently, Bao et al. [15], have performed bibliometric analysis for studies on the impact of the electrification of vehicles on air quality. Hu et al. [7] have applied bibliometric analysis to evaluate research trends of EVs published from 1993 to 2012. Though attempts have been made to perform bibliometric analysis in E-mobility, the researchers have limited their scope of work by focusing on a specific domain in the field. No recent studies have focused on the bibliometric analysis of global research in the field. In addition, bibliometric information is dynamic and the reliability of the results of these studies is questionable, especially in the evolving field like E-mobility. The present study addresses the identified research gap. It provides the researchers with an overview of the research being carried out in the field of e-mobility with the help of bibliometric analysis. Four research questions (RQ), as presented below, are identified to achieve the objective of the study:

- **RQ1** - What is the scientific research trend related to E-mobility?
- **RQ2** - Who are the top contributors in research related to E-mobility in terms of authors, sources and countries over the period?
- **RQ3** - What are the thematic focus, shifts and current status of different research fields in E-mobility?
- **RQ4** - Who are the most influential contributors in terms of articles and authors?

3 Methodology

The methodology adopted for the present study is divided into various phases, as depicted in Figure 1. The study's first phase is research design, which includes formulating research questions, keyword selection, database selection etc. According to Dhamija and Bag [16], the reliability of systematic reviews like bibliometric analysis are highly dependent on selecting suitable keywords. Looking at the importance of keyword choice, authors have tried the combination of different keywords for data collection. Finally, the keywords "E-Mobility, E Mobility, Electric-Mobility and Electric Mobility" have been selected to include all the relevant research and thus maximizing the scope of the study. According to Alsharif and Baharun [17], Scopus is considered the most extensive database, with comprehensive coverage of subjects. Hence, the authors have selected the Scopus database for the present study.

The second phase of the study is data collection. It includes the loading of bibliometric data from an online database. The SCOPUS database is mined with

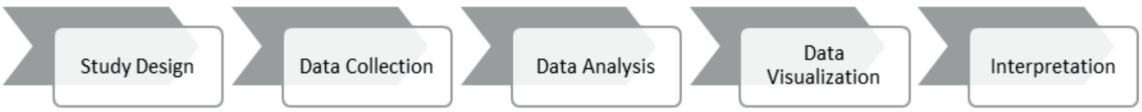

Figure 1 *Study Methodology*

Table 1 *Main bibliometric characteristics of the dataset*

Description	Results
Timespan	2001:2021
Sources (Journals, Books etc.)	735
Documents	1737
Average citations per document	9.701
Average citations per year per doc	1.544
References	50169
Keywords Plus (ID)	7935
Author's Keywords (DE)	3953
Authors	4566
Author Appearances	6071
Authors of single-authored documents	170
Authors of multi-authored documents	4396
Single-authored documents	248
Documents per Author	0.38
Authors per Document	2.63
Co-Authors per Documents	3.5
Collaboration Index	2.95

***Table 2** Distribution of documents*

Document Types	No. of Documents	%
Conference Paper	953	54.86
Article	626	36.04
Book Chapter	53	3.05
Review	38	2.19
Conference Review	33	1.90
Note	13	0.75
Short Survey	9	0.52
Book	6	0.35
Editorial	5	0.29
Erratum	1	0.06

the search string "TITLE-ABS-KEY ("E-Mobility" OR "Electric Mobility" OR "Electric-Mobility" OR "E Mobility")" resulting in 2,780 publications starting from 1924 to 2022. After screening, 1737 articles are included in the study.

The third phase of the study is data analysis, under which bibliometric analysis is performed on the collected data. Different software can be utilized to visualize data in the fourth phase of the study. Here, looking at the tools' abilities to meet the study's objectives, the authors have used RStudio to satisfy the need of the present study. In the final phase of the study, an interpretation of the results was made.

4 Bibliometric analysis results and discussion

4.1 Descriptive analysis

4.1.1 Dataset characteristics

1737 documents are extracted from the Scopus database, published in 735 sources from 2001 to 2021. The analyzed documents have an average citation rate of 9.701 and average citations per year per document of 1.544. The papers under the study have used a total of 50169 references. The keywords used by the authors of analyzed documents are 3953, which is more than two times the documents. At the same time, keyword plus, identified by the database, is 7935, about four times the documents and two times the authors' keywords. 4566 authors were identified, who appeared 6071 times in these documents. Of these, 170 have worked alone and the remaining 4396 have worked in collaboration. Out of 1737 documents analyzed, 248 are single-authored documents. On average, each author has published 0.38 papers and each article has 2.63 authors. In addition, the average number of co-authors per document is 3.5. The collaboration index, which is the ratio of the total number of authors of multiauthor papers to that of the total number of multiauthor documents, is 2.95 for the documents analyzed. Other characteristics of the data set are shown in Table 1.

4.1.2 Distribution of document types

The documents analyzed by the present study comprised 11 document types. The most frequently used document type is conference paper (953), accounting for 54.86% of scientific production. This is similar to Hu et al. [7], with 59.57% of total production as conference papers. The conference papers are followed by Article (626), which accounts for 36.04% of total scientific production. Conference papers and articles combined account for over 90% of total production. The distribution of the document is shown in Table 2.

4.1.3 Annual production of research

The present study analyzed scientific production from 2001 to 2021. The annual scientific production in E-mobility is depicted in Figure 2. The research in E-mobility had a slow growth from 2001 to 2008, with just 20 publications accounting for just 1.15% of total production. The remaining period (2009-2021) shows a constant growth in scientific output. In addition, most publications (98.84%) are from this period. Overall research production has shown an Annual Growth Rate (AGR) of 31.77%. Compared to the average science growth rate given by Bornmann and Mutz [18], which is around 8 – 9% per year, the growth rate for research in E-mobility is much higher. This growth indicates the interest of researchers in various sectors related to EVs, with the introduction of EVs in multiple markets.

4.1.4 Top Contributors

4.1.4.1 Authors

As discussed earlier, 4566 authors responsible for 1737 articles were identified, from which the authors having the highest number of publications are discussed in this section. Benjamin K. Sovacool is the most contributing author, with 29 articles published from 2016 to 2021. Johannes Kester and Lance Noel follow

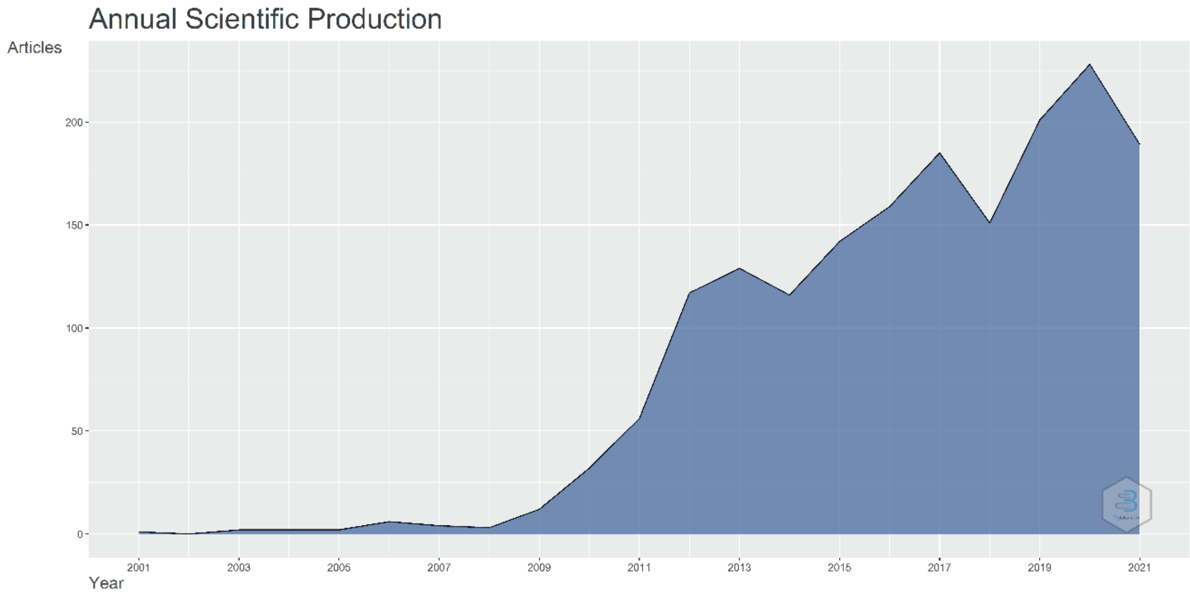

***Figure 2** Annual Scientific Production*

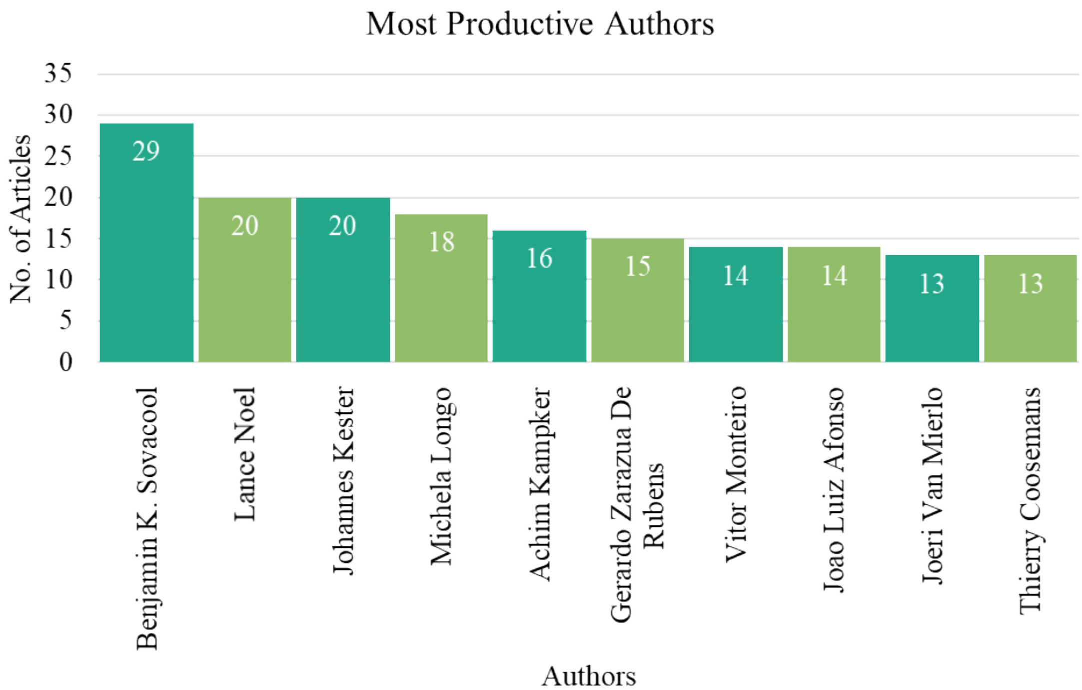

***Figure 3** Most productive authors*

Benjamin K. Sovacool with 20 publications each. Figure 3 shows the top 10 authors with the highest number of documents published during the period under consideration.

Of the top ten authors, Achim Kampker, Joao Luiz Afonso and Vitor Monteiro have the highest experience of 10 years each. Though some authors have heavily contributed to the field of E-mobility, there is no proof of productive elites. The above inference can be backed by the observation that 3,789 authors, which account for around 83% of all authors, have published only a single article. The possible explanation for this may be the interest of young researchers in the field. These results also indicate that research in E-mobility has interest from many researchers, characterizing it as a topic in trend.

4.1.4.2 Sources

As discussed earlier, 735 sources responsible for publishing 1,737 articles were identified, from which the sources with the highest number of publications are discussed in this section. Table 3 shows the top ten sources publishing the highest number of documents. As per the table, EVS 2017 has the highest number of publications (51). From the category of journals, WEVJ has the highest number of publications (49) having the

Table 3 *Top 10 sources publishing research on E-mobility*

Sources	Articles
EVS 2017 - 30th International Electric Vehicle Symposium and Exhibition	51
World Electric Vehicle Journal (WEVJ)	49
Sustainability (Switzerland)	36
Transportation Research Procedia	35
VDI Berichte	33
SAE Technical Papers	30
Procedia CIRP	28
Applied Energy	26
EVS 2016 - 29th International Electric Vehicle Symposium	23
Automotive Industries AI	23

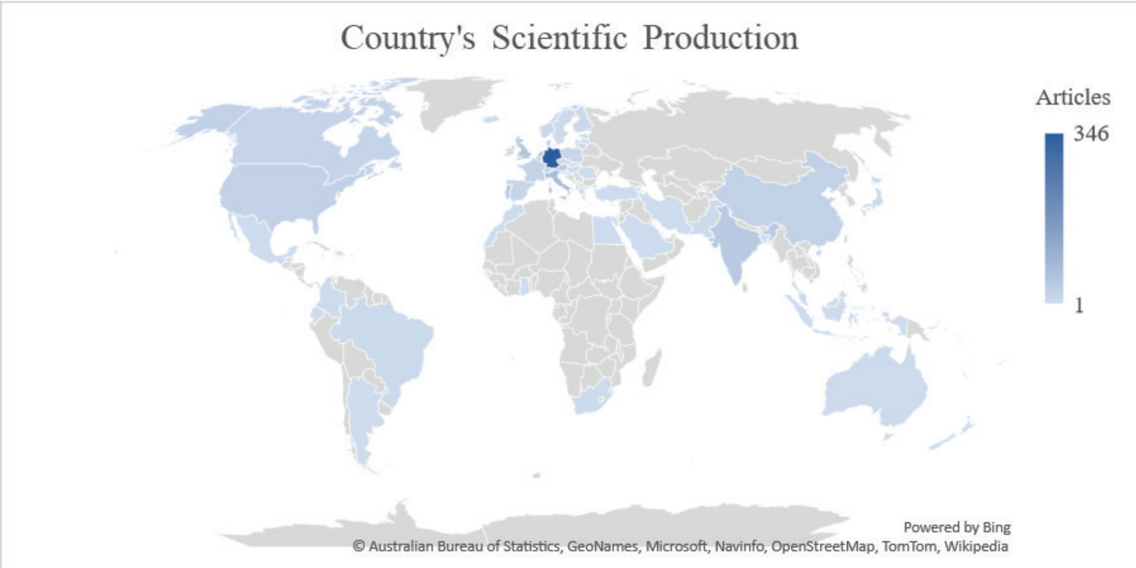

Figure 4 *Country's Scientific Production*

keyword E-mobility. The distribution of articles can explain the presence of conferences in the list of top contributing sources discussed earlier, which indicated conference papers account for 54.86% of total articles.

The authors have also carried out Bradford's Dispersion Law Analysis [19]. Bradford's law describes how the research is dispersed throughout the scientific publishing sources. In Bradford's Dispersion Law Analysis, sources of articles are first arranged in decreasing order according to the number of articles per source. Then the articles are divided into three distinct zones, such that each zone contains approximately 1/3rd of the total articles. According to this analysis, zone 1, which shows the most productive sources, has 27 sources with 577 publications. Zone 2, which includes many less productive sources, contains 167 sources responsible for 587 articles. At last, zone 3, which depicts more sources with lesser publications, has 541 sources with 573 publications. Hence, out of 735 sources responsible for publications in E-mobility, only 27 sources, which account for just 3.4% of all the sources, were responsible for approximately 1/3rd of publications.

4.1.4.3 Countries

From the documents analyzed, 70 countries have been identified as having scientific contributions to E-mobility. Figure 4 shows the countries according to their scientific production. According to the country of the corresponding author, Germany has the highest, i.e., 346 articles. This can be explained by Germany being considered an automobile hub, responsible for new developments in the automotive industry. Germany is followed by Italy, the UK, India and Austria, with 71, 49, 43, 43 and 40 articles in the top five. This shows that the European countries have more dominance in publishing research articles in E-mobility research.

4.1.5 Most influential contributors

4.1.5.1 Documents

21 articles have received more than 100 global citations and 569 have received zero citations. Out

Table 4 Top 20 authors with the highest citations

Authors (Global citation)	TC	Authors (Global citation)	TC
Benjamin K. Sovacool	724	Sungu Hwang	542
Simone Abram	619	Ji-Eun Jeong	542
Merlinda Andoni	619	Jinyoung Kim	542
David Flynn	619	Seo-jin Ko	542
Dale Geach	619	Thanh Laun Nguyen	542
David Jenkins	619	Tae Joo Shin	542
Peter McCallum	619	Mohammad Afsar Uddin	542
Andrew Peacock	619	Bright Walker	542
Valentin Robu	619	Han Young Woo	542
Hyosung Choi	542	Seungjib Yum	542

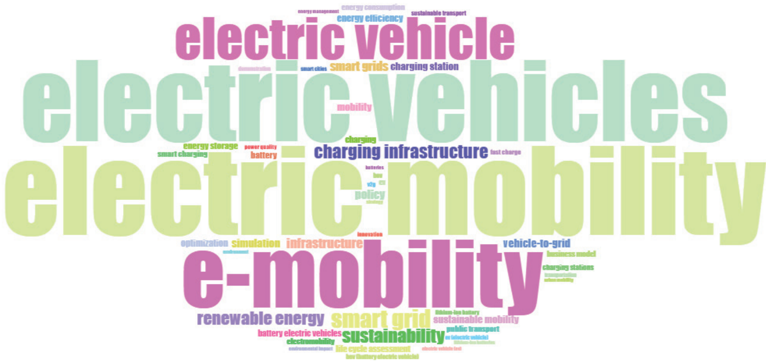

Figure 5 *Word cloud - Author's keywords*

of these 569 articles, 107, accounting for 18.80% of articles with zero citations, were only published in 2021. This can be the possible explanation for fewer citations. The most influential research is by Andoni et al. [20], with 619 citations. This study identifies challenges and opportunities to blockchain technology for various sectors, including E-mobility. Based on local citations, the most influential document is by Dijk et al. [21], with 38 local and 198 global citations. This paper reviews EV's development before and after 2005, focusing on factors responsible for the shift to E-mobility and factors acting as barriers towards the further growth. The second most influential document, based on local citations, is by Franke et al. [22], with 20 and 243 local and global citations, respectively, focusing on understanding psychological barriers in E-mobility adaptation. Next is by Sovacool [23], with 17 local and 61 global citations. According to the bibliometric analysis of the present study, the author is the most productive in E-mobility. In this paper, the author integrates the theory of mobility with actor-network theory and a unified theory of acceptance and the use of technology and proposes a framework for E-mobility adoption.

4.1.5.2 Authors

This section identifies the most influential authors based on the number of global citations. A total of 4566 authors responsible for publishing 1737 articles have been identified in the study. Only 116 authors, accounting for 2.54% of the total, have received more than 100 citations. The author Benjamin K. Sovacool has received the highest number of citations (724) for his work. 1255 authors out of 4566, accounting for 27.5%, have received no citation. This again proves the non-existence of a productive elite. Table 4 shows the top 20 most influential authors in E-mobility. It can be seen that except for Benjamin K. Sovacool, all other authors having the highest citations are responsible for two articles, Andoni et al. [20] and Nguyen et al. [24]. Hence, they cannot be considered the most influential authors of E-mobility.

4.2 Thematic trend analysis

4.2.1 Most frequent keywords

1737 documents analyzed in the present study identified 3,953 authors' keywords. The top ten most frequently used Authors' keywords include "electric mobility (256)", "electric vehicles (234)", "e-mobility (196)", "electric vehicle (121)", "smart grid (53)", "charging infrastructure (41)", "sustainability (41)", "renewable energy (39)", "infrastructure (30)" and "smart grids (28)". It can be observed that authors use a variety of keywords indicating the same ideas

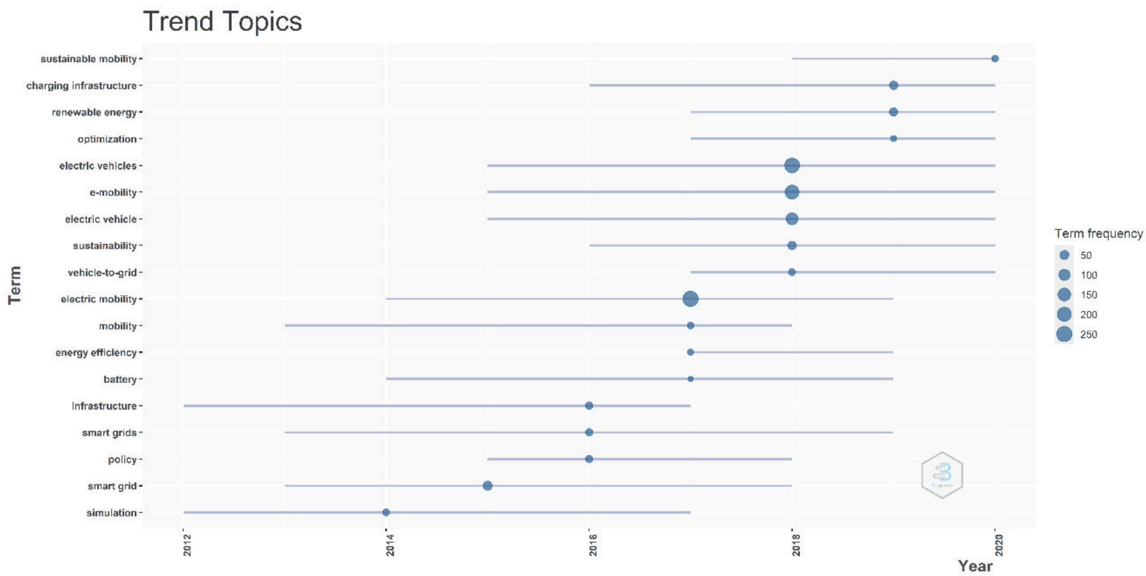

***Figure 6** Trend topics*

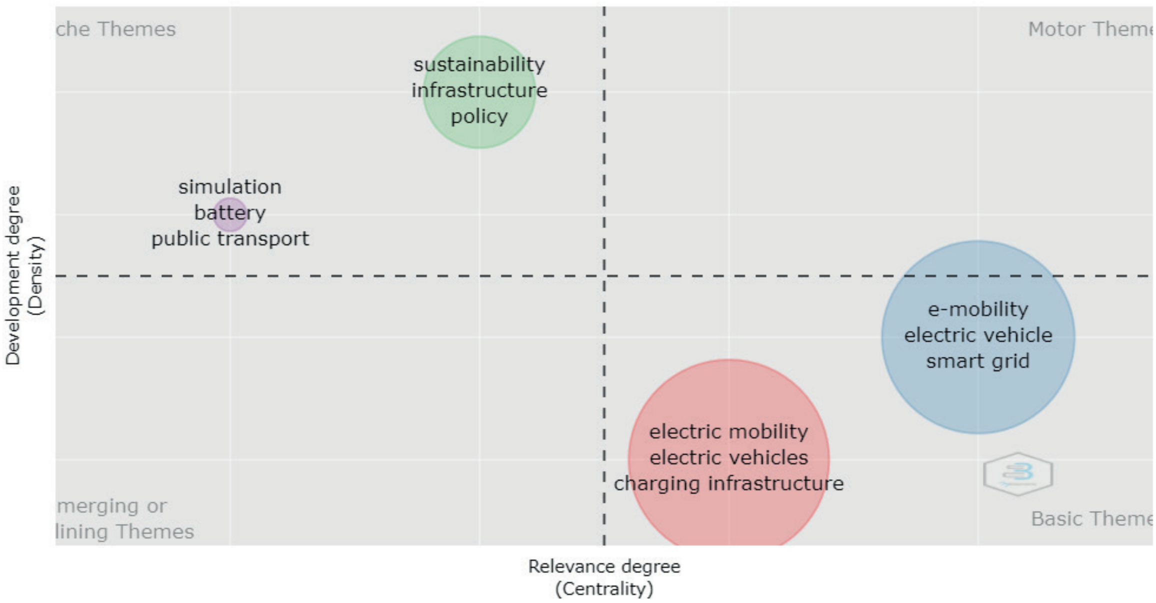

***Figure 7** Thematic Map*

with slight variations. In addition, the same word is sometimes used in singular or plural forms by different researchers. For example, "Electric Vehicles," "Electric Vehicle," "EV," and "EVs," etc. This presents the authors with the challenge of drawing scientific inferences from the results. Figure 5 shows the word cloud for authors' keywords, showing the top 50 words, with frequency as a word occurrence measure. A word cloud is a diagram showing frequently used words in which the size of the word represents the frequency.

4.2.2 Trend topics

Figure 6 shows the trend topic analysis based on authors' keywords, with parameters for minimum frequency as 20 and the number of words per year as 5. The plot generated shows 18 keywords with their research trends. According to Figure 6, the topic of interest for researchers during the period 2014-2016 included keywords like smart grid, policy etc. During the period 2016-2018, the interest of the researchers shifted towards energy efficiency. After 2018, the topic of interest for the researchers shifted towards the sustainable mobility, charging infrastructure, renewable energy etc. From the above observation, it can be inferred that E-mobility is a continuously evolving field. The focus of researchers has shifted to sustainable mobility and renewable energy in the present times. This also reflects the increasing awareness of sustainability in the community.

4.2.3 Thematic map

Figure 7 shows the thematic map generated with parameters, number of words as 90, minimum cluster frequency per thousand documents as 5 and number of labels for each cluster as 3, on authors' keywords identified from the extracted database. The thematic map divides the research into four themes: emerging or declining themes, basic themes, motor themes and niche themes based on development degree and relevance degree. Figure 7 shows that research related to the blue cluster has very high relevance and medium development, including keywords such as electric vehicle, smart grid etc. Cluster red, which includes the keywords charging infrastructure, optimization etc., has high relevancy and low development. Next, clusters green and purple are under niche themes with high to very high development and low to medium relevance. These clusters include keywords like policy, climate change, public transport etc.

From the above observation, it can be inferred that though the cluster red has high relevance, development is very low. Hence, the researchers may focus more on that cluster. Cluster blue, the cluster having the highest relevance and moving towards high development, indicates that the cluster will transfer from a basic theme to a motor theme in due time. The clusters green and purple, suggesting niche themes, show the areas connected with E-mobility with lower relevance but comparatively higher development.

4.2.4 Potential research trends

Based on the above discussions, the authors have identified potential research topics. According to the authors, research areas like vehicle, battery and charging technology have been researched intensively in the past few years. Hence, it can be said that these areas have been developed to a satisfactory level. Presently, researchers focus on challenges of mass adoption, policies, mass diffusion of technology etc. According to the authors, the potential research areas for future researchers can be optimization of range, charging infrastructure planning and related services, making EVs affordable for mass adoption, battery recycling, smart grid etc.

5 Conclusion

The study analyzed bibliometric information from 1737 pieces of research published in 735 sources from 2001 to 2021. A total of 4566 authors from 70 countries have contributed to these researches. Research in the field gained momentum after 2009. Overall, publications have shown an AGR of 31.77%, making it a topic of interest for research. The publications are distributed among 11 document types, among which conference papers account for more than half of total production. Conference papers are followed by journal articles combinedly, accounting for more than 90% of scientific production.

According to the analysis, Benjamin K. Sovacool is the most contributing author, with 29 articles published between 2016 and 2021. In terms of time, Achim Kampker, Joao Luiz Afonso and Vitor Monteiro have contributed for ten years in the field. Out of 4566 authors identified, 3789 authors have published a single article. Hence non-existence of productive elites has been observed in the field. For sources publishing research related to E-mobility, EVS 2017 has the highest number of articles published, followed by the World Electric Vehicle Journal. In addition, Bradford's [19] dispersion law identified the top 27 sources responsible for approximately 1/3rd of articles. According to the analysis, Germany is the most productive country, responsible for 346 publications. A clear dominance of European countries has been observed in research in the field.

The results of the thematic analysis state that out of 3935 keywords mentioned by authors, "Electric Mobility," "Electric Vehicles," "E-mobility," and "Electric Vehicle" are highly frequent. According to trend topic analysis, the current topic of interest includes "Sustainable Mobility," "Charging Infrastructure," "Renewable Energy," etc. According to the thematic map, publications with keywords like "Electric Vehicle," "Smart Grid," etc., are identified as highly relevant and relatively more developed. In comparison, publications with keywords "Charging Infrastructure," "Optimization," etc., are identified as highly relevant but relatively less developed.

The articles by Andoni et al. [20], Nguyen et al. [24] and Peters et al. [25] are among the most influential articles based on global citation. Based on the local citation, the most influential papers include Dijk et al. [21], Franke and Krems [26] and Sovacool [23]. The most influential and top contributing author is Benjamin K. Sovacool.

According to the authors, as vehicle technology has been developed satisfactorily, it can be a topic of declining interest. Topics like charging infrastructure and smart grids are expected to stay in trend for a few years. Battery technology can also be expected to remain in trend due to the need for an alternative to what is presently available because of its environmental impact. In the future, topics related to business models for charging infrastructure, battery swapping technology, flash charging, wireless charging etc., are expected to stay in focus. Other than these, research focused on optimizing technology to make it more affordable is expected to remain on-trend.

6 Limitations and future scope of the study

The first potential limitation is that the bibliographic information is dynamic and is expected to change with time. Hence, the study can be revised after further growth to incorporate future developments. Despite Scopus being a comprehensive database, journals are indexed in various databases or non-indexed. Research published in such journals may have been lost. More accurate results can be obtained by including such journals in future studies. In addition, authors may use different initials, multiple names, or different names in various publications. This limitation can cause a slight deviation in the results of bibliometric analysis.

Grants and funding

The authors received no financial support for the research, authorship and/or publication of this article.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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CHANGES IN MECHANICAL PROPERTIES DUE TO HEAT TREATMENT ON ADDITIVE MANUFACTURED Ti-6Al-4V

József Hlinka[1,*], László Dániel Erőss[1], Ármin Fendrik[2], Krisztián Bán[1]

[1]Department of Automotive Technologies, Faculty of Transportation Engineering and Vehicle Engineering, Budapest University of Technology and Economics, Budapest, Hungary
[2]MouldTech Systems Ltd., Zalaegerszeg, Hungary

*E-mail of corresponding author: hlinka.jozsef@kjk.bme.hu

József Hlinka 0000-0001-8737-6913, László Dániel Erőss 0000-0003-4430-0112, Krisztián Bán 0000-0001-9262-1784

Resume

Laser-based additive manufacturing (AM) of Ti-6Al-4V has become increasingly important for use in components of transportation devices. The most significant advantage over conventional steel structures is the reduction in specific weight. Complex geometries can be produced with the layer-by-layer manufacturing process and the personalised, unique part production can be faster and produced with the lower costs and less material waste than the conventional manufacturing techniques. Between the manufacturing process of an additively manufactured part and its use, the post-processing is an essential factor related to the strength properties or porosity of the finished product. The heat treatment is a possibility to change the final part properties.

Article info

Received 28 July 2022
Accepted 9 October 2022
Online 4 November 2022

Keywords:

AM
heat treatment
inert atmosphere
mechanical properties
Ti-6Al-4V

Available online: https://doi.org/10.26552/com.C.2023.001

ISSN 1335-4205 (print version)
ISSN 2585-7878 (online version)

1 Introduction

Additive manufacturing (AM), also known as 3D printing, is a technology with a lot of potential in the modern manufacturing industry, where metallic materials, including the important engineering materials, steel, aluminium and titanium can be manufactured with metal-based AM [1-3].

Titanium alloys are widely used in the aerospace industry, medical applications and motorsports despite the high costs compared to other materials [4]. In equilibrium, at ambient conditions, Ti-6Al-4V (Ti6Al4V, Ti64) is a dual-phase material; primary phase α-Ti (HCP) co-exists with β-Ti (BCC). Increasing utilization of additive manufacturing (AM), enables fabrication of stronger and lighter parts with more intricate geometries [5].

This alloy is therefore used for many airframes and engine parts. Furthermore, there are many actual applications of this alloy in aircraft where the high reliability is required and further, the availability of abundant data promotes its application. In airframes, it is used for general structural material, bolts, seat rails and the like. In engines, due to the relatively low allowable temperature of about 300 °C, the alloy is used for fan blades, fan cases and the similarly in the intake section, where temperatures are relatively low [6].

Ti-6Al-4V is a frequently chosen material due to the lower mass compared to structural steels, resistance to temperatures occurring in flight, resistance to corrosion, as well as the possibility of joining titanium with composite materials [7].

The DMLS (Direct Metal Laser Sintering) method is similar to the SLM (Selective Laser Melting) method, which uses a laser to melt metallic powder layers. The metallic powder is spread on a movable platform and a laser beam heats particles of metal powder in specific places, causing their melting. After a finished layer, the mobile platform is lowered and another layer of powder is applied to the melted layer. All over again, the powder melting process is carried out. These operations are repeated until the manufactured part is created. After that, the manufactured part is heat treated and the supports are removed.

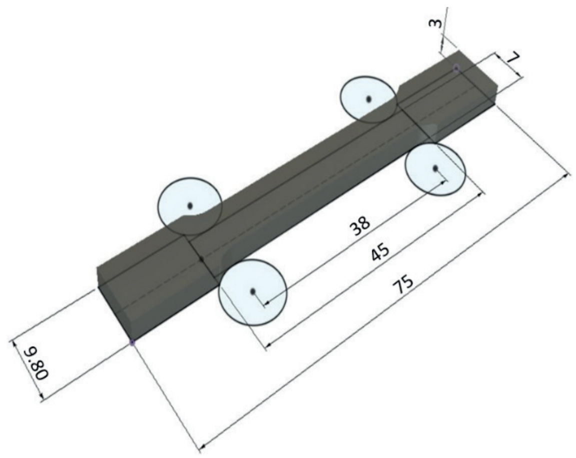

Figure 1 Tensile test sample geometry

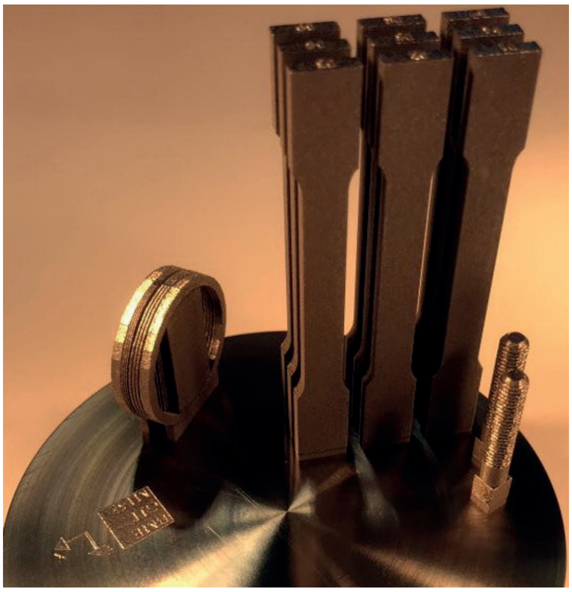

Figure 2 Tensile test sample manufacturing layout

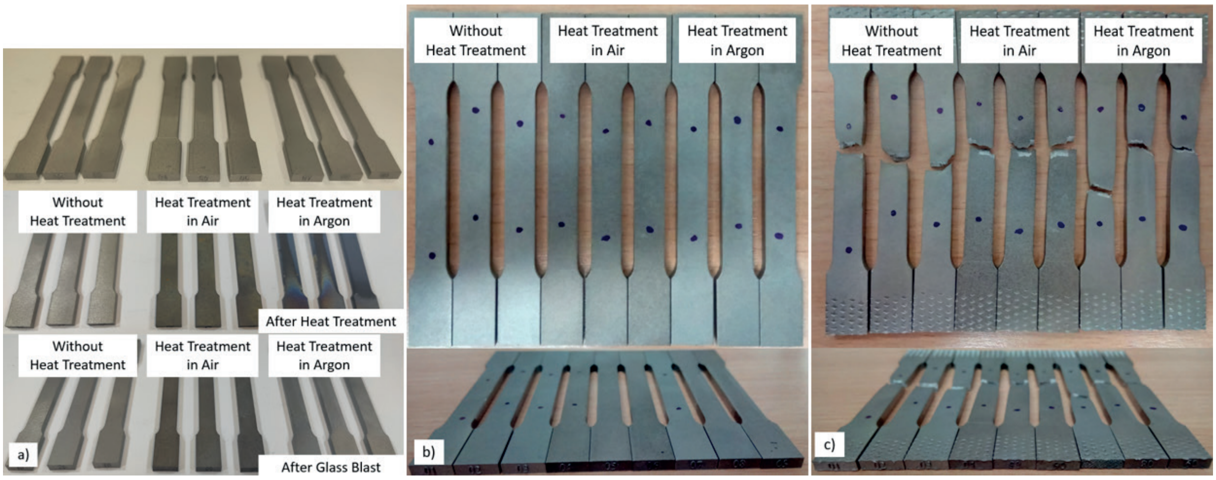

Figure 3 Ti-6Al-4V tensile test samples a) as manufactured, after the heat treatment, after the heat treatment and glass blasted, b) before the tensile test, c) after the tensile test

The heat treatment can improve Ti-6Al-4V parts microstructure and mechanical properties. Titanium is a particularly sensitive material to oxidation, so the heat treatment is carried out in an inert atmosphere or vacuum [8].

This study focuses on that how different heat treatments affect the additively manufactured Ti-6Al-4V tensile properties and how the cooling rates affect on the surface hardness of the samples.

2 Experimental materials

The static tensile test samples were manufactured with an EOS M100 DMLS powder-bed additive manufacturing equipment. The used Ti-6Al-4V powder was EOS Titanium Ti64 [9], which is the machine manufacturers' recommended stock material. The parts are manufactured with the basic parameter set recommended for this stock material from EOS. The spread layer thickness was 20 μm. The longest dimension of the tensile test samples was built in the Z direction, so the tensile force is parallel to the building direction, perpendicular to the layers. The shape of the tensile test samples and the layout is illustrated in Figures 1 and 2.

Static tensile tests were performed on a Zwick Z250 testing machine at room temperature according to EN 10002 standard, with a test rate of 2 mm/min, clamping distance 47 mm. The optical strain gauge was a Mercury Monet DIC and the gauge length under test was 26 mm.

Three types of tensile test samples were examined (3 pieces in each condition), shown in Figure 3. There were samples in as manufactured condition, samples that were heat treated in air and samples that were heat treated in Argon (inert gas) atmosphere.

The heat treatment profile was the same in both atmospheres. The peak temperature of the heat treatment was 650 °C, the heating rate was 230 °C/h

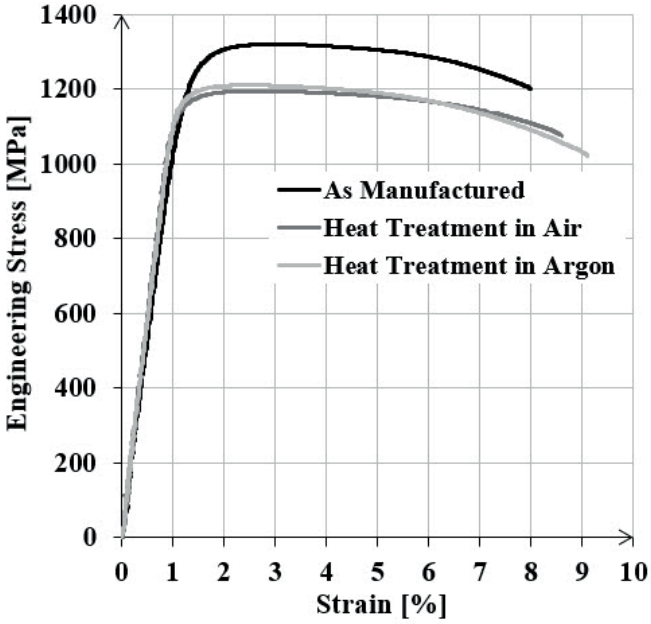

Figure 4 *Engineering stress-strain curves of as manufactured and heat-treated Ti-6Al-4V*

Table 1 *Average of measured mechanical properties of as manufactured and heat-treated Ti-6Al-4V*

Condition	R_m [MPa]	$R_{p0.2}$ [MPa]	A [%]	E [MPa]
As Manufactured	1318 ± 6	1178 ± 40	7.5 ± 0.5	114 ± 8
Heat Treatment in Air	1190 ± 7	1136 ± 10	7.6 ± 0.7	116 ± 3
Heat Treatment in Argon	1202 ± 10	1151 ± 12	8.4 ± 0.2	119 ± 4

and the soaking time was 3 h. The samples were let to cool down freely in air or in continuous Argon ventilation. According to the literature, the used heat treatment results in stress relieving, the strength and elongation remain unchanged, while the internal stresses are relieved [5-6, 8-9].

After the heat treatment, the samples were micro-glass blasted. With this procedure, any powder particles attached to the samples during the manufacturing and oxidised surfaces formed during the heat treatment process, have been removed from the surface of the samples. Figure 3 shows the samples as manufactured, after the heat treatment and after the micro-glass blast. The colour of the heat-treated samples in the air atmosphere became darker grey than of the as manufactured samples. After micro-glass blast this colour change remained.

According to the manufacturers data in the case of a part made of EOS Ti64 powder in vertical direction as manufactured state has the tensile strength (R_m) 1240 ± 50 MPa, the yield strength ($R_{p0.2}$) 1120 ± 80 MPa, elongation at break (A) 10 ± 3%, modulus of elasticity (E) 110 ± 15 GPa, Vickers Hardness 320 ± 12 HV5 [9].

To get information about the hardness differences due to different heat treatment cooling rates, samples were cooled down to room temperature after the heat treatment in the furnace or removed from the furnace and cooled in the open air.

3 Results and discussion

Figure 4 shows the engineering stress-strain curve for each examined condition of Ti-6Al-4V tensile test samples and Table 1 shows the results data of the tensile tests. The tensile strengths show that without the heat treatment the Ti-6Al-4V has bigger tensile strength and that applied stress relieving heat treatment causes 9.2% reduction. Smaller reduction can be seen in the yield strength. The elongation at break shows a minimal increase as a result of the heat treatment but it is to the margin of deviations. The examination shows that the heat treatment atmosphere has no effect on the mechanical properties of the tensile test samples. In this measurement, the orientation of samples had no effect on the results. All the samples were manufactured in the same conditions.

All of the measured samples were glass blasted so the adhesive powder particles which stuck to the surface and partially melted by laser due to insufficient laser energy had no effect on the measured properties. Those bonded powder particles could form sharp corner transition regions, which act as stress concentrators, which could lead to decreased ductility.

Figure 5 shows the Vickers hardness values of different types of Ti-6Al-4V samples. The Vickers hardness, according to the material datasheet is 320 ± 12 HV5 [9]. On the as manufactured type,

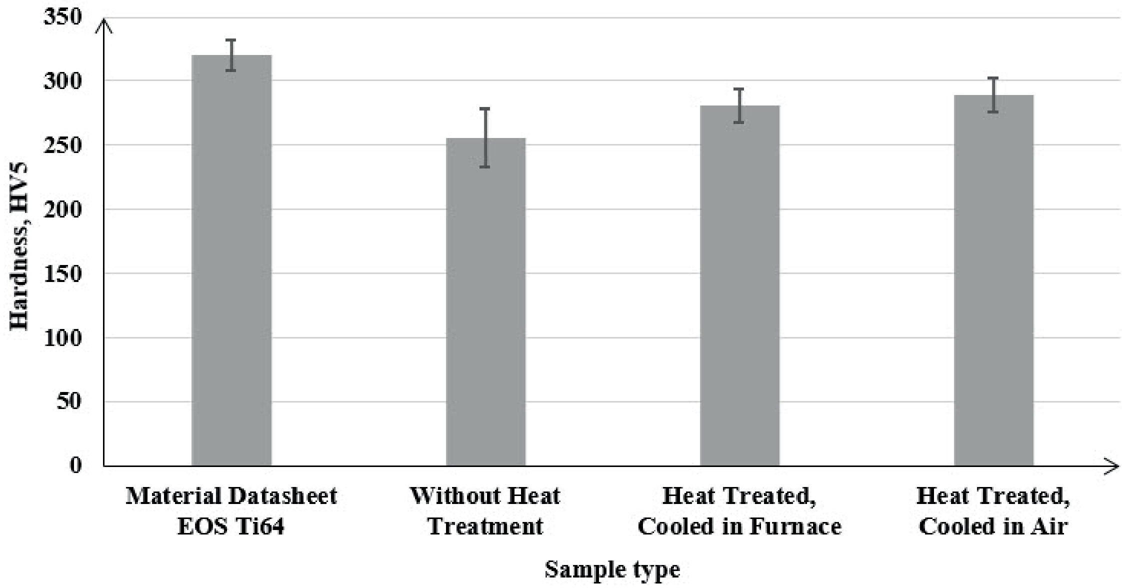

Figure 5 *Vickers Hardness (HV5) of Ti-6Al-4V AM samples with and without the heat treatment*

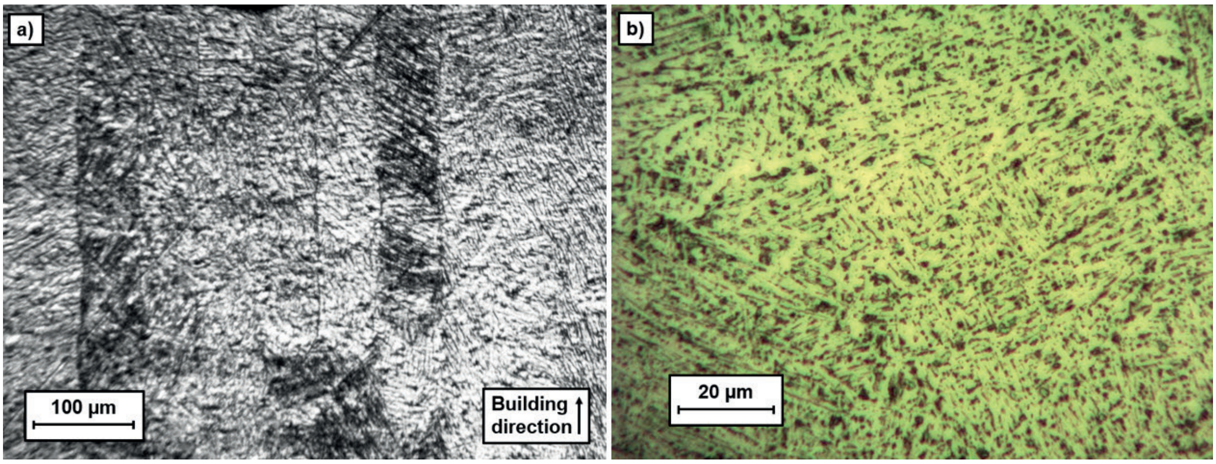

Figure 6 *Microstructure of as-built Ti-6Al-4V AM sample*

without the heat treatment, samples from the same Ti64 powder manufactured with EOS M100 machine had the average hardness value of 255 ± 22 HV5. After the heat treatment the samples cooled in the furnace or removed from the furnace and cooled in the open air. The measured average hardness value is 281 ± 13 HV5 in the case of cooling in the furnace and 289 ± 13 HV5 in case of cooling in open air. The hardness in the datasheet is 20% higher than the manufactured samples without the heat treatment. This difference also occurs for parts manufactured in different regions of the production area. The effect of the heat treatment can be noticeable. The measured hardness after the heat treatment is 10-13% higher than the as manufactured state. The difference between the different cooling rates shows a little bit higher hardness in the case of the faster cooling rates, but this average hardness difference can be compared to the standard deviation of the measurement.

During the DMLS process, the created melt pool is tiny and the cooling rate is thought to be within the range of 10^3-10^5 °C/s and faster than the crucial cooling rate of 410 °C/s that is necessary for martensitic transformation (β to α’) in Ti-6Al-4V. The additively manufactured Ti-6Al-4V typically consists of acicular α’ martensite rather than equilibrium α and β phases [10]. In Figure 6(a) columnar grains, the common microstructure characteristic of additively manufactured samples, can be seen. The building direction is parallel to the grain growth direction due to the thermal history of the layer-by-layer fabrication. The as-built phase composition, α’ martensite needles, are shown in Figure 6(b). During the heat treatment, when the temperature is higher than the martensite dissolution temperature (T_{Mdiss} 400 °C), the α’ martensite needles can dissolute partially or completely [11], which depends on the temperature. During the stress relief heat treatment, the decomposition of the α’ martensite possibly creates fine (α + β) lamellar structure. The reduction of strength values and higher elongations hint to these structural modifications, which are more likely partial because of the applied temperature. The literature is not uniform on the issue of whether the decomposition of martensite takes place completely in this temperature range [10-12].

4 Conclusions

Based on the results, it can be stated that for the Ti-6Al-4V samples, the applied heat treatment reduced the tensile strength by 9.2% compared to without the heat treatment condition and the atmosphere applied during the heat treatment had no detectable effect on the mechanical properties of samples. After the heat treatments, the samples' surface discoloured when the heat treatment was in air atmosphere and after the micro-glass blast, this colour change remained. The geometry of the tensile test samples did not change by more than 0.01 mm after the micro-glass blast. The results found are based on a static examination. Further dynamic tests on samples can be used to investigate the effect of heat treatment atmosphere on fatigue properties.

Examination of the hardness of the heat-treated samples shows that no significant change in the examined cases can be measured. The differences are comparable to the standard deviation of the measurement results. After the heat treatment, it seems that in this case, the cooling rate had no to effect on formation of the structure, which would affect the hardness.

Acknowledgment

The project is funded by the National Research, Development and Innovation (NKFIH) Fund. Project titles: "Development of multi-purpose fixed-wing drone based on innovative solutions and the creation of necessary competencies". The application ID number: 2019-1.1.1-PIACI-KFI-2019-00139. The authors want to express their thanks or the financial support.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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ESTIMATION OF THE PUBLIC TRANSPORT OPERATING PERFORMANCE: EXAMPLE OF A SELECTED CITY BUS ROUTE

Miroslaw Smieszek[1], Nataliia Kostian[2], Vasyl Mateichyk[1], Jakub Mosciszewski[1,*], Liudmyla Tarandushka[2]

[1]Department of Technical Systems Engineering, Rzeszow University of Technology, Rzeszow, Poland
[2]Department of Automobiles and Technologies for their Operating, Cherkasy State Technological University, Cherkasy, Ukraine

*E-mail of corresponding author: j.mosciszews@prz.edu.pl

Miroslaw Smieszek 0000-0002-4508-6309, Nataliia Kostian 0000-0002-1599-4007, Vasyl Mateichyk 0000-0002-3683-7246, Jakub Mosciszewski 0000-0002-0800-8547, Liudmyla Tarandushka 0000-0002-1410-9088

Resume

The efficiency of the public transport use is a complex indicator formed from a set of partial assessments of its economic, technical and environmental efficiency. Special attention must be paid to the evaluation of efficiency based on energy consumption, taking into account transport work on the city route. The article is devoted to study of the operation performance of a diesel city bus on the selected city route and determines its energy efficiency by specific fuel consumption per unit of transport work. Based on statistical data, the distribution patterns of the speed and acceleration of the bus on the studied route were determined. The analytical dependence of the specific fuel consumption on the average daily passenger flow capacity on the route is obtained and its adequacy is confirmed. Using the dependence obtained, the fuel consumption of the bus was estimated in individual hauls and a certain section of the route.

Article info

Received 9 May 2022
Accepted 10 October 2022
Online 10 November 2022

Keywords:

urban public transport
city bus route
operating performance
specific fuel consumption
statistical analysis

Available online: https://doi.org/10.26552/com.C.2023.002

ISSN 1335-4205 (print version)
ISSN 2585-7878 (online version)

1 Introduction

Sustainable economic development currently emphasizes environmental protection and lower consumption of harmful fossil fuels. According to the EU recommendations, in the long term of transport development, the goal is to achieve climate neutrality [1-2]. However, as of today, it is not yet fully possible. Transport is a field that is largely responsible for the fuel consumption and the emission of harmful substances into the environment [3-4]. One form of transport is a public transport within cities. It can be implemented by various means; the impact on the environment is presented in [5]. Zero-emission measures, such as city bikes and electric vehicles, are the most desirable [6]. In the case of electric vehicles, an important factor is the source of primary energy from which the electricity is generated. Currently, the public transport using fossil fuels dominates in medium-sized cities. In large cities, where there is an extensive metro, tram and city rail system, the share of transport using fossil fuels is smaller. According to data from work [7], diesel buses are still the dominant group of public transport in Europe. As a part of current activities, the effects of which can be seen immediately, public transport is preferred and thus efforts are made to limit individual transport. Activities of this type are implemented in many European cities and examples can be found in [4, 8-9]. Public transport, in addition to reducing the fuel consumption per passenger, contributes to reducing traffic, noise and emissions of harmful pollutants [10]. It also prevents the exclusion of certain groups of society. To demonstrate the benefits that can be achieved in energy consumption through the use of public transport, the article analyzes the fuel consumption necessary to perform transport work, expressed in the number of passengers transported in a given route section. In [11] the characteristics of urban road transport of the transport system are systematized, affecting its energy efficiency and productivity. Such groups of characteristics are considered significant, which describe individual vehicles, traffic flow in general and means of traffic control, as well as road, climatic and weather conditions. Based on expert assessments, ranges of values and implementation options have been identified for each characteristic. Criteria are proposed to evaluate energy efficiency and productivity as target functions of 22 system parameters. The work is theoretical in nature; no experimental studies have been conducted. The continuation of this work was reflected in a study [12], of which, based on statistical criteria, reduced the set of system parameters to a basic set of 10 parameters. The category, type of power plant, age, degree of use of load capacity (passenger capacity) of a vehicle, the level of traffic complexity, the degree of road resistance, the degree of curvature of the roadway, the level of motorization of the city, time interval and weather conditions are defined as basic parameters. The resulting parameter of the system is the level of energy efficiency, which is calculated as the ratio of the energy required for the movement of a vehicle in a given mode on a horizontal road in high gear in moderate weather conditions, to the actual energy consumed. At the same time, correction factors are used that consider the traffic conditions. However, the correction factors have errors that depend on the experience of the experts and the vague presentation of the observational data. Therefore, the question of determining the amount of energy consumption in a given range of accuracy remains open. The results of experimental research of different states of the transport system made it possible to obtain a mathematical model in the form of a linear multiple regression equation to estimate the energy efficiency of transport in urban mobility.

The energy consumption and fuel demand can be determined analytically or based on measurement data. In the work [13], developed mathematical models were used to determine the energy consumption of the traffic. In the presented study, data from the city authorities of Rzeszow and MPK Rzeszow (Rzeszow Urban Transport Company) were used to determine the energy consumption. Those data included information on the daily fuel consumption of a vehicle, its daily mileage and the transported passengers. In addition, data from the remote monitoring system were recorded, containing data on the speed and position of the vehicle. Those data can be collected from the monitoring system described in [14] or from the GPS module itself [13, 15]. The data used are from February and March 2022, that is, the period without pandemic restrictions. Compared to data before the pandemic, passenger transport by public transport in the city of Rzeszow decreased approximately twice. The impact of the pandemic itself on changes in traffic and transport has been described in the literature [16-17]. With a significant decrease in passenger transport, an interesting question is what the data on energy consumption in traffic look like. In the analysis carried out, data on transports with vehicles equipped with a diesel engine were used. These vehicles still represent almost half of the city bus fleet in the city of Rzeszow. The second significant group is the CNG-powered vehicles and the third group is electric buses, which represent approximately 5% of the fleet. Nonlinear models to determine the current fuel consumption, based on the speed and acceleration of vehicles, are presented in [18-19]. However, the model was maintained with the caveat that it should not be used for data outside the scope of a typical vehicle. In [18], microscopic modelling was also used to quantify the dependence of transportation fuel consumption on demand for transport flows, considering the configuration of the transport network. The study was carried out using the example of US transport networks.

The paper consists of six sections. Section 2 describes the study objects and data collection methods. In Section 3, the characteristics of the bus indicators on the studied route are described. Section 4 contains a statistical analysis of fuel consumption indicators; Section 5 shows simulation calculations of specific fuel consumption and energy efficiency of the bus in individual hauls and a certain section of the route. Discussion and conclusions are presented in Section 6.

2 Characteristics of research objects

The city route #13 in the city of Rzeszow (Poland) was chosen as the object of research. The route is shown in Figures 1 and 2.

The total length of the route from A to B is 16.376 km and from B to A is 16.805 km. On the route from A to B there are 35 bus stops and from B to A there are 38 bus stops. The distances between the bus stops are shown in Table 1.

The GPS data was collected using the Teltonika FMB920 intelligent tracker with Bluetooth connectivity (Figure 3). The Teltonika FMB920 specifications are shown in Table 2.

Main characteristics of the studied bus Mercedes-Benz O530 with diesel engine are shown in Table 3.

3 Characteristics of the bus operating indicators on the studied route

Measurement of operational indicators of the Mercedes-Benz O530 bus on the studied route was carried out in 25 working days in the period from 16.02.2022 to 29.03.2022. During the motion and stops of the bus, the data from the GPS receiver on the coordinates (longitude and latitude) of the vehicle were read and recorded in 1 second increments. The speed V and the acceleration a of the bus at each step were determined as the first and second derivatives of the traveled distance, respectively and they are the average speed and the average acceleration during 1 second. Table 4 shows a fragment of the generated data set.

For a typical working day, 70705 bus speed values

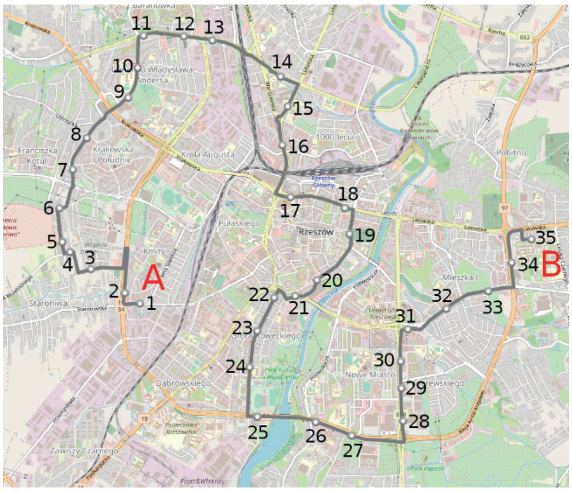


***Figure 1** Bus route #13 from A to B*

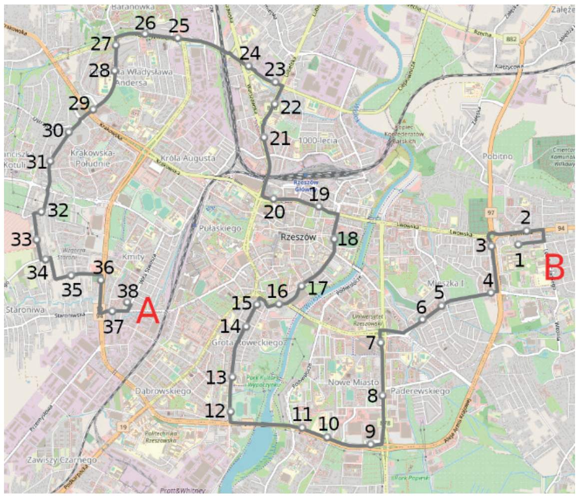


***Figure 2** Bus route #13 from B to A*

***Table 1** Distances between bus stops*

Bus stop number	Distance from previous bus stop m		Bus stop number	Distance from previous bus stop m		Bus stop number	Distance from previous bus stop m	
	A to B	B to A		A to B	B to A		A to B	B to A
1	0	0	14	857	588	27	416	381
2	313	542	15	470	257	28	769	259
3	1064	553	16	484	347	29	352	483
4	416	526	17	711	320	30	288	358
5	182	533	18	607	646	31	412	348
6	400	249	19	299	461	32	497	545
7	465	602	20	693	496	33	490	342
8	399	559	21	343	738	34	528	263
9	630	614	22	326	382	35	445	447
10	333	461	23	395	279	36		388
11	396	298	24	399	329	37		446
12	445	837	25	612	803	38		403
13	309	365	26	631	357			
			sum, m				16376	16805

***Figure 3** Teltonika FMB920 tracker*

Table 2 Specifications of Teltonika FMB920 tracker

Module name	Teltonika TM2500
Module technology	GSM/GPRS/GNSS/BLUETOOTH (for external devices)
GNSS	GPS, GLONASS, GALILEO, BEIDOU, SBAS, QZSS, DGPS, AGPS
Cellular technology	GSM
2G bands	Quad-band 850 / 900 / 1800 / 1900 MHz
Data transfer	GPRS Multi-Slot Class 12 (up to 240 kbps), GPRS Mobile Station Class B
Data output	Raw data
Communication with server	GPRS
SIM	Micro-SIM
Memory	128MB internal flash memory
Bluettoth specification	4.0 + LE
Supported bluetooth peripherals	Temperature and Humidity sensor, Headset, OBDII dongle, Inateck Barcode Scanner, Universal BLE sensors support
Receiver	33 channels
Tracking sensitivity	-165 dBM
Position accuracy	< 2.5 m CEP
Velocity accuracy	< 0.1 m/s (within +/- 15% error)
Frequency	1 Hz

Table 3 Specifications of Mercedes-Benz O530

Characteristics		Value
Length, m		11.95
Width, m		2.55
Year of production		2012
Passenger capacity	Seating	35
	Standing	55
	Total	90
Engine type		Diesel
Emission standard		EURO V
Average fuel consumption, $l*(100km)^{-1}$		44
Engine capacity, cm^3		6374
Max power, kW		210
Max torque, Nm		1120

Table 4 Fragment of a data set

#	Date, time	Longitude	Latitude	Speed V, $km \cdot h^{-1}$	Acceleration a, $m \cdot s^{-2}$
1	11.03.2022, 04:24	22.022043	50.069363	4	1.1111
2	11.03.2022, 04:24	22.022106	50.069368	6	0.5556
3	11.03.2022, 04:24	22.022133	50.069380	6	0.0000
4	11.03.2022, 04:24	22.022153	50.069400	7	0.2778
5	11.03.2022, 04:24	22.022170	50.069421	8	0.2778
6	11.03.2022, 04:24	22.022185	50.069448	9	0.2778
7	11.03.2022, 04:24	22.022211	50.069471	10	0.2778
8	11.03.2022, 04:24	22.022253	50.069490	11	0.2778
9	11.03.2022, 04:24	22.022323	50.069506	11	0.0000
10	11.03.2022, 04:24	22.022373	50.069526	12	0.2778

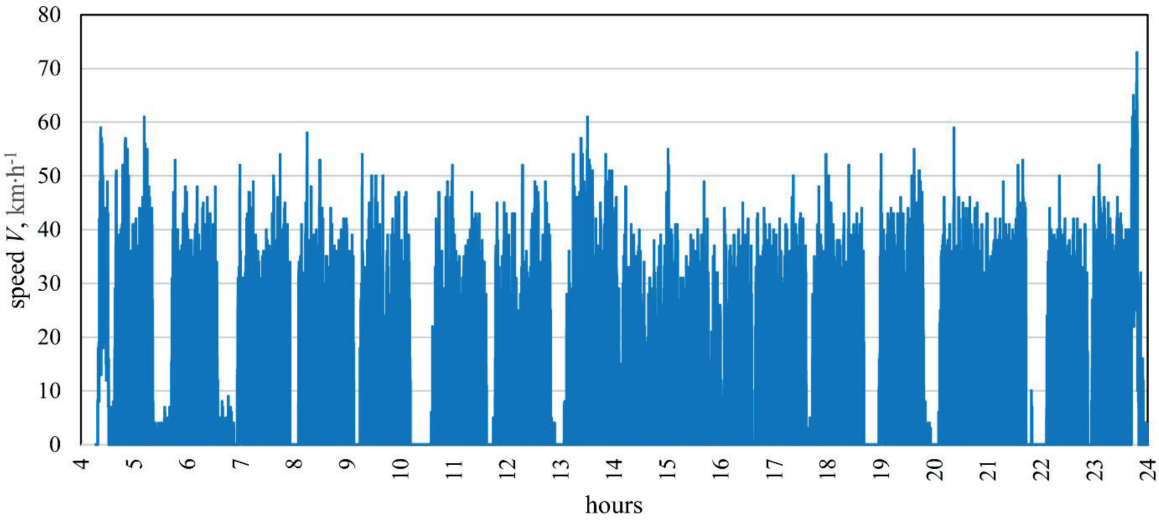


Figure 4 *Bus speed profile during the day*

were obtained in the time interval from 4:19 to 24:00. The bus speed profile, during the day on the route studied, is presented in Figure 4.

To ensure an objective assessment of the parameter studied, the required amount of the experimental sample has been determined according to Equations (1)-(2):

$$N = \frac{t_\alpha^2 \cdot \sigma^2}{\eta^2} \tag{1}$$

where:
t_α - confidence probability function;
σ - standard deviation, km·h^{-1};
η - extreme error allowed, km·h^{-1}.

$$\eta = \Delta \cdot V_{avg} \tag{2}$$

where:
Δ - relative accuracy of accounting; assume Δ = 0.01;
V_{avg} - average value of the speed for the entire working day, km·h^{-1}.

For confidence probability θ = 0.95, function of confidence probability is t_α = 1.96. As a result is obtained:

$$N = \frac{1.96^2 \cdot 14.849964^2}{(0.01 \cdot 14.14)^2} \approx 43000 < 70705$$

Thus, the reliability of the experimental sample is justified.

The values of the bus speed were divided into class intervals, the number of which was determined by the Sturgess's Equation, [20]:

$$k = 1 + 3.32 \cdot \lg(n) \tag{3}$$

where: n - sample size.
$k_V = 1 + 3.32 \cdot \lg(70705) = 17.1$.

After rounding in the larger direction, a value obtained was k_v = 18. The size of the class interval λ_V is calculated by:

$$\lambda_V = (V_{\max} - V_{\min})/k \tag{4}$$

where:
V_{max}, V_{min} - the largest and smallest speed values in statistical samples, km·h^{-1}.

λ_V = (73 - 0)/18 = 4.06.

It is appropriate to assume $\lambda_V = 5$. Furthermore, in the first interval, measurements under conditions V = 0, are assigned. Based on this, a new value is defined as k_v = 16. Similar indicators of the grouped distribution of acceleration during the day are calculated: k_a = 18, λ_a = 0.71. However, from a practical point of view it is advisable to use λ_a = 1 and corresponding to it k_a = 10. The formation of class groups made it possible instead of 70705 values of each parameter to determine (Table 5) grouped frequencies for each group.

Speeds above 60 km·h^{-1} are possible when the bus is traveling back to the bus depot, but accelerations above 4 m·s^{-2} and decelerations below - 4 m·s^{-2} are probably measurement errors.

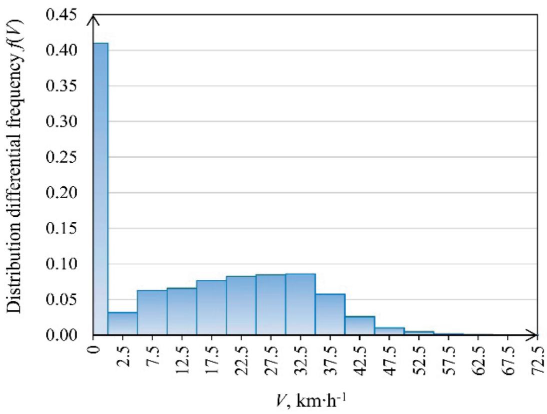
For visual analysis, the distribution graphs of the speed and acceleration of the investigated bus during the day are shown in Figure 5.

Statistical analysis of the speed distribution revealed that the average speed of the bus movement is 23.31 km·h^{-1} and the average speed on the route, considering the time of stops at bus stops and delays in traffic flow, is 14.14 km·h^{-1}. The main part of the acceleration values is in the range [-1,1]. The statistical distribution of acceleration is close to the normal distribution, which, based on the values obtained of the sample average and variance, is described as follows:

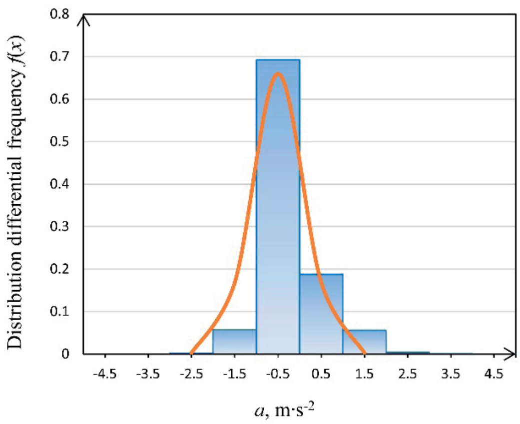
$$f(a) = \frac{1}{\sqrt{2 \cdot \pi \cdot 0.366123}} \cdot e^{-\frac{(a-0.00001)^2}{0.732245}} \approx \approx 0.6593207 \cdot e^{-\frac{a^2}{0.732245}} \tag{5}$$

***Table 5** Results of calculations of the speed and acceleration of the bus interval distributions on the route*

Speed differential frequencies				Acceleration differential frequencies			
i	Value ranges V, km·h^{-1}	absolute m_i	relative f_i	i	Value ranges a, m·s^{-2}	absolute m_i	relative f_i
1	$V_1 = 0$	28971	0.4097	1	$a_1 \le -4$	4	5.66×10^{-5}
2	$0 < V_2 \le 5$	2239	0.0317	2	$-4 < a_2 \le -3$	33	0.000467
3	$5 < V_3 \le 10$	4427	0.06261	3	$-3 < a_3 \le -2$	153	0.002164
4	$10 < V_4 \le 15$	4637	0.06558	4	$-2 < a_4 \le -1$	4040	0.057139
5	$15 < V_5 \le 20$	5420	0.07666	5	$-1 < a_5 \le 0$	48951	0.692327
6	$20 < V_6 \le 25$	5836	0.08254	6	$0 < a_6 \le 1$	13262	0.187568
7	$25 < V_7 \le 30$	5969	0.08442	7	$1 < a_7 \le 2$	3926	0.055526
8	$30 < V_8 \le 35$	6071	0.08586	8	$2 < a_8 \le 3$	271	0.003833
9	$35 < V_9 \le 40$	4060	0.05742	9	$3 < a_9 \le 4$	56	0.000792
10	$40 < V_{10} \le 45$	1824	0.02580	10	$4 < a_{10}$	9	0.000127
11	$45 < V_{11} \le 50$	718	0.01016				
12	$50 < V_{12} \le 55$	320	0.00453				
13	$55 < V_{13} \le 60$	135	0.00191				
14	$60 < V_{14} \le 65$	61	0.00086				
15	$65 < V_{15} \le 70$	14	0.00020				
16	$70 < V_{16} \le 75$	3	0.00004				
	Sum	70705	1		Sum	70705	1
V_{max}=73.0000 km·h^{-1}				a_{max} =7.5 m·s^{-2}			
V_{min} =0 km·h^{-1}				a_{min}= -5.2778 m·s^{-2}			
Average V_{avg} =14.14 km·h^{-1}				Average a_{avg}=0.00001 m·s^{-2}			
Dispersion $D(V)$=220.52143				Dispersion $D(a)$=0.366123			
The standard deviation σ_V=14.849964				The standard deviation σ_a=0.605081			



a



b

***Figure 5** Differential distributions of bus speed and acceleration during the day: a - speed, b - acceleration*

The efficiency of urban passenger transport depends on the passenger load of the bus on individual hauls of the transport network. Changes in the passenger traffic parameters cause fluctuations in fuel consumption during the day. In the process of monitoring the dynamics of passenger traffic for 25 days on some sections of route #13, the length of individual hauls, the number of passengers who came and went at the beginning of the haul and the power of the hauls were determined. Based on the data obtained, the volumes of passenger traffic P are calculated (Figure 6), the corresponding transport work performed for each working day of the observation

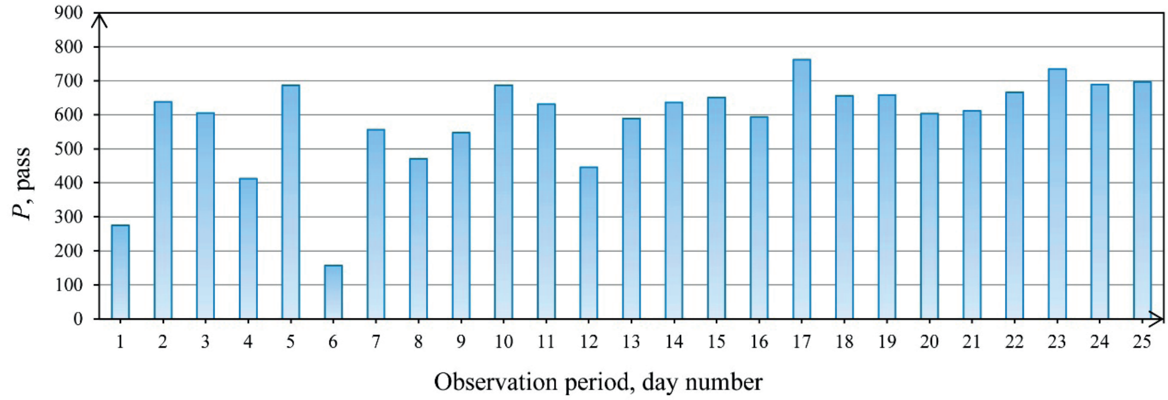


Figure 6 *Daily passenger traffic volumes for the entire observation period*

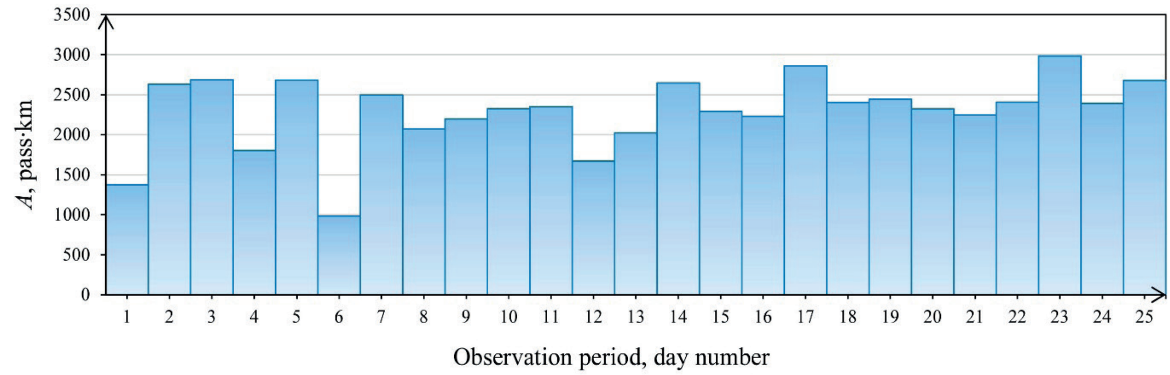


Figure 7 *Transport work performed during the observation period*

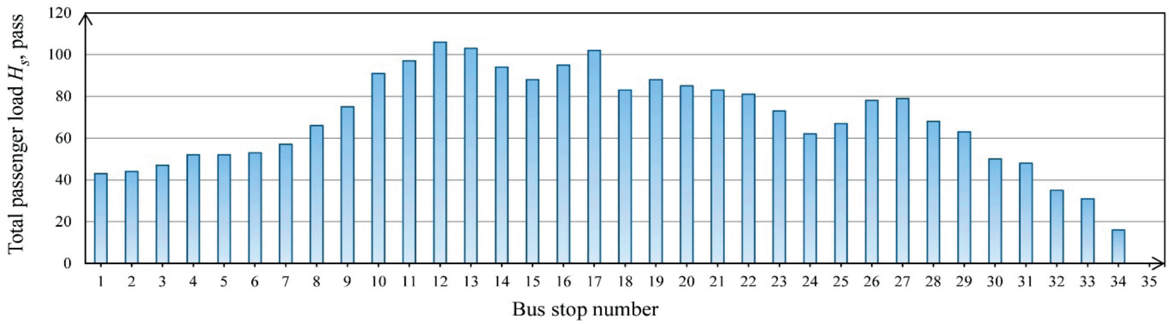


Figure 8 *The total passenger load of the bus on the hauls of the direct trip during the day*

period A (Figure 7) and the average daily passenger load H_{avg}.

Since the parameters P and H_{avg} give only generalized and average estimates of passenger traffic, it is advisable to study the dynamics of changes in their components, depending on the time of day and when performing individual trips.

Figure 8 shows the dependence of the total daily passenger load Hs_i on each haul of a direct trip from A to B, passing through 35 stopping points. The histogram was constructed for the 15th day of the observation period (11.03.2022). In the perspective of passenger traffic analysis, this day is typical, because P_{15} belongs to the class interval with the highest value of the relative differential frequency of distribution: $\max_{1 \le i \le 6} f_i(P) = f(P)_{[650.750]} = 0.4$.

Figure 8 shows that most of the passenger traffic is concentrated in the middle part of the route, which passes through the city center. The Hs_i concentration decreases at the final stops on the route.

To analyze the dynamics of passenger traffic during the day, the working day was divided into six intervals and the total values for each interval were calculated. According to Figure 9 and Figure 10, it can be concluded that the main passenger traffic occurs in the morning, from 6:30 to 9:30.

The dynamics of changes in passenger load on individual trips is similar and repeats the dynamics of the passenger load accumulated on all the trips per day. The histogram of the transport work performed in the time interval from 6:30 to 9:30 for one voyage on a direct trip is shown in Figure 11.

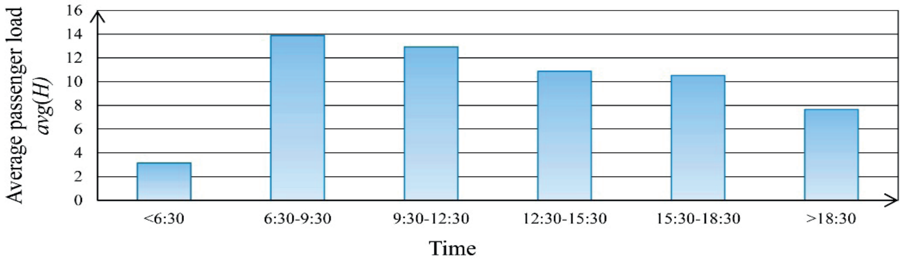


Figure 9 *Average passenger load of the bus according to time intervals*

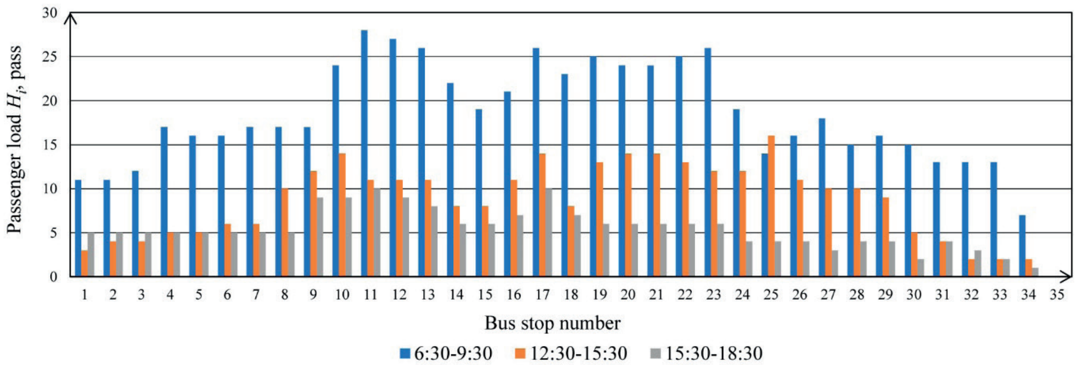


Figure 10 *Passenger load of the bus on direct trip hauls [11.03.2022]*

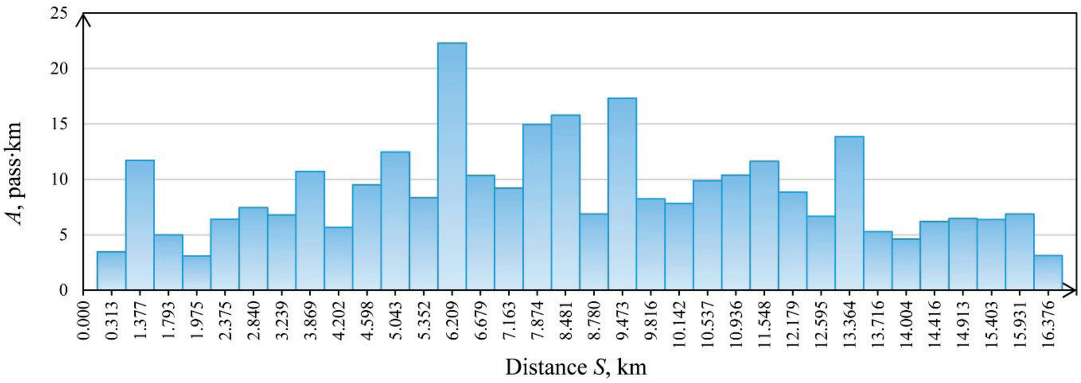


Figure 11 *Transport work on the hauls of the direct trip*

4 Statistical analysis of the bus fuel consumption indicators

To assess the energy efficiency of the passenger transport system as a whole, it is necessary to know the energy consumption for the transportation of passengers in certain sections of the transport network. However, determining the fuel consumption over short periods of time can be complicated and requires specialized equipment. In this study, measurement of the fuel consumption Q was performed once a day at the end of the working day for 25 days. To secure high accuracy of daily fuel consumption the following measures were taken: Urban Transport Company has its own petrol station; only 1 employee of a company is allowed to refuel the bus, this employee always uses the same pump and the same pistol, position of the vehicle must be within 2 m due to fuel hose length, bus had no people onboard - the weight of the vehicle was always the same, during the studied period bus tire pressure was within range of 20 kPa (± 10 kPa from standard pressure). These measures allowed the accuracy of the daily fuel consumption measurement to be within 2%. Based on the measurement data, the fuel consumption per 100 km q is calculated (Figure 12).

A sufficient sample size of 25 is obtained with a relative accuracy of Δ = 0.02 and a confidence level of θ = 0.9. Consumption per 100 km each day of the study period did not exceed 50 l. The distributions of the differential frequencies $f(q)$ and the integral frequencies $F(q)$ are presented in Figure 13.

The number of classes, according to Sturgess's

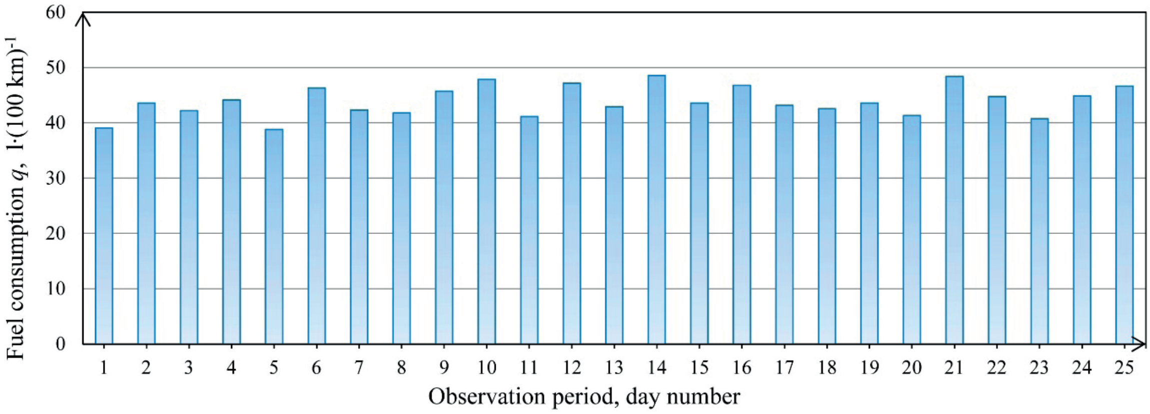


Figure 12 *Fluctuations in fuel consumption q during the study period*

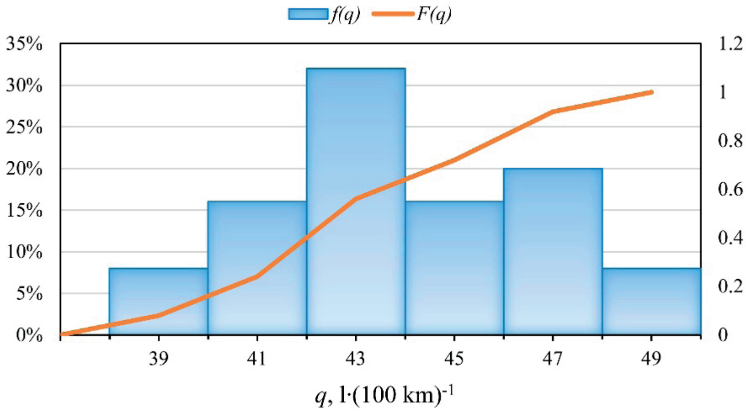


Figure 13 *Distribution grouped by relative frequency of fuel consumption q*

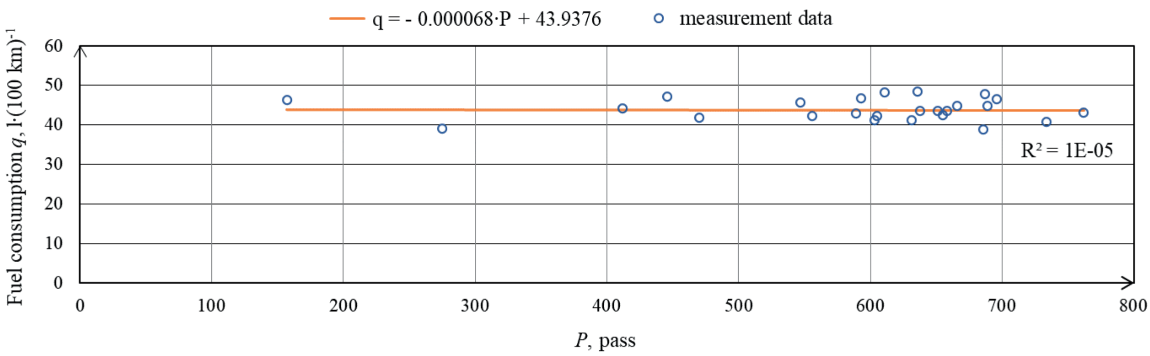


Figure 14 *Course of the average daily fuel consumption per 100 km based on the volume of passengers transported*

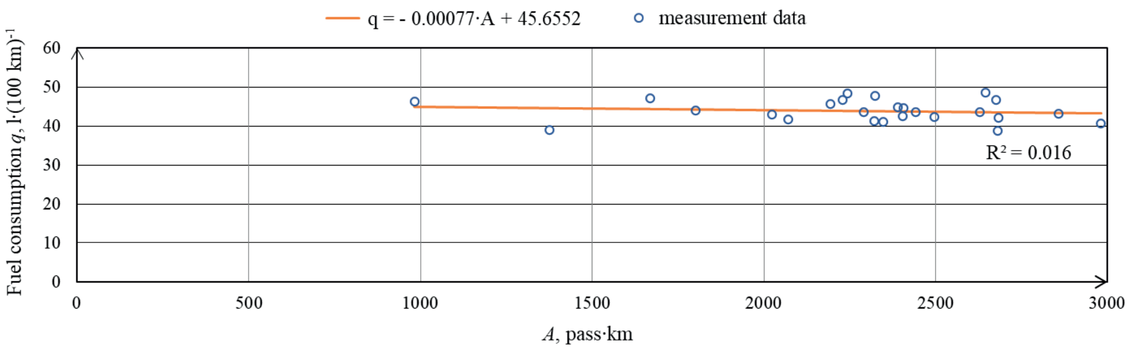


Figure 15 *Course of the average daily fuel consumption per 100 km in transport work*

formula, is 6 and the width of the interval is 2. This distribution has a mathematical expectation μ = 43.9 and a variance σ^2 = 7.27. Accordingly, the standard deviation σ is 2.7. The maximum value of daily expenses is 48.54 l·(100 km)$^{-1}$ and the minimum is 38.78 l·(100 km)$^{-1}$. Most often, the value of fuel consumption is characterized by the mode of distribution Mo = 43 l·(100 km)$^{-1}$.

To estimate the fuel consumption of public transport, graphs were constructed: $q(P)$ taking into account the volume of passengers transported (Figure 14) and $q(A)$ taking into account the transport work performed (Figure 15). Generalized daily values of the necessary indicators for all the periods of supervision were used for construction.

Observation data are approximated by linear dependencies with very small coefficients of determination: $R_1^2 = 10^{-5}$ and $R_2^2 = 0.016$, according to the order of the given graphs, which indicates a lack of relationship between the generalized values of parameters. Furthermore, the issue of determining the fuel consumption in sections of the transport network of arbitrary length remains relevant. As shown in [21], there is a very little impact of passenger load in the range 0 to 1200 kg on the fuel consumption of a public bus.

5 Simulation and estimation of the bus fuel consumption

The fuel consumption Q_i of the passenger transport on the i-th haul is calculated as follows:

$$Q_i = \frac{Q_p \times S_i \times H_i}{1000} \tag{6}$$

where:
Q_p - specific fuel consumption per working day, l·(pass·km)$^{-1}$;
S_i - haul length, m;
H_i - passenger load on the i-th haul, pass.

The specific daily fuel consumption Q_p is proposed as a function of the average daily passenger load H_{avg}. To determine the analytical form of the function $Q_p = f(H_{avg})$, the statistical values of Q_{pj} were approximated, j is the day number in the statistical sample (1 ≤ j ≤ 25). For the j-th day, Q_{pj} is calculated by the expression (Table 6):

$$Q_{pj} = \frac{Q_j}{A_j} \tag{7}$$

Table 6 *Initial data for modeling*

j	Date	$H_{avg\,j}$, pass	A_j, pass ·km	Q_j, l	Q_{pj}, l·(pass·km)$^{-1}$
1	16.02.2022	4.6979	1374.864	117.14	0.085
2	17.02.2022	9.0225	2629.396	129.82	0.049
3	18.02.2022	9.0690	2683.914	125.68	0.047
4	21.02.2022	6.1097	1801.674	131.85	0.073
5	22.02.2022	9.1994	2680.839	115.18	0.043
6	23.02.2022	3.4122	982.571	138.42	0.141
7	24.02.2022	8.6184	2496.292	124.83	0.050
8	25.02.2022	7.0500	2071.587	124.55	0.060
9	28.02.2022	9.6289	2193.880	106.45	0.049
10	02.03.2022	10.3648	2324.406	110.55	0.048
11	03.03.2022	10.5299	2348.132	95.02	0.040
12	07.03.2022	7.8736	1669.282	105.57	0.063
13	08.03.2022	9.7107	2022.193	92.64	0.046
14	09.03.2022	11.6303	2646.082	112.62	0.043
15	11.03.2022	10.1807	2289.453	100.61	0.044
16	15.03.2022	10.2188	2228.978	105.68	0.047
17	16.03.2022	12.6611	2857.928	100.1	0.035
18	17.03.2022	10.6059	2404.323	97.79	0.041
19	18.03.2022	10.8716	2441.713	101.08	0.041
20	21.03.2022	10.4274	2321.299	96.22	0.041
21	22.03.2022	10.0484	2243.759	112.16	0.050
22	23.03.2022	10.6421	2406.034	103.77	0.043
23	24.03.2022	13.0821	2981.571	94.05	0.032
24	25.03.2022	10.7011	2389.165	103.64	0.043
25	29.03.2022	11.7254	2676.303	107.73	0.040

where:
Q_j - fuel consumption, l;
A_j - performed transport work, pass·km;
j - workday number.

The hyperbola and exponential functions were chosen for approximation and reduced to a linear form by equivalent transformations. The approximation was performed using the least squares method.

As a result of the approximation, analytical dependencies are obtained:

$$Q_{p1} = \frac{0.457}{H_{avg}} - 0.00075 \tag{8}$$

$$Q_{p2} = 0.1669 \cdot e^{-0.1286 \cdot H_{avg}} \tag{9}$$

The sum of the squares of deviations of the model values, Q_{p1} and Q_{p2}, from the statistical data, is S_1=0.0004452 and S_2= 0.0014413, respectively. Based on that, the hyperbola function was chosen for further calculations (Figure 16).

The standard deviation of the model values from the experimental ones is $\bar{\sigma} = 0.0000178$. The relative standard deviation is $\bar{S}_r = 0.57\,\%$. As can be seen in Figure 16, the value of the specific fuel consumption Q_{p1} increases markedly with reduction of H_{avg} passenger traffic capacity to 20 passengers and below.

To validate the model obtained, the daily fuel consumption of Q_{calc} was calculated for three days of the observation period.

$$Q_{calc} = \sum_{i=1}^{n} Q_i \tag{10}$$

where:
n - the number of hauls the bus traveled during the working day.

The deviation errors of the calculated values from the statistical ones are determined (Table 7).

Based on the testing results, it can be stated that the model is quite adequate. The relative error δ of the calculated values does not exceed 10%. The magnitude of the simulation error is influenced, on the one hand, by the scattering of Q_{stat} fuel consumption statistics on individual days and, on the other hand, by the distance of technical mileage of the bus without passengers and its modes of movement in these sections.

The dependence obtained in Equation (8) allows to estimate the current values of fuel consumption of the bus on individual hauls, as well as on the section of the city route. Using this dependence, the current and total fuel consumption on the section of the route studied under the traffic conditions shown in Figure 11 were simulated for the time intervals of 6:30 and 9:30. The values obtained for the current and total fuel consumption of the bus on the route from the initial to the final stop are shown in Figure 17.

Fuel consumption is shown to be in the range of 0.081-0.477 l. The total fuel consumption in the study area is 7.257 l. The high fuel consumption in the 2nd and 13th hauls (Q_2=0.48 l, Q_{13} = 0.38 l) is explained by their length S_2 = 1.06 km and S_{13} = 0.86 km, respectively, which are the largest among other hauls on the route. Therefore, the current fuel consumption depends both on the passenger load of the bus and the length of the haul.

6 Discussion of research results and conclusions

Based on global priorities of energy savings and environmental safety, the management of modern urban passenger transport systems should focus on efficient use of passenger transport. Thus, there are issues of increasing the productivity of vehicles, reducing energy consumption and, therefore, reducing emissions of pollutants into the atmosphere. Research on this issue has shown that the solution of relevant problems is impossible without monitoring and evaluating the vehicle performance, such as speed, acceleration

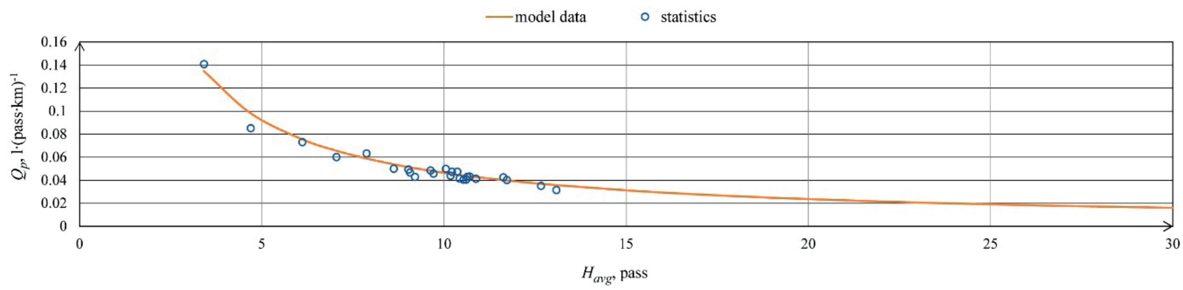


***Figure 16** Approximation of values of the bus specific fuel consumptions Q_p by hyperbola*

***Table 7** The results of the model testing*

Date	H_{avg}, pass	Q_p, l·(pass·km)$^{-1}$	Q_{calc}, l	Q_{stat}, l	Absolute error Δ, l	Relative error δ, %
23.02.2022	3.412	0.133178908	130.858	138.42	7.562	5.46
07.03.2022	7.8736	0.057293419	95.639	105.57	9.931	9.41
11.03.2022	10.181	0.044140827	101.058	100.61	0.448	0.45

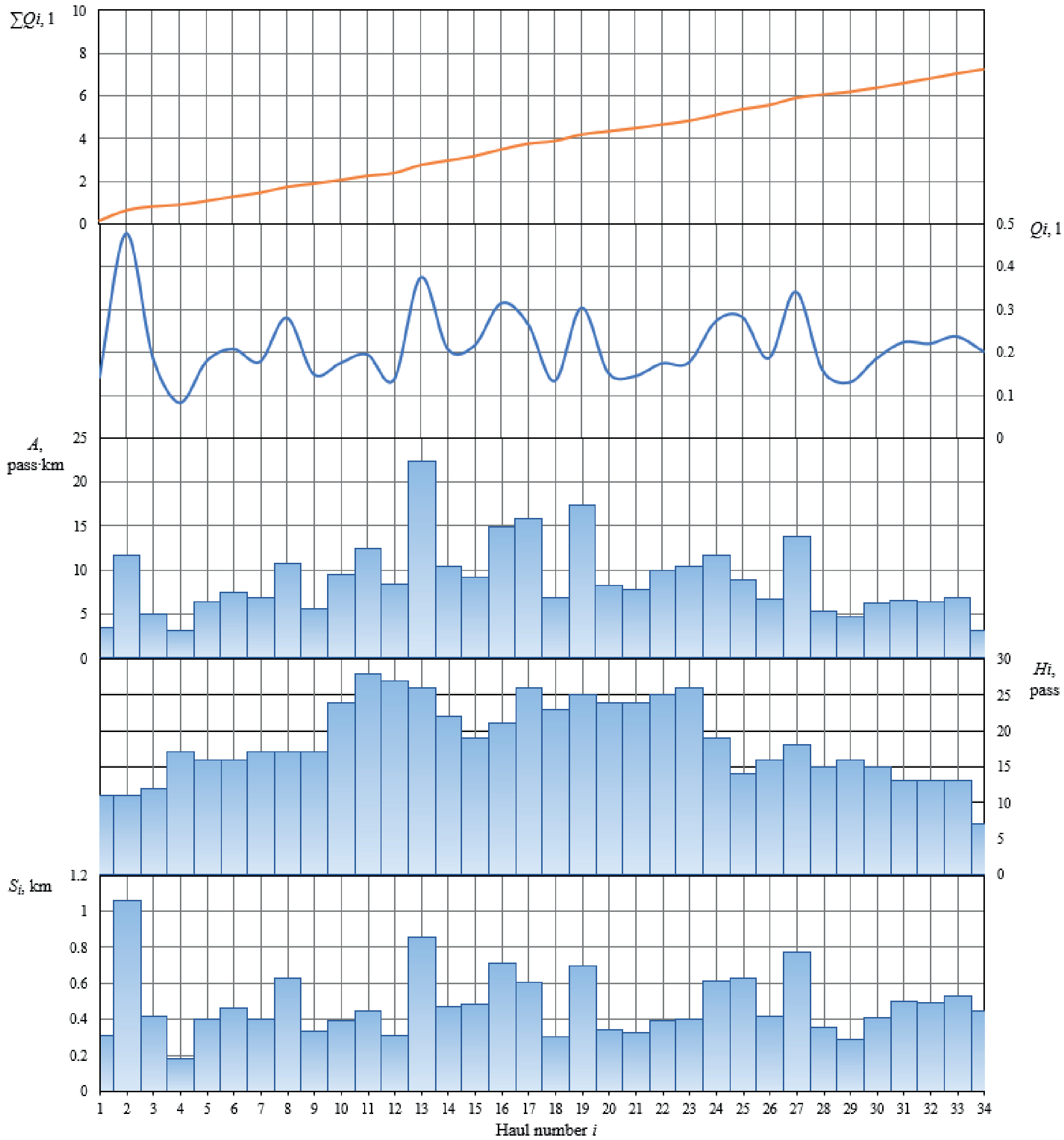


Figure 17 *Simulated bus fuel consumption in the individual hauls of the route*

in different modes of movement, fuel consumption, considering the distance passed and passenger flow parameters that change during the day.

As a part of the study, these indicators were measured on the bus route #13 in the city of Rzeszow with 35 stops in the direct and 38 stops in the back direction. The observation was carried out in 25 working days. The scientific substantiation of the volumes of the corresponding experimental samples is given. Statistical analysis of 70705 speed and acceleration values revealed that the average speed of the bus is 23.31 km·h^{-1} and the average speed on the route, considering the time of stops at bus stops and delays in traffic flow is 14.14 km·h^{-1}. The constructed distribution of the movement acceleration indicates that the main part of its values is in the range [-1,1] m·s^{-2}. The approximation of this distribution to the normal one is proved, which simplifies the further estimation of the general population parameters, according to the estimates of the sample statistics. The ranges and average values of speed and acceleration correspond to similar indicators of a large class of city buses in operation [13].

An analysis of the passenger traffic dynamics during the day was performed for a typical working day, which is selected by the volume of passenger traffic belonging to the class interval [650, 750] passengers per day with the highest distribution frequency of 40%. The working day was divided into six typical time intervals. The nature of changes in passenger traffic capacity in a fixed sequence of courses at different times of the day is shown to be similar and repeats the dynamics of total daily capacity in these hauls. Therefore, the time interval from 6:30 to 9:30 in the morning peak was considered to estimate the fluctuations in fuel consumption in individual hauls.

Analytical dependencies of fuel consumption on the number of passengers transported and the transport work performed per 100 km are built. The results of the obtained dependencies correlation analysis indicate insufficient correlation between these parameters of the system, that is, the inability to assess the nature of the Stat direct impact of transport work parameters on the absolute indicators of energy consumption. Based on this, it is proposed to estimate the energy consumption indirectly, through the specific fuel consumption per 1 passenger-kilometer. Approximation of experimental data is performed and the mathematical models are obtained that express the dependence of specific costs on the average daily power of the passenger traffic on the route. Among the approximating functions, the hyperbolic one is chosen, which gives the smallest sum of squares of deviations of the model values of specific costs from the experimental ones. In this case, the relative standard deviation is 0.57%. Dependence analysis shows that the specific fuel consumption increases significantly (up to 8%) when passenger load decreases below 15, increases significantly (more than 15%) with less than 10 passengers and increases rapidly (more than 37%) when passenger load decreases below 5.

The built model provides an opportunity to accurately determine the specific fuel consumption per passenger kilometer and, based on those, to calculate the absolute values of fuel consumption in individual hauls and sections of the route. The results obtained make it possible to determine the fuel consumption q per 100 km. The average value of q is 43.9 $l \cdot (100\ km)^{-1}$ and the most probable - 43.9 $l \cdot (100\ km)^{-1}$. The specified data confirm the results obtained in the work [13], where the average value of q, under the similar operating conditions, is equal to 43.2 $l \cdot (100\ km)^{-1}$. During the peak hours q reaches higher values than during the normal hours and is in the range 43.61-45.18 $l \cdot (100\ km)^{-1}$. Each city is characterized by its own specificity and traffic intensity, thus direct comparison of public bus fuel consumption is impossible. However, the scope of changes in fuel consumption influenced by the number of passengers is similar to that in the works [10, 21].

The model was evaluated according to the three days of the observation period. The days were chosen in such a way as to cover the ranges of average daily passenger traffic capacity: low, medium and high. The accuracy of the daily fuel consumption is in the 90.59-99.55% interval. The relative error of the estimated daily values of fuel consumption does not exceed 10%, which indicates a sufficient adequacy of the dependence. The magnitude of the simulation error is influenced, on one hand by the scattering of the statistical data on fuel consumption on certain days and, on the other hand, by the distance of technical mileage of the bus without passengers and its modes of movement in these sections.

The model was implemented in separate hauls of the transport network in the section of the studied bus route in the morning from 6:30 to 9:30. The estimated fuel consumptions on the hauls are in the range of 0.08 to 0.48 l and the total fuel consumption on the section of the route is 7.26 l. The high fuel consumption in the 2nd and 13th hauls (Q_2 = 0.48 l, Q_{13} = 0.38 l) is due to their maximum length S_2 = 1.06 km and S_{13} = 0.86 km, respectively, which are the largest among the hauls on the route. Therefore, the current fuel consumption depends both on the load of the bus and the length of the hauls.

Further research will be aimed at the energy efficiency of passenger vehicles taking into account driving modes, actual speed and acceleration on individual hauls and sections of the city route, driving style, as well as comparing the obtained results with the data of on-board means of fixing parameters. The influence of passenger load during the hauls on other characteristics of passenger transport, including fuel consumption in liters per 100 km, will also be investigated.

In addition, the obtained results will become the basis for development of new models and methods for determining other partial assessments of technical, economic and environmental efficiency as a part of a complex indicator of the transport systems functioning efficiency at different levels of detail.

Grants and funding

The authors received no financial support for the research, authorship, and/or publication of this article.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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INFLUENCE OF TRAFFIC CONDITIONS ON THE ENERGY CONSUMPTION OF AN ELECTRIC VEHICLE

Adriana Skuza*, Rafał Jurecki, Emilia Szumska

Department of Automotive Engineering and Transport, Faculty of Mechatronics and Mechanical Engineering, Kielce University of Technology, Kielce, Poland

*E-mail of corresponding author: askuza@tu.kielce.pl

Adriana Skuza 0000-0001-7381-1590, Rafał Jurecki 0000-0003-0105-1283, Emilia Szumska 0000-0001-6024-6748

Resume

Traffic conditions are constantly changing when driving in urban areas. Depending on the hour the vehicle is moving, the drive is more or less smooth. The aim of this study is to determine how the traffic conditions affect the energy consumption of an electric vehicle. Simulations carried out in AVL Cruise software, based on real-world testing, were used to determine this issue. The methodology for conducting the research and performing the simulations is also described. The energy consumption of the vehicle, on each route and during the hours studied, was compared to each other based on the results from the simulation software. The results of the study showed that the influence of traffic conditions on the vehicle energy consumption is significant. Simulations have shown that the need for numerous stops and driving at low speeds requires increased energy consumption.

Article info

Received 6 May 2022
Accepted 9 17 October 2022
Online 9 November 2022

Keywords:

electric vehicle
traffic conditions
energy consumption

Available online: https://doi.org/10.26552/com.C.2023.004

ISSN 1335-4205 (print version)
ISSN 2585-7878 (online version)

1 Introduction

Electric vehicles have varying energy consumption, which is affected by many factors. This is particularly important for EV (Electric Vehicle) drivers who are concerned about discharging their vehicle while driving. Papers [1-2] present the phenomenon of range anxiety, which is directly related to vehicles energy consumption. Paper [3] outlines how to plan a route in relation to range concerns. To this end, an algorithm was created that takes into account the driver's feelings to create a route where the risk of unexpected events is low.

The energy consumption of electric vehicles is one of the core areas of electric vehicle testing. The methods for its analysis usually include simulation based on the real data or simulation only.

The authors of the paper [4] used the AVL Cruise simulation software to investigate the energy consumption of an electric vehicle. For this purpose, well-known, ready-made cycles such as NEDC (New European Driving Cycle) and JC08 (Japan Cycle) were used. The range resulting from the simulations was compared for both cycles and two different vehicles. A similar approach was used by the authors of [5], who used the NEDC, WLTP (Worldwide Harmonized Light Vehicle Test Procedure) and highway cycle in the AVL Cruise software for simulations. In addition, different ambient temperatures, vehicle load and battery state of charge were introduced into the simulation. Paper [6] simulates the energy consumption of electric vehicles based on geographical route data. The road model and its characteristic points were created based on geographical information, a map and GPS.

A different approach was used by the authors in the paper [7]. They collected actual data based on driving in Shanghai. Based on those, they created a real driving cycle, which was used to simulate energy consumption using the ADVISOR software. In paper [8], vehicle testing on a chassis dynamometer was used. This data was used to create a simulation that provided information on the factors affecting the energy consumption of an electric vehicle.

In paper [9], real data collected in Beijing was used to estimate energy consumption. The route information was collected by driving a Nissan Leaf. Energy consumption was estimated using mathematical models.

Table 1 *A literature review of factors influencing vehicle energy consumption*

Factors influencing energy consumption	Reference	Results of studies on the factor
Ambient conditions	Air temperature [10]	The authors showed that the influence of temperature on energy consumption varied, particularly above 30 °C and below 10 °C. An interaction between ambient temperature and the use of a heater or air conditioner was demonstrated. The rational use of these devices will save around 10% of energy.
	Air temperature [11]	The air temperature was measured over a period of four years of research. The results show that specific energy consumption is almost twice as high when the temperature is around 0 °C as when it is close to 19 °C. This dependency mainly applies to short trips.
	Wind [12]	The authors showed that wind is clearly relevant to the energy consumption of electric vehicles. Based on analyses of routes in the UK, the difference in energy demand was shown to be 14% more for a flat route without varying speed limits on a windy day than compared to a non-windy day. For a hilly route with numerous speed restrictions, the demand was 5% higher than on a day with no wind.
Route characteristics	Road gradient [13]	The influence of the road gradient on energy consumption was investigated. The results showed that the energy increases almost linearly with increasing absolute gradient. Electric vehicles are more efficient than conventional vehicles in mountainous areas due to the possibility of energy recovery.
	Road gradient [11]	Results from real-world tests have shown that an increase in gradient increases energy consumption. For a gradient of 3%, specific energy consumption is 50% higher than when driving on a flat road. When the gradient decreases to -3%, the specific energy consumption is reduced by 80% compared to a flat road.

The energy consumption of a vehicle is affected by certain factors. Those may be related to external conditions, the characteristics of the route, the way the vehicle is driven or directly to the vehicle. A literature review, related to factors affecting the energy consumption of an electric vehicle, is presented in Tables 1 and 2. They summarize the type of factor that was analyzed and its results. The vehicles tested in the given literature sources are not the same as in this paper. The main aim of the literature review was to determine the scope of the influence of various traffic conditions on the energy consumption of an electric vehicle.

It is important to remember that other factors, such as braking energy recovery, the initial state of charge of the battery or its general condition, also affect the amount of energy consumed after a trip. Table 3 summarizes the factors that affect the energy efficiency of an electric vehicle.

The problem of energy management does not only concern individual vehicles driven by "casual" drivers. It also appears in larger concentrations, i.e. in fleets. In the paper [20], the authors presented the problem of route planning for electric vehicle fleets. A model is presented, including route, speed, braking and power transmission system information. A numerical experiment based on the Gothenburg routes, was also carried out. What was important in the authors' approach was the listing of junctions and the detailed presentation of the road topography. The results show that the estimation error of energy consumption is 2.28% and of time is only 3.48%.

The aim of this paper was to determine the influence of traffic conditions on the energy consumption of an electric vehicle based on simulations performed under the real-world conditions. This study of the topic offers the possibility of further research and simulations related to other conditions under which the vehicle moves, e.g. changes in land elevation, road curvature etc. By creating simulations, it is possible to determine the range of the vehicle while driving in urban areas.

In this study, an approach is used that allows seeing how the vehicle energy consumption changes as a function of route alignment and traffic conditions. It is extremely important that the research was carried out using actual trip data. With the information used, it is possible to take advantage of the opportunities offered by AVL Cruise.

2 Research methodology

2.1 Real-world study

The research involved taking actual measurements of speed, distance and time using a test vehicle. This data was used as input in the AVL Cruise simulation software.

The trip was made in the area of Kielce, a medium-

Table 2 A literature review of factors influencing vehicle energy consumption 2

Factors influencing energy consumption	Reference	Results of studies on the factor
	Type of road and travel time [14]	The paper shows the difference in energy consumption related to travel time and road type. Travel times increase during the peak traffic periods. In addition, stopping at red lights, sharp bends and speed bumps can increase energy consumption by up to several hundred percent. This is especially true for drivers with an aggressive driving style
	Traffic conditions [11]	The authors showed that on shorter routes, specific consumption is about 9.7% higher than on long distances. In addition, the greater the proportion of stops and the lower the average travel speed, the higher the specific consumption (up to 19%), especially on short routes.
	Differentiation of cycles [5]	In this paper, the authors compared energy consumption based on known driving cycles in the AVL Cruise software. The results for the NEDC, WLTP and highway cycle test were compared to each other for different values of vehicle load, ambient temperature and battery charge. It has been shown that as the average vehicle speed per cycle increases, energy consumption also increases. In addition, the simulation showed that negative temperatures increase energy consumption by around 24% in relation to driving at 20 °C.
Driver's driving style	[11]	The authors considered the influence of driving conditions on the specific energy consumption of an electric vehicle, based on actual data. The driving method was determined on the basis of the product of acceleration and speed. If 9 5% of the calculated values were above 75% of the dynamic work limit, then driving was defined as aggressive. If the values were below 25% of the dynamic work limit, then driving was defined as passive. The results showed that the more aggressive the driving, the more energy is consumed. Compared to calm driving, the difference is 16%, while moderate driving is 7.1%.
	[14]	The study compared aggressive, normal and eco-driving styles of drivers. The driving method was determined on the basis of the values of acceleration, braking, driving speed, lateral acceleration and the effectiveness of regenerative braking. The difference between the most dynamic and economical driving is relatively around 17% and changes with increasing speed. When accelerating, an aggressive driver uses up to 25-30% more energy.
Vehicle-related factors	Vehicle weight [12]	The paper shows that vehicle weight significantly affects the energy consumption of an electric vehicle. This is particularly related to overcoming the resistance to motion and the route the vehicle takes.
	Use of auxiliary equipment [15]	The use of equipment to heat or cool the interior of an electric vehicle has been shown to reduce its range. The percentage reduction in range varies from 35 to 50% and is related to the weather conditions outside. Analysis of ranges in individual cities in the US shows that milder seasons result in less energy being used to heat the vehicle, resulting in a greater range.
	Battery weight [16]	The paper shows how the weight of the battery affects the energy consumption of the vehicle. Batteries with more weight have been shown to consume more energy.

Table 3 A literature review of factors influencing energy efficiency

Factors influencing energy efficiency	Reference	Results of studies on the factor
SOC	[17]	The authors of the study highlighted the relationship between the state of charge of the battery and energy consumption. According to them, if the SoC level increases, the power consumption decreases. Maintaining a constant power output is possible by consuming more energy with a reduced battery state of charge.
Regenerative braking	[18]	The paper examines how driving with energy recovery affects energy efficiency. According to the results, energy flow efficiency increased by 41.09%, while driving range increased by 24.63%.
SOH	[19]	The authors used a method that allows the remaining life of the battery to be determined based on information related to its health.

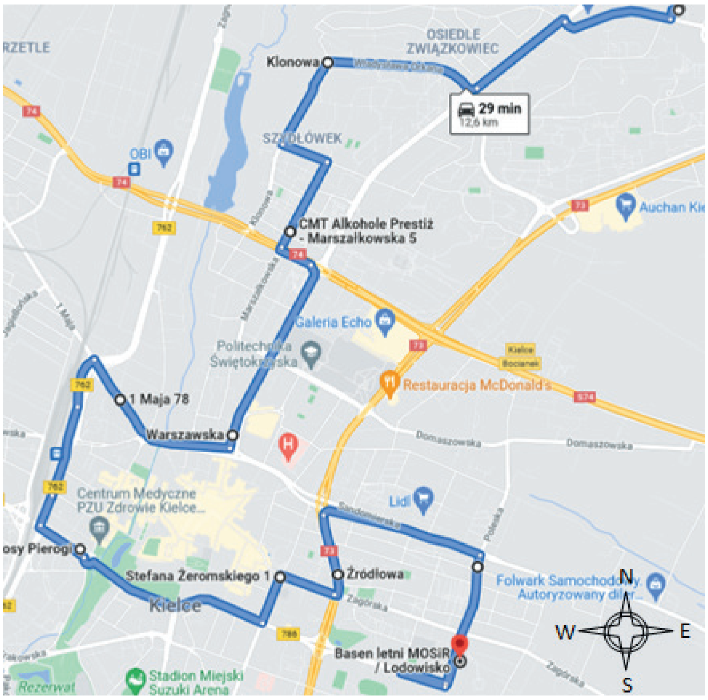

Figure 1 *Route surveyed in Kielce (Poland)*

Figure 2 *Test vehicle - Ford Transit*

sized city, three times a day due to the different traffic conditions. The times chosen were 7.30 a.m., 11.30 a.m. and 3.30 p.m., as these are the most characteristic time slots found in the city. Carrying out the road tests made it possible to record the actual driving parameters. This approach allowed to determine the actual speed, braking, acceleration, stopping time or duration of the trip. The information recorded by the measuring devices on the Ford Transit made it possible to simulate a vehicle with an electric drive under the same driving conditions. A similar methodology for route and time of day selection was used by the authors in [21-22].

There are three routes, designated as T1 (Figure 1), T2 and T3, running from the northeast to the southeast of Kielce. The route T2 ran in the same way as the T1 route, shown in Figure 1, but in the opposite direction. The T3 road was a loop of the T1 and T2 routes.

Kistler brand equipment was used to prepare the measurements, consisting of a TAA KCD15911 acceleration module, a Datron S-350 optoelectronic sensor, a Kistler GPS CDA module and a KIDAQ 5501A Data Acquisition Station. The equipment was mounted on a Ford Transit test vehicle (Figure 2), which is available at the laboratory of the Kielce University of Technology. This type of measuring device and vehicle was used by the authors in the studies described in [23-24], to determine the parameters of vehicle movement and the driver's manner of driving under different road conditions.

2.2 Simulation studies

The simulation was carried out using AVL Cruise, a product of the Austrian company AVL List GmbH. The tool allows both electrified and conventional vehicles to be analyzed from the point of view of, among other things: fuel and energy consumption, power distribution,

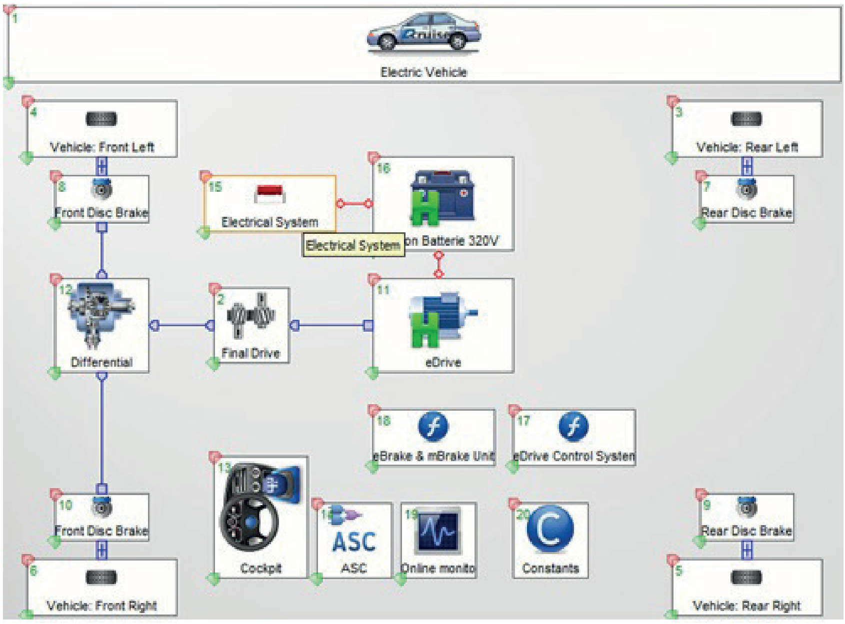

Figure 3 *Electric vehicle model in AVL Cruise software*

Table 4 *Characteristic parameters of the driving cycle on each route at indicated times*

Route	T1			T2			T3		
Hour	7.30 a.m.	11.30 a.m.	3.30 p.m	7.30 a.m.	11.30 a.m	3.30 p.m	7.30 a.m.	11.30 a.m.	3.30 p.m.
Route length [km]		11.45			11.59			23.04	
Time of travel [s]	2248	1805	3002	1756	1685	2657	4004	3490	5659
Average speed [km/h]	18.3	22.8	13.7	23.8	24.7	15.7	20.7	23.8	14.7

hill climbing, braking, power loss, exhaust emissions or gear ratios. The AVL Cruise allows using commonly known driving cycles, as well as introducing a custom cycle. The software gives the possibility to use already prepared vehicles, change their parameters, as well as to build the model of the actual vehicle by oneself [25]. The findings of simulation studies using it are described in paper [26], where the software was used to simulate range changes under the well-defined conditions during the WLTP cycle. Based on the simulation, the vehicle's driving capabilities were determined. The authors in [27] used the capabilities of the software to show how the gear ratios or engine parameters affect vehicle performance and how they can be optimized. In [28], a simulation was carried out to determine the carbon monoxide emissions and energy consumption of a taxi fleet in Brazil. The forecasts were based on replacement of the rolling stock from conventional to electric and energy production conditions.

The vehicle used in the simulation is a front-wheel drive electric car. Its mass during the simulation was 1300 kg. The frontal area of the vehicle is 1.97 m^2, while the drag coefficient is 0.284. The vehicle model (Figure 3) contains all the necessary vehicle components, i.e. the electric motor, clutch, gearbox, electrical components, etc. The battery is characterized by parameters such as an initial state of charge of 95 %, a voltage of 350 V and an energy capacity of 47.5 Ah. Furthermore, the battery consists of five rows of compartments, one cell in each.

3 Analysis of the results obtained

3.1 Analysis of the speed profiles

Based on the measurements obtained, parameters related to the driving cycle on each route were determined (Table 4). The length of route T1 was 11.45 km, for T2 it was 11.59 km and for T3 it was 23.12 km. The routes are characterized by varying travel times and average speeds. On route T1, the fastest trip was at 11.30 a.m., while the longest was at 3.30 p.m. A similar dependency occurred on routes T2 and T3. When analyzing the average speed, the relationship between the highest and lowest values is analogous to that for the travel time.

For the routes studied, speed profiles were drawn up as a function of time, showing the dynamics of speed changes during travel. In addition, it was also possible to create a speed distribution from the data collected. Figures 4-6 show the speed profiles and distributions for routes T1, T2 and T3 in the analyzed time intervals.

A significant reduction in traffic speeds is evident in the graphs for the 7.30 a.m. and 3.30 p.m. travels on route T1 (Figures 4a, c). During the afternoon peak, the

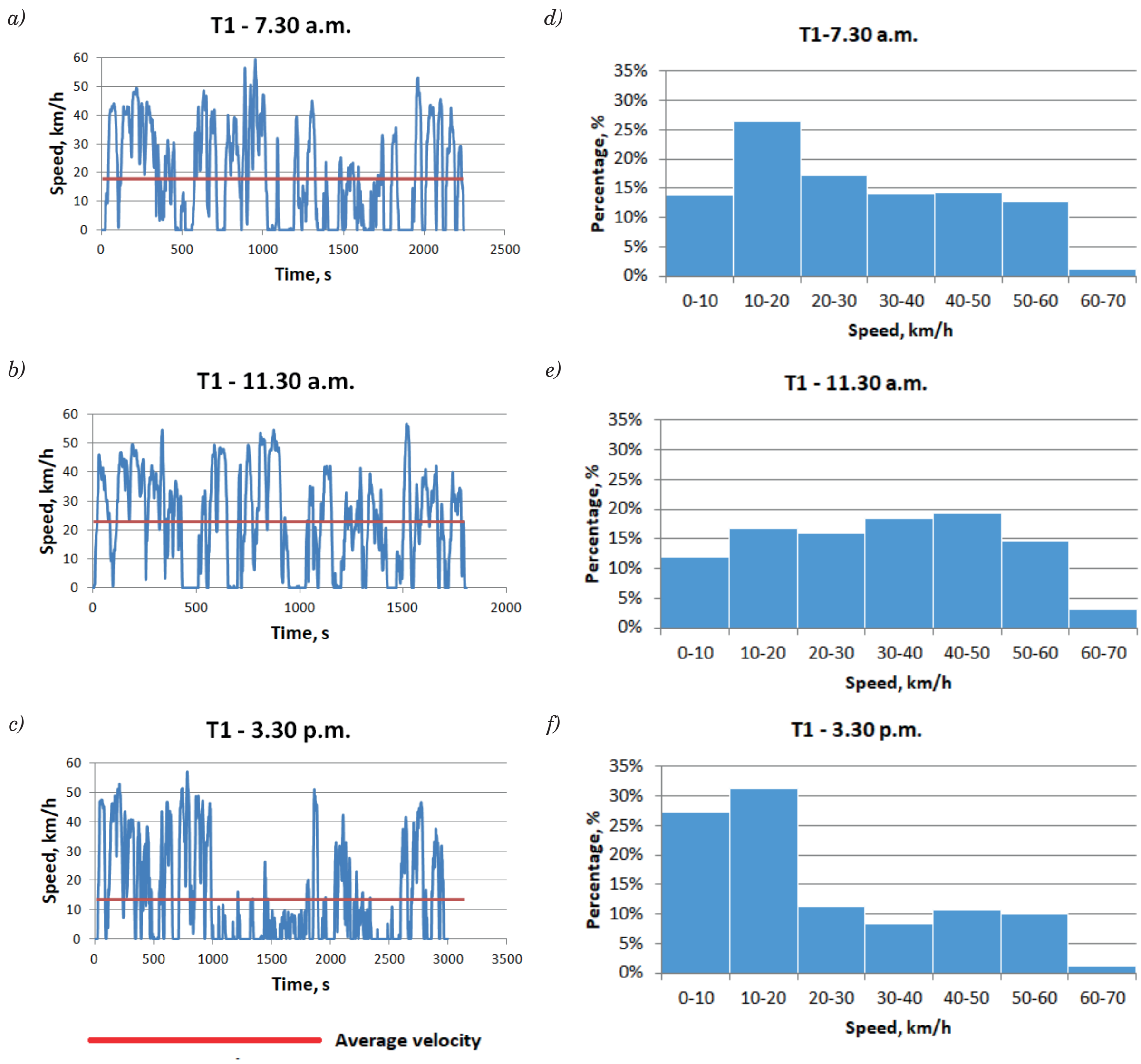

Figure 4 *Vehicle speed characteristics for route T1 in each of the analyzed hours: a - Vehicle speed profile at 7.30 a.m., b - Vehicle speed profile at 11.30 a.m., c - Vehicle speed profile at 3.30 p.m.; d - Vehicle speed distribution at 7.30 a.m., e - Vehicle speed distribution at 11.30 a.m., f - Vehicle speed distribution at 3.30 p.m.*

vehicle often stopped or moved at much lower speeds as evidenced by an average speed of about 13.7 km/h (Figure 4c). At 11.30 a.m., traffic was relatively at its smoothest and, even despite the repeated stops, the average speed reached its highest value (Figure 4b). Meanwhile, it can be seen that at this time of day the shares of the different speed ranges are most evenly distributed (Figure 4e). The distributions for 7.30 a.m. and 3.30 p.m. are significantly different in this respect, where the proportion of speeds below 20 km/h is 40 and 60% respectively (Figures 4d, f).

For route T2 (Figure 5), the speed profiles are characterized by more dynamic changes in the speed curve. Comparing the lines on the graph, it can be seen that the vehicle accelerated and braked more frequently. However, in this case, the low speeds and frequent stops characteristic of driving on a congested street, occur less frequently than on route T1. On route T2, the conclusions regarding the average speeds recorded for route T1 were qualitatively confirmed. Again, the highest average speed of around 25 km/h was recorded at 11.30 a.m. (Figure 5b), slightly lower at 7.30 a.m. (Figure 5a) and the lowest in the afternoon peak at 3.30 p.m. (Figure 5c). The distribution of speeds clearly shows the changes that occurred from hour to hour and it can be seen that speeds of 30-50 km/h dominate at 11.30 a.m. (Figure 5e).

The longest route, T3, is characterized by strongly varying profiles where it is noticeable that the vehicle was traveling at a below average speed at times of heavy traffic. The lowest average speed occurred during the 3.30 p.m. trip, as confirmed by the speed distribution (Figure 6f), where speeds of 0-20 km/h have the largest share. The vehicle was traveling at its highest average speed at 11.30 a.m. The distribution of speeds is relatively evenly distributed (Figure 6e), with the most common speeds being the 30-50 km/h range.

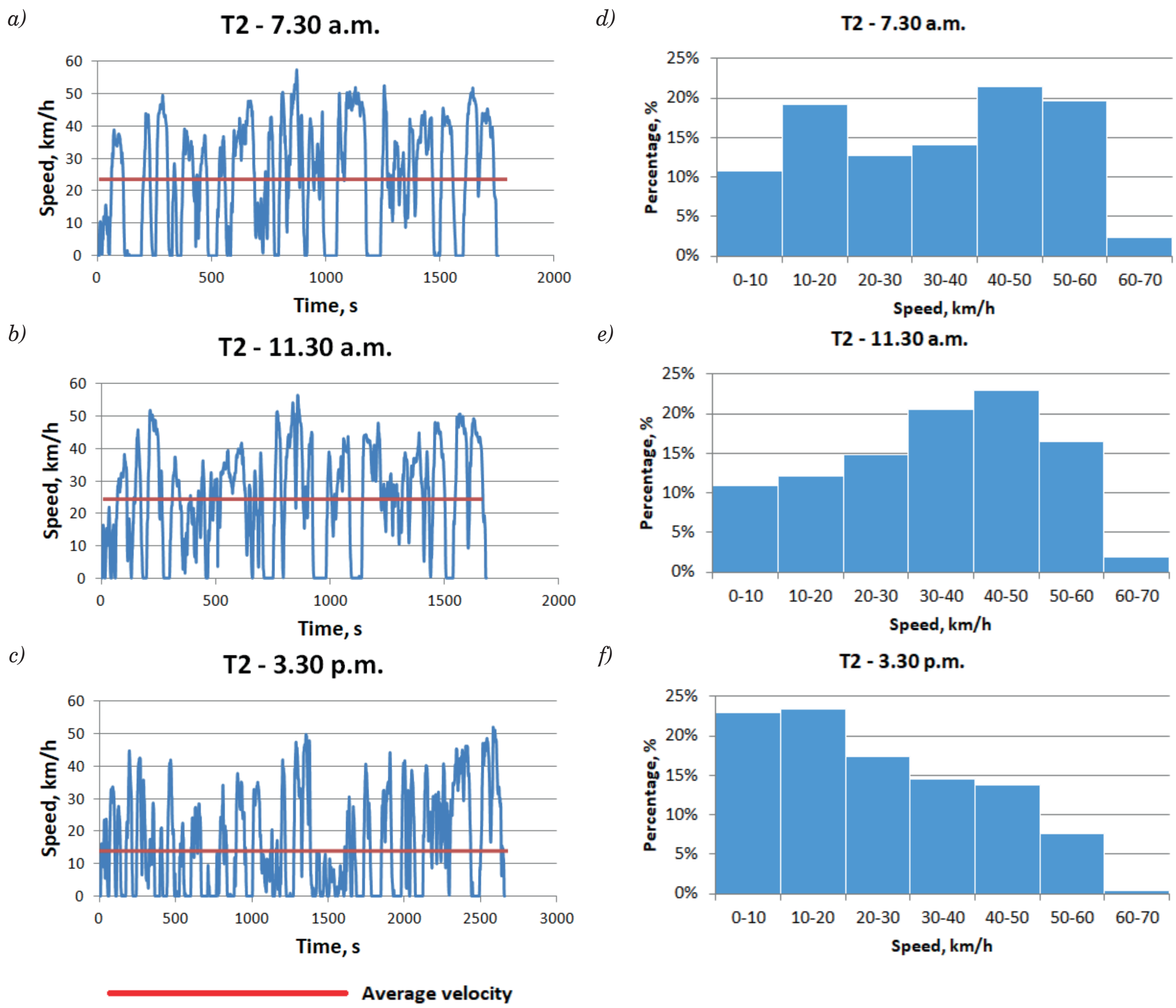

Figure 5 *Vehicle speed characteristics for route T2 in each of the analyzed hours: a - Vehicle speed profile at 7.30 a.m., b - Vehicle speed profile at 11.30 a.m., c - Vehicle speed profile at 3.30 p.m.; d - Vehicle speed distribution at 7.30 a.m., e - Vehicle speed distribution at 11.30 a.m., f - Vehicle speed distribution at 3.30 p.m.*

3.2 Energy consumption analysis

The results of the tests, related to obtaining the real speed profiles, allowed simulations to be performed in the AVL Cruise software. In order to obtain the results, data related to driving time and speed had to be imported into the software. Based on suitable algorithms, the software calculated, among other things, the energy consumption per kilometer, the energy lost and recovered during the trip and the battery charge at the end of the trip.

Figure 7. shows a comparison of the output and input energy consumption curves that were calculated during the simulation and a comparison of their final values. The energy output is the energy that was used to propel the vehicle, whereas, the energy input is the energy that the vehicle has recovered from braking during the trip.

For route T1, the level of energy lost was the highest at 3.30 p.m. and the lowest at 11.30 a.m. The difference between the energy consumption was 8%. The energy recovered by the vehicle, on the other hand, was similar in each hour and oscillated around 1900 kJ. The test graph (Figure 7d) shows that the input energy has a more flattened character than that of the output energy. The shorter the route, the steeper the change in energy consumption. It can be seen that initially the lines of the graph (Figure 7d) coincide for both types of energy, while the visible differences start after about a half of the route. The energy lost is more than twice as high as the energy recovered.

On route T2, the output energy reached its highest value during the trip at 3.30 p.m. The vehicle also recovered the least amount of energy during the drive at this time. The input and output energies for the 7.30 a.m. and 11.30 a.m. trips are similar. The difference between the highest and lowest energy consumption is 5%. This can also be seen in the graph showing the curve of energy consumption. The lines in the graph (Figure 7e) overlap, showing slight differences at the start phase and at the end of the route, due to the length of the trip.

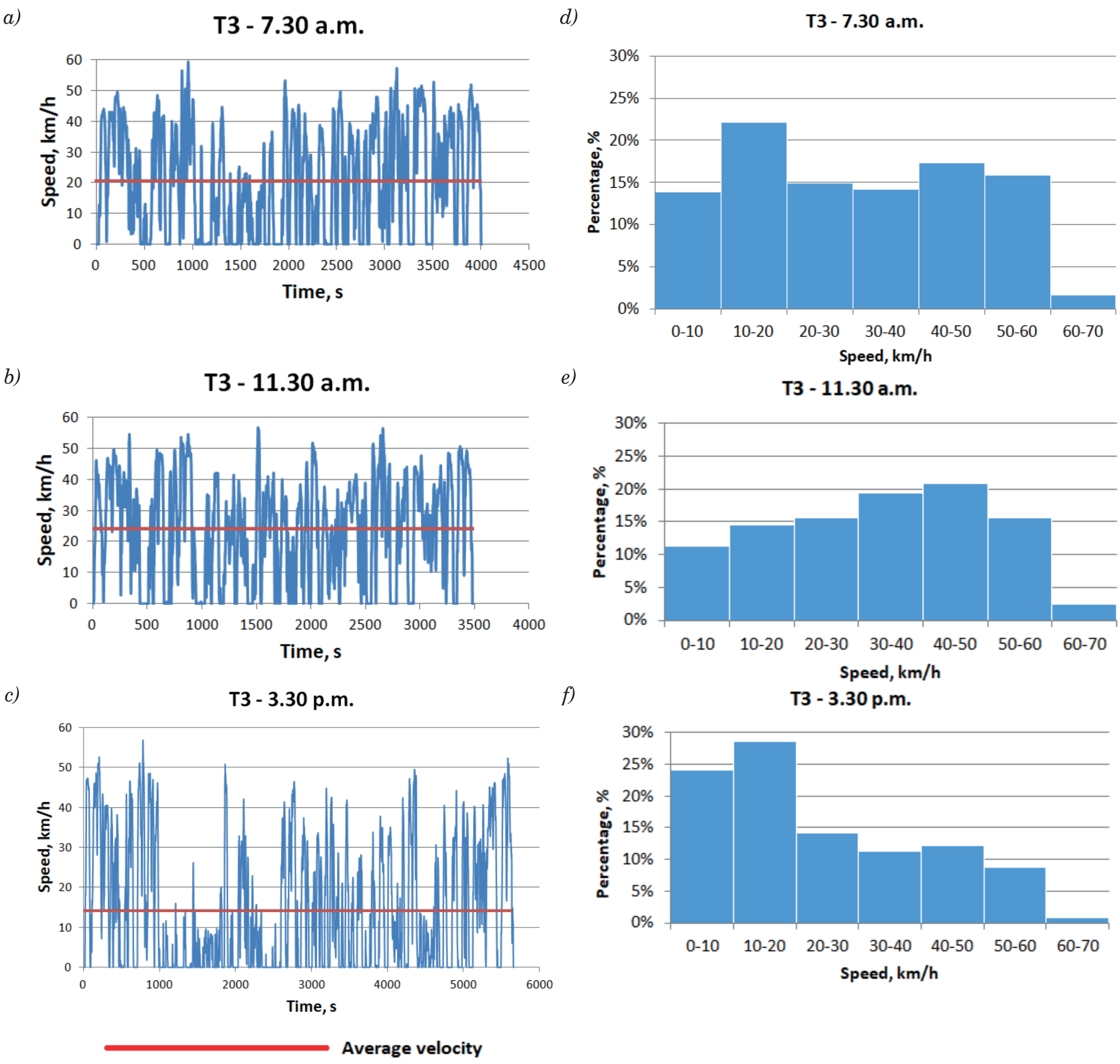

Figure 6 *Vehicle speed characteristics for route T3 in each hour analyzed: a - Vehicle speed profile at 7.30 a.m., b - Vehicle speed profile at 11.30 a.m., c - Vehicle speed profile at 3.30 p.m.; d - Vehicle speed distribution at 7.30 a.m., e - Vehicle speed distribution at 11.30 a.m., f - Vehicle speed distribution at 3.30 p.m.*

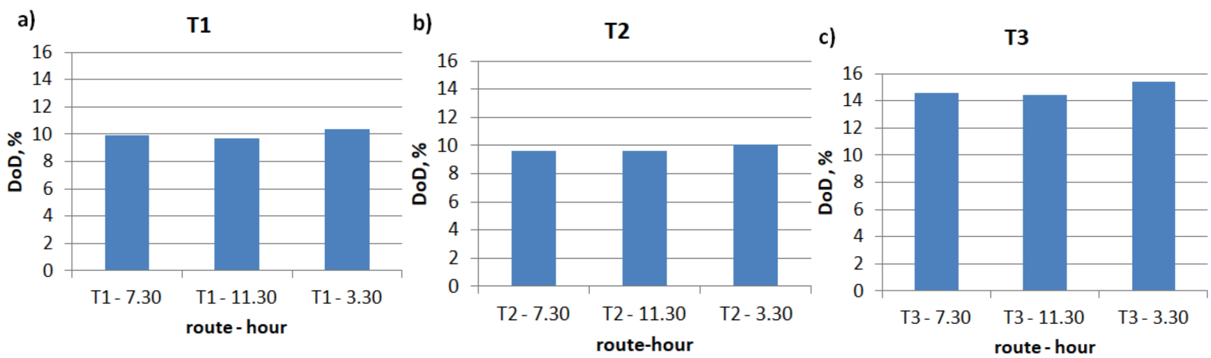

Figure 8 *Battery depth of discharge in the analyzed hours after completing routes a) T1, b) T2, c) T3*

For route T3, as for routes T1 and T2, the highest value of energy lost was calculated at 3.30 p.m. and the lowest at 11.30 a.m. The vehicle therefore used 6% more energy in the afternoon. The energy recovered oscillates around a similar value of 3700 kJ for all of the times of the day studied, but it is the lowest in the afternoon. The

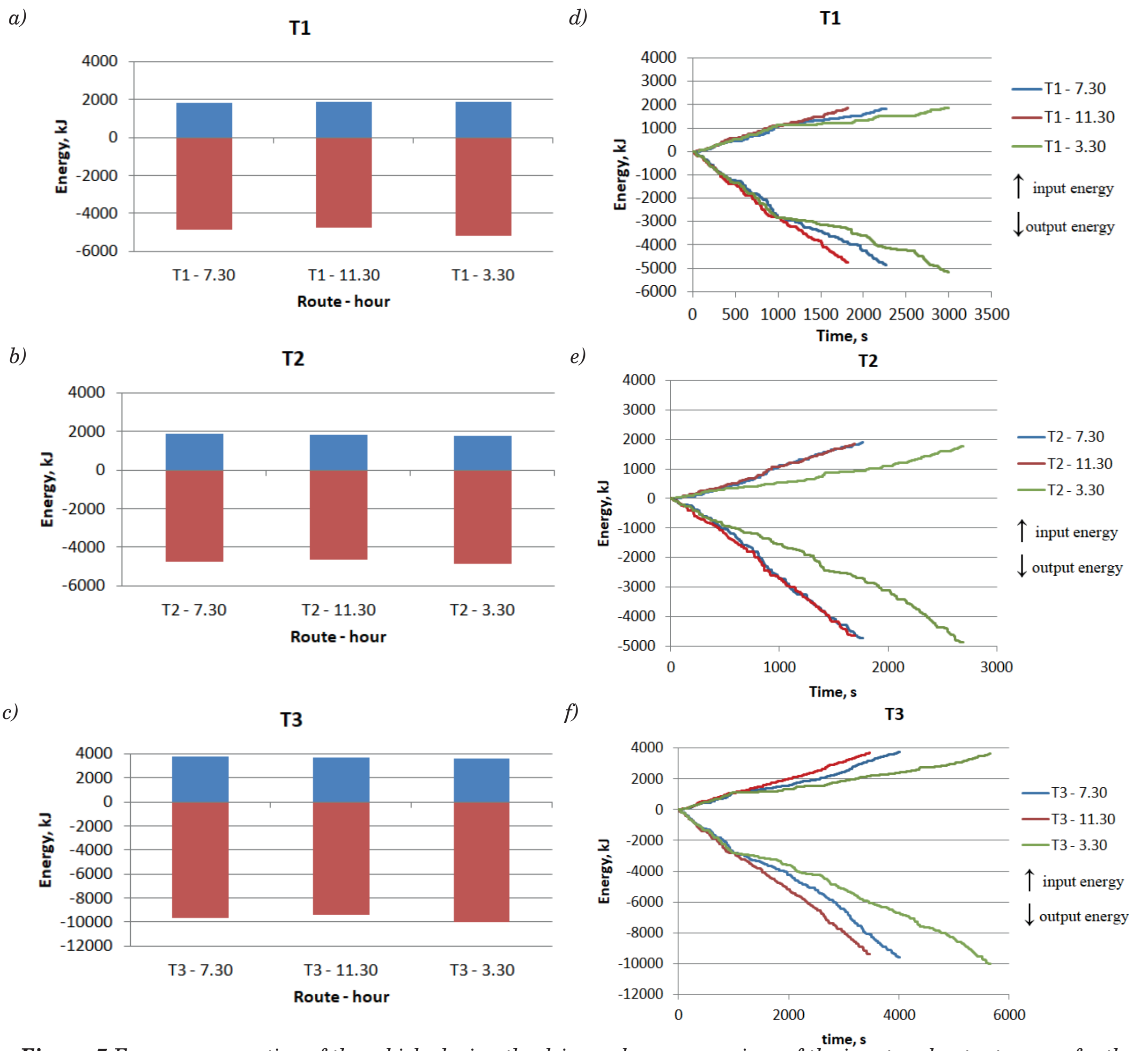

Figure 7 *Energy consumption of the vehicle during the drive: a, b, c - comparison of the input and output energy for the routes T1, T2 and T3, respectively in the tested hours, e, f, g - the curve of the input and output energy consumption for routes T1, T2 and T3, respectively*

input and output energy consumption patterns are the most varied of all the collated routes. There is a small overlap between the lines in the graph (Figure 7f). It is noticeable that there are no sudden collapses and that changes occur smoothly.

The amount of energy absorbed to complete each route was also represented by the depth of discharge (DoD) of the battery. This value is expressed as a percentage and represents, in percentage terms, the amount of energy consumed from the battery per trip. For routes T1, T2 and T3 the depth of discharge is shown in Figure 8.

The depth of discharge of the battery on route T1 is the highest at 3.30 p.m. and is 10.4%. The vehicle then covered the specified distance in the longest time, in addition to often standing in traffic congestion or traveling at low speed. The battery was discharged the least at 11.30 a.m., which is when the trip took the shortest time. In the afternoon, the battery discharge was relatively 7% higher than at midday.

On route T2 the depth of battery discharge was the greatest in the afternoon. In contrast, for the two earlier trips the value of this parameter is similar. The trip, took place under similar conditions, which can also be seen in the curve of energy use (Figure 7).

A very similar relationship to the results for route T1 is shown in the graph for route T3. The depth of discharge of the battery at 3.30 p.m. is the greatest, while at 11.30 it is the least. The depth of discharge was relatively 5% greater.

Energy consumption was also presented on a per kilometer basis, in the form of an hour-by-hour comparison on a given route (Figure 9).

When comparing the graphs to each other, it can be seen that the highest energy consumption occurred on route T1 at 3.30 p.m., reaching a value of almost 350 kJ/km. This is relatively 28% more than during the least energy-consuming trip on road T1. The relative difference between the highest and lowest consumption for route T2 is 9% and for the route T3 is 12%.

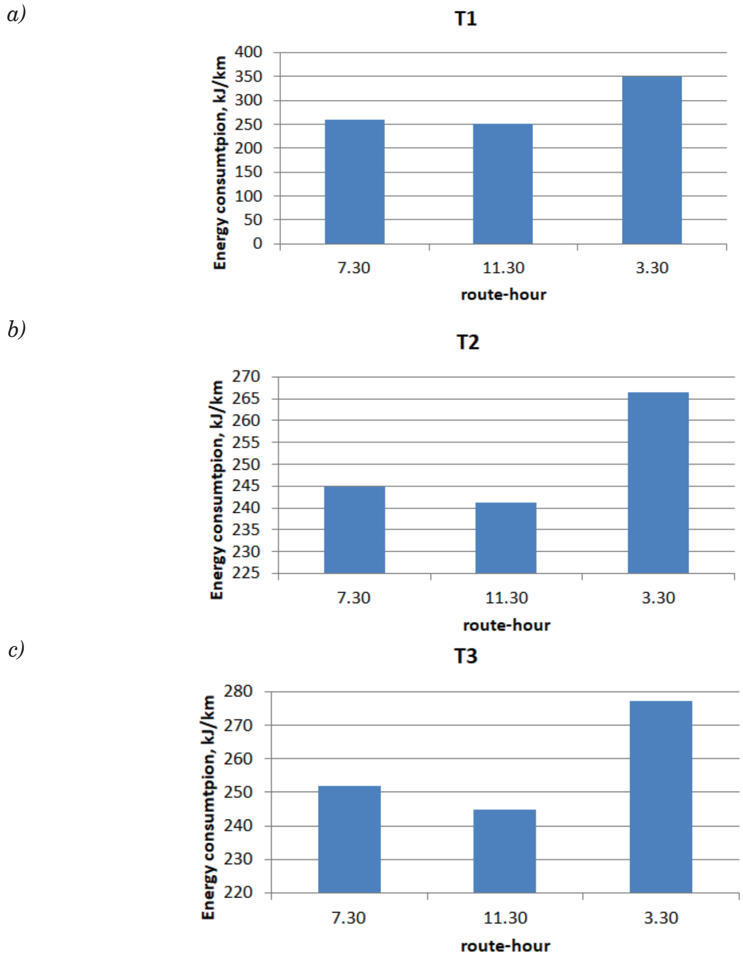

Figure 9 *Energy consumption in different traffic conditions per 1 kilometer for routes: a) T1, b) T2, c) T3*

4 Conclusions

In summary, the energy consumption of a vehicle varies depending on the conditions under which the vehicle is driven. This is confirmed by every parameter calculated from the simulation software. The reason for differences is mainly due to the time of day the vehicle traveled and the road conditions. On each route, the afternoon trip around 3.30 p.m. was the longest and was characterized by the long stopping times or driving at low speeds, typical of urban rush-hour driving. This is when the amount of energy that an electric vehicle needs is the greatest and the battery discharges the most.

The complete opposite was recorded for the 11.30 a.m. trip, where the traffic flowed most smoothly. From the analysis of the speed distribution and profile, it can be seen that the car traveled the route under similar conditions. The speed distribution was more uniform. The vehicle repeatedly braked and accelerated, while then the proportion of stopping time was small. These driving conditions affected energy consumption. The amount of energy used or the depth of discharge of the battery were the lowest.

The 7.30 a.m. driving time combined features of the midday and afternoon driving conditions. The vehicle moved quite smoothly and the stops or periods of slow driving that occurred were much shorter than at 3.30 p.m. This has resulted in average values that lie between the highest typical values of 3.30 p.m. and the lowest characteristic values of 11.30 a.m. The exception is the result obtained for the morning and midday cycle on route T2. The speed distribution and its profile indicate that the route was driven in very similar conditions, hence the values for energy consumption or the battery discharge were very similar.

Performing simulations based on the real-world testing has produced very specific analyses and conclusions. It can therefore be seen that the more difficult the traffic conditions on the road, involving traffic jams, stop or slow driving, the more energy-consuming the electric vehicle becomes. This kind of information is extremely important for drivers who own an electric vehicle that they drive around town. This allows for planning the steps involved in charging and driving in rush hour. With this information, the driver will be able to avoid being stressed about the vehicle's range and possible battery drain while driving.

Grants and funding

The authors received no financial support for the research, authorship, and/or publication of this article.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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GAP ANALYSIS IN ECO CATEGORIES, ELECTRIC VEHICLE COMPARISON AND SOLUTIONS TO GLOBAL TRANSPORT CHALLENGES

Ventsislav P. Keseev

Telecommunications Department, University of Ruse "Angel Kanchev", Ruse, Bulgaria

*E-mail of corresponding author: vkeseev@uni-ruse.bg

Ventsislav P. Keseev 0000-0002-8640-1889

Resume

Nowadays, the world is facing many challenges that require a fast environmental and energy transition, but some obstacles have been found. A gap analysis has been made and the conclusion is that there are flaws in the eco categories distribution of different types of electric vehicles. A comparison is done and the conclusions are that hybrid electric vehicles (HEVs) and plugin hybrid electric vehicles (PHEVs) with smaller batteries are the most versatile, while the battery electric vehicles (BEVs) are good primarily for urban driving. The BEVs reduce the urban pollution, but the global ecological effects are rather controversial and their usage still has many limitations. A discussion of adequate options and solutions for the transport pollution and energy problems is presented. The ultimate goal is to provoke adjustments in government transportation policies towards appropriate solutions that solve today's pollution problems in better and more adequate way.

Available online: https://doi.org/10.26552/com.C.2023.008

Article info

Received 14 September 2022
Accepted 14 November 2022
Online 29 November 2022

Keywords:

AM
consumption
ecology
electric
energy
fuel
hybrid
vehicle

ISSN 1335-4205 (print version)
ISSN 2585-7878 (online version)

1 Introduction

The world is on the brink of global climate changes, rising world conflicts, energy prices and many other complex problems that require urgent solutions. The transport is one of the biggest polluters and electric vehicles (EVs) are expected to be one of the main solutions. The problem is that some of them still have many drawbacks and for that reason they cannot become an immediate solution.

Nowadays, a lot of money are invested in development of the battery technology and breakthroughs are expected in that field, but the future is uncertain and the working solutions are expected to take years until applied in real life. At the same time the whole developed world wants to make the green technology transition now. This leads to a high demand of green technologies, but low initial supply. The supply of different car building materials is under question with the rising world conflicts and the broken supply chains. At the same time, all the prices are matter of supply and demand. The low supply and high demand automatically mean higher prices. The high prices make the green technologies less competitive and stop their widespread use. This is especially true for lithium batteries that are built of rare components. Most of the lithium nowadays comes from Asia and this could be a problem because of the rising international tensions. All the mentioned problems could stop or slow down the EV wide adoption.

One of the solutions to these problems are expected to be the hybrid electric vehicles (HEVs), but they seem to be underestimated. An earlier investigation led to the conclusion that HEVs are the best transitional option from internal combustion engine vehicles (ICEVs) to battery electric vehicles (BEVs). They are greener than traditional ICEVs, especially for the city use and one of their benefits are the comparatively small batteries. The batteries are one of the most expensive components consisting BEVs and at the same time they have comparatively short calendar and cyclic lives. Their prices are still too high and they suffer from high flammability risks. Until the battery technologies develop or their prices fall enough, the HEVs are going to be the best transitional option. The expectations are the HEVs to be economically and ecologically viable at least in the next 10 years.

The problem is that many cities in the developed world started creating green zones for the BEVs and plugin hybrid electric vehicles (PHEVs) only. At the same time the HEVs are being put in the same eco category as the regular ICEVs. This is happening in Bulgaria too and it is a problem, since BEVs and PHEVs have many drawbacks yet and most of all, they are not affordable and economically viable, which means that only a few people will buy one. Most of their problems come from the big batteries and their drawbacks. The BEVs could be used for comparatively short trips only because of lack of charging stations and other deficiencies. For such short trips, usually, there are good public transportation systems and the owning of an expensive BEV is pointless. The BEVs may become widely spread if companies for shared use of BEVs are created. There are such companies for bicycles, electric bicycles and electric scooters.

The aim of this work was to analyze different types of vehicles and to find out how environmentally friendly and competitive HEVs are compared to them. The advantages of HEVs, compared to their corresponding traditional ICEVs, prove that they should not be treated in the same eco category with the same limitations. If the HEVs have access to all already created and future city green low emission zones, this will stimulate their widespread use and will help for the faster solution of the ecological problems. Various adequate solutions to the transport pollution problems are presented. The ultimate goal is to invoke adjustments to the government transportation policies towards appropriate solutions that solve the pollution problems of today in a better and more adequate way.

2 Methodology

The main types of vehicles and their main differences are presented for use in the following analysis. The HEVs are being underestimated nowadays and this problem is considered in more detail. An analysis concerning the HEVs pollution and competitiveness is done in comparison to other types of vehicles. It is based on real measurements and calculations done by other authors and on author's research and experiences. In this regard, the actual pollution of different Euro class ICEVs is presented. Their urban fuel consumption is compared to that of HEVs and it becomes clear that the vehicle consuming less fuel must be considered as more ecological and must fall in higher eco category. The results are backed up with studies investigating how different types of vehicles behave under different road conditions. Their conclusions are that, on average, the HEVs consume a lot less fuel than the corresponding ICEVs.

An analysis of different scientific research is done that consider the emissions of different types of vehicles based on road conditions, speed, charging conditions and different levels of carbon generated by the grid. The results clearly show how different vehicles behave in different cases. The conclusions are that the HEVs and PHEVs are the most versatile, while the BEVs are good primarily for urban driving.

Investigations concerning the current BEVs ecological effects on global and local urban levels are presented. The conclusions are that they reduce the urban pollution, but the global ecological effects are rather controversial. Their pollution might be even higher than that of ICEVs for extra-urban high-speed driving.

Everything that is economically viable is easily spread widely. This is important because people decide what vehicle to buy. In this regard, the competitiveness of the various vehicles is compared. The conclusion is that the HEVs and PHEVs with smaller batteries are the economically viable and competitive option now and their usage must be stimulated now. The finding of the right vehicle for the timely reduction of transport pollution is important, however, there are and other effective measures that can be applied now. Different adequate solutions to the rising transport pollution and energy problems are presented in a structured way in relation to each other.

The aim of the research is to provoke adjustments in government transportation policies towards appropriate solutions that solve today's pollution problems in better, safer and more adequate ways, which will accelerate the green transition.

3 Main features of different types of vehicles

Nowadays there are five main types of vehicles:

- Internal combustion engine vehicles - they run entirely on oil fuel engines and have high fuel consumption and pollution, especially in cities.
- Hybrid electric vehicles - they have a petrol engine and an electric motor and run mostly on fuel, but regenerate energy in comparatively small battery. The batteries could be NiMH or Li-Ion ones and are usually with 1.3 kWh capacities. They are a lot more fuel efficient and cleaner especially in city environments than ICEVs.
- Plugin hybrid electric vehicles - these are practically HEVs with bigger batteries. The batteries are Li-Ion and are usually with about 8 kWh capacities. In comparison to HEVs, they could be charged from the grid and have higher run per battery charge. It could be fairly stated that with good design, tailored to current battery technology drawbacks, the PHEVs could combine the advantages of HEVs and BEVs and could become the most favored transitional option to more ecological transport.
- Battery electric vehicles - they have only an electric motor and run entirely on electricity stored in a big battery. Their batteries currently are Li-Ion and usually are with capacities over 20 kWh. For

example, usually different Tesla models are with battery capacities from 75 to 100 kWh.

- Fuel cell electric vehicles - they run on hydrogen. They are not included in this analysis because our experience points out that they are still with poor competitiveness and this technology is not expected to improve much in the near future.

4 Imperfections analysis of eco categories

In 2020, the Bulgarian government changed the regulation No. H-32 for periodic examinations of the technical health of road vehicles. According to this ordinance, five ecological groups for passenger vehicles are created. The government intends to use these ecological groups for car limitations in certain green city areas. These vehicle division groups have been applied from the summer of 2021. Their aim seems to be good, however, in reality, this regulation equates HEVs with ICEVs and this is completely wrong from ecological point of view. According to it, HEVs are regular ICEVs and only PHEVs, BEVs and fuel cell electric vehicles are considered to be ecological vehicles. This incorrect classification leads to many pitfalls which are expected to hinder the expected ecological effects.

It seems that in Europe the ecology restrictions are mostly done based on the registered CO_2 emissions of the vehicles, but it is unclear if they take under consideration that the actual urban values are 30 - 50 % lower for the HEVs than for corresponding ICEVs. A study concludes that the current policies in the EU and Germany are not making use of the full environmental potential of EVs and therefore regulatory gaps have been identified. It was shown that existing policies do not differentiate sufficiently between different EVs. While the regulatory focus on exhaust pipe emissions might be reasonable for the era of combustion vehicles, regulation risks with this current scope to turn a blind eye to the real-world carbon emissions of EVs and therefore undermine climate mitigation efforts [1].

The HEVs and ICEVs are very different technologies and their distinctions stand out especially when driving in an urban environment, where these groups should apply. At the same time, today, the HEVs are the more competitive vehicles compared to PHEVs and BEVs due to some of their distinctive advantages. Most of these advantages are due to the smaller batteries and the problems of current battery technologies. There are expectations for many of these problems to be solved soon, but they are not solved yet. There are already some promising laboratory results in this regard, but nothing has been proven in real-life tests yet and very often the real-life conditions and results are very different.

5 Environmental and costs comparison of different vehicles

The research led to the conclusion that most ICEVs, no matter if they are new or old, burn 30 % to 50 % more fuel in urban driving than in extra urban driving. This is valid for regular cars since for the more powerful models the urban fuel consumptions could be a lot more than 50 %. The difference between new and well-maintained older cars is that the new models are licensed for higher eco category which should mean that they emit less poisonous gases and CO_2 for certain amount of burned fuel. Real-life measurements of different vehicle emissions, done with Emissions Detecting and Reporting (EDAR) system, prove that in most cases the higher emission categories lead to lower release of some

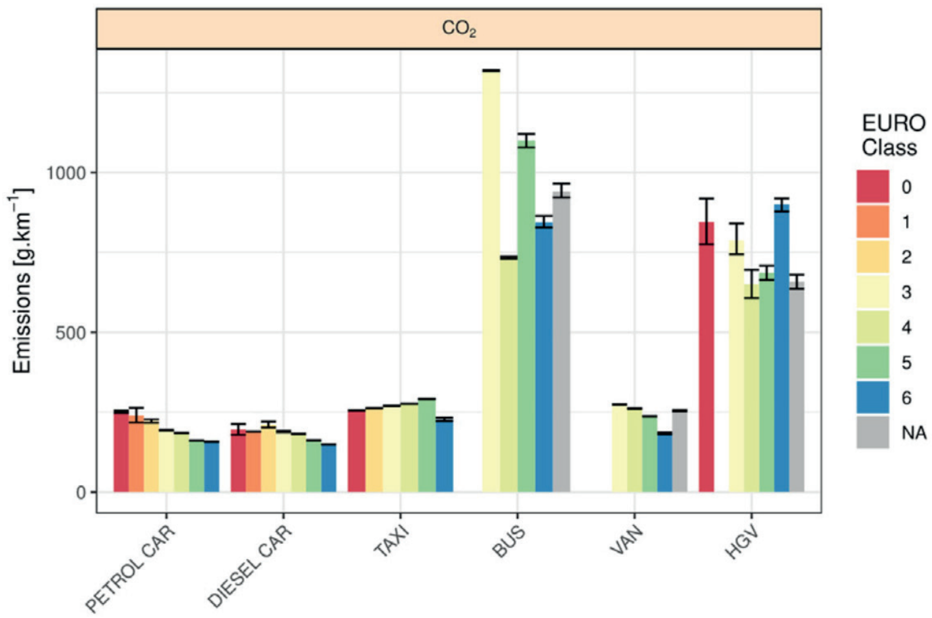

Figure 1 *Average CO_2 emissions from ICEV vehicles observed during the EDAR campaigns [2]*

Table 1 *Characteristics of the considered powertrains [4]*

Powertrain	Body type	Engine capacity, cm^3	Battery capacity, kWh	Maximum power, kW	Weight, kg
ICE	Sedan	1,798	-	103 (Petrol Engine)	1,315
HEV	Sedan	1,798	1.3	90 (System)	1,410
PHEV	Hatchback	1,798	8.8	90 (System)	1,540
BEV	SUV	-	44.5	105 (Electric motor)	1,532

of the measured gases, but not all the emitted gases are measured and the difference for some of the pollutants is not high between different Euro standards [2-3]. For example, the difference of the emitted NO_x gases should be 5 times if Euro 3 and Euro 6 emission standards are compared, but the real-life measurements show about 3 times difference. The particulate matter difference should be 10 times and the real-life measurements show about 10 %. The real-life CO_2 difference is about 10 - 20 %, Figure 1.

In comparison, most HEVs almost always burn the same amount of fuel in urban as well as in extra-urban driving. This is because every time the vehicle slows down or stops, energy is being regenerated and stored in the battery, which is being used after that. On average, the HEVs ability to regenerate energy is their major advantage over corresponding ICEVs. Due to this advantage the HEVs consume a lot less fuel in city environments than corresponding ICEVs and this cannot be changed even with major internal combustion engine (ICE) developments, because the HEVs also possess an ICE. Almost every innovation in ICE exhaust treatment systems or alternative fuel systems could be applied to HEVs, as well. If the ICEs develop further, this will improve the HEVs ecology too. If under certain rare conditions the ICEVs perform better, then for them, the driver should have the option to drive the vehicle as regular ICEV. This possibility could be created if a scientific analysis proves it to be economically viable. The research points out that modern HEVs perform better than modern ICEVs in most of the scenarios. If they do not, in certain special cases, it is a matter of better automatic or driver control.

This practically means that each HEV consumes 30 to 50 % less fuel than the corresponding ICEV models and this automatically means 30 to 50 % lower release of CO_2 and other poisonous gases in the city environment. The conclusion is that the fuel economy of a vehicle is more important for determining the eco category used for the low emission zone limitations. It could be fairly stated that HEVs are 30 to 50 % less polluting in city environments than the corresponding ICEVs from the same emission standard. Even the first HEVs, created by Toyota and licensed for Euro 2, seem to be competitive to corresponding modern Euro 6 vehicles for urban environments, but in Bulgaria they will fall into the 2nd ecological group and most likely will be restricted at some point. The real-life measurements of regular Euro 2 vehicles show about 30 % difference in CO_2 emissions, 4 - 5 times difference in NO_x and about the same PM emissions which could be even with lower values compared to Euro 6 ones [2-3]. This means that Euro 2 HEVs are supposed to have only about 2.5 - 3.5 times higher NO_x emissions because they consume 30 - 50 % less fuel in urban environments. At the same time, they are expected to have 30 - 50 % lower PM emissions and about 0 - 20 % lower CO_2 emissions. If we consider that the NO_x gases are considered the more toxic then they could be accused to be a little more polluting than a corresponding regular Euro 6 vehicle, but the difference for urban environments does not seem to be a lot.

Real-life measurements of the HEV and ICEV fuel consumptions, driven under different road conditions, show that the HEV has 49.3 % lower fuel consumption than the corresponding ICEV for the city driving and this result overlaps with our findings [4]. On average of all the route modes, the Well-to-Wheel CO_2 emissions of HEV and PHEV and the Well-to-Tank emissions of BEV, are about 65 %, 50 % and 35 % respectively, compared to the corresponding ICEV. For extra urban driving the HEV has 35.4 % lower fuel consumption for prevailingly flat road and 31.1 % for hilly roads [4]. The characteristics of the compared vehicles are presented in Table 1. Vehicles with such parameters are widely used nowadays.

This scientific research [4] is new and such achievements are normal for the HEVs built after 2009, especially for the models built after 2015. The results seem to be great, but another study concludes that BEVs consume significant energy for heating the interior and windscreens to prevent condensation in cold weather leading to an estimated reduction in range of approximately 28 % in some situations [5]. Our experience is the same, but it is noticed that in cold weather HEVs also consume more fuel. The problem for both is partially due to the at least initially cold battery, which has lower usable capacity. A scientific investigation concludes that for increasing the range of city electric vehicles it is better to focus on a systems, which can heat the batteries to the appropriate temperature when the battery has low internal resistance [6].

Another analysis concludes that the BEVs have the lowest emissions for city driving and the highest for the high speed highway driving, Figure 2. The PHEVs are with a little higher emissions from BEVs for city driving, but with twice smaller than those of the corresponding ICEVs. They have the lowest emissions for the high-

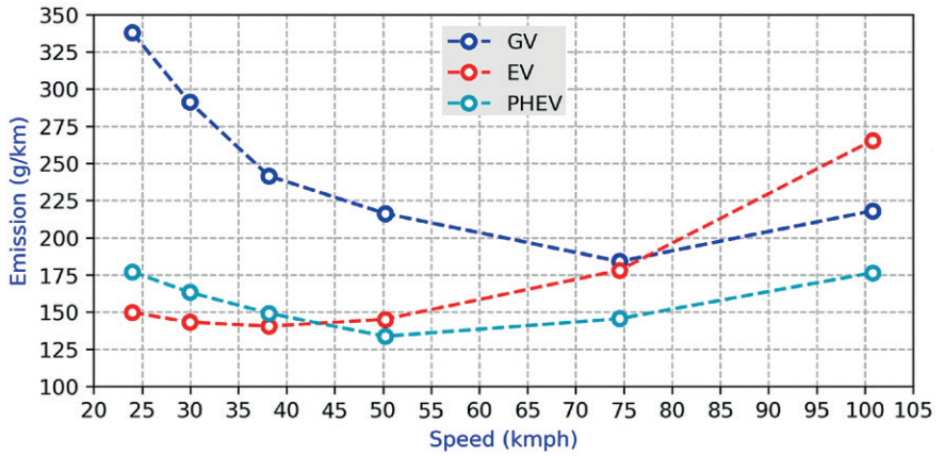

Figure 2 *Emission versus speed plot of different vehicles for the Texas electricity generation mix [7]*

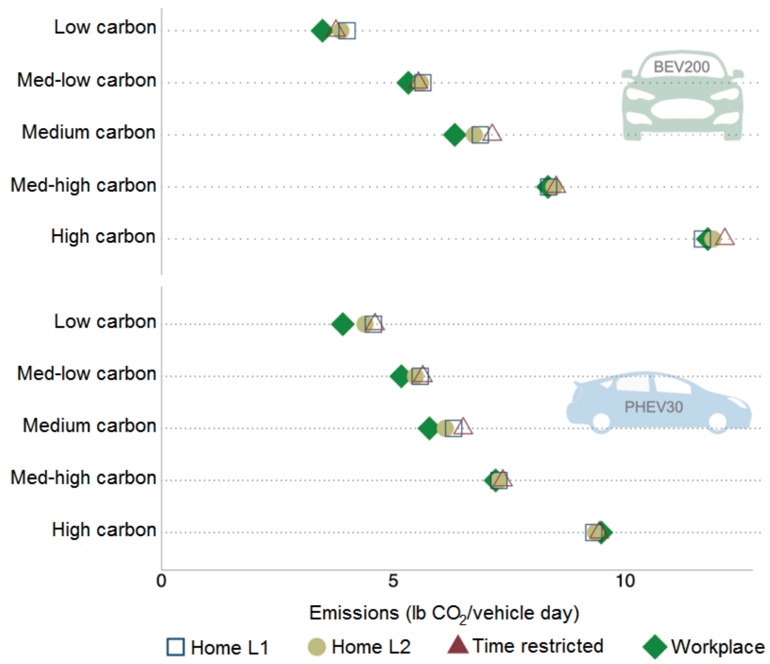

Figure 3 *Total emissions per vehicle day by region, vehicle type and charging scenarios [8], BEV200 is a vehicle with 200 miles full charge range and PHEV30 is a vehicle with 30 miles full charge range*

speed highway driving [7]. The energy for the BEVs charging comes mostly from conventional nonrenewable energy sources, which is the common case nowadays.

Another study concludes that the PHEVs have lower total emissions than ICEVs and yield lower total emissions than BEVs in four of the five grid types. The low-carbon grid is the only case in which BEVs have lower total emissions, Figure 3 [8]. The analysis is done for BEVs and PHEVs with different full charge electric ranges.

The studies [7-8] do not consider HEVs, but usually they have about the same or even better mixed fuel/energy consumption than the PHEVs, most likely due to their lower weight. If more kilometers are driven by electric power, then PHEVs perform better, but if they are driven entirely in hybrid or mixed mode, or if the percentage of electric kilometers part of the total is insignificant, then HEVs perform better. The HEVs are better for prevailingly long distance extra urban driving, while the PHEVs are better for prevailingly short distance urban driving or close to city driving. The difference is that HEVs are with lower costs of usage because of the smaller batteries.

There is certain variation of the results of different studies, but the research led to the conclusion that most of them agree that on average HEVs and PHEVs are a lot cleaner and more fuel-efficient than the corresponding ICEVs. The difference varies depending on the road conditions, type of grid, charging scenarios, vehicle speed, vehicle types and others.

There is a certain level of disagreement between different studies, considering how clean the BEVs really are, but on average, it seems to prevail the opinion that they could be greener alternative to HEVs and PHEVs only for low-carbon grids. For low speeds in urban areas, they have a significant advantage, but for extra-urban high-speed driving their advantage disappears. The problem is that usually the conclusions are based on a lot of calculations and approximations and it is difficult to properly take all factors into account. A study analyzes the CO_2 emissions in eight leading countries in relation to the stock of electric vehicles and concludes that, BEVs have an overall negative effect on CO_2 emissions, while they weakly and positively affect EVs [9]. Research concludes that the application of vehicles with an electric motor is ecologically justified only in cases of obtaining electricity in an environmentally friendly way and that in other cases there is no profit in an ecological sense. From an economic point of view, if there were no subsidies to manufacturers and buyers of electric cars, they would not be competitive with internal combustion engines now [10]. If we consider the fact that two corresponding vehicles need the same amount of energy to move, the ICEV will generate that energy through direct fuel combustion and the BEV will receive it from the grid. The conventional power plant also needs fuel to generate energy, but it can do that cleaner and with higher efficiency than an ICE. The problem is that this energy must be transported and there are transmission and conversion losses on the way to the final consumer. Then, it must be converted and stored in the BEV's battery and then converted again to power the electric motor. All the mentioned steps generate losses. Additionally, the battery production process is energy-intensive and dirty. The main difference is that the ICEV engines are constantly running and burning fuel, while the BEVs use energy only when needed and can regenerate some of it back. The conclusion is that the BEVs are cleaner than conventional ICEVs for lower speeds and even for predominantly high-carbon grids. For high speeds and predominantly high-carbon grids they might be more polluting even than the ICEVs.

The main sure disadvantage of the BEVs is that they are not economically viable. A contemporary study for Scotland concludes that if all diesel and petrol light-duty vehicles are replaced with BEVs, this will lead to a reduction in the total amount of carbon emissions by approximately 33.7 %, but the owners would spend about 75.7 % more money as initial costs compared to conventional cars. In the long term, electric vehicles are expected to save money to their owners, because of the considerably low price of electricity, with estimated savings of about 69.1 % per annum [5]. The ecological effect is possible only if the electricity is generated prevailingly from the renewable energy sources. The savings may not be real if the owner has to replace the battery at some point, because the new battery may cost as much as the new BEVs. The current battery shelf-lives are 15 years and the warranties are about 8 years. This means that the batteries will have to be replaced every 10-12 years and the owners most likely will have to draw away the vehicles and to buy new ones if the price of the battery replacement is about the same. Only a few can afford to buy a new vehicle every 10-12 years and the old one drawing away will not have a good ecological effect. The BEVs receive energy from other sources and their lives are better to be extended to at least 25 years. Nowadays, the reasonable life expectancies of many vehicles are about 25 years. This limit is due to the contemporary chemicals used for winter road cleaning, that corrode all the metal parts of the cars. For that reason, at some point their maintenance becomes a burden. The conclusion is that, today, from the global point of view, BEVs cannot be cleaner alternatives compared to the other types of vehicles under consideration.

From this analysis it could be concluded that the HEVs and PHEVs are the most versatile vehicles and they are good for urban as well as for extra urban driving. The BEVs are the best for the city driving only and the ICEVs are the worst. The main disadvantage of the HEVs is that they could have higher maintenance costs, if poorly designed, compared to corresponding ICEVs, but on average, the positive effect of lower fuel consumption outweighs. The BEVs have the lowest maintenance costs if the battery replacement at certain mileage or age is not considered. The final conclusion is that the HEVs deserve to be classified in a higher eco category than the corresponding ICEVs.

6 Analysis of the limitations of electric vehicles

Most of the limitations of electric vehicles come from their batteries. The current battery technology has many drawbacks. At the same time the battery is the single most carbon-emitting component of an EV, accounting for 31 - 46 % of the total EV manufacturing emissions [11]. The widely used lithium batteries have comparatively low calendar and cyclic lives. Luckily, it seems that the cyclic life could be improved significantly with a good cooling system design, but the real calendar life implications are unknown yet.

The high flammability of the lithium batteries is another major problem. The more the electric vehicles, the more fire incidents are expected to occur. There have been already many fire incidents with Tesla EVs during car crashes. At the same time, the major fire problems usually occur during the lithium battery charging processes, especially when they get older [12-13]. If we consider that charging is expected to be done more often at home, then apartment buildings and their inhabitants for example may be threatened with higher fire risks than the usual.

The current lack of many charging stations is another major problem which is expected to be solved in the recent years. Study concludes that the potential of the PHEVs to reduce emissions is highly linked to the availability of a charging point at home or at work for regular charging [14]. At the same time, electric vehicles suffer from the long charging times and comparatively short run per battery charge. These problems currently limit their usage to certain areas around big cities. Another problem is that not many people living in cities need a car for just city use. Usually, there are good transportation systems in cities, which makes such an investment useless in many cases.

Scientific investigations suggest that the power grid and power plants may not be prepared for the upcoming electric loads due to the expected wide use of electric vehicles. Study for the Netherlands concluded that uncoordinated charging would increase national peak load by 7 % at 30 % penetration rate of EVs and household peak load by 54%, which may exceed the capacity of existing electricity distribution infrastructure. At 30 % penetration of EVs, off-peak charging would result in a 20 % higher, more stable base load and no additional peak load at the national level and up to 7 % higher peak load at the household level. Therefore, if the off-peak charging was successfully introduced, electric driving may not require additional generation capacity, even in case of 100% switch to electric vehicles [15].

A study of Scotland estimates that approximately 4 GWh per annum of additional electricity will be needed to compensate for such growth in electricity demand [5]. New power plant and electricity distribution infrastructure projects take years for development and all of this goes on the top of the rising global conflicts and energy prices.

The PHEVs and especially BEVs have high-capacity batteries which are too expensive. For that reason, their initial purchasing costs are higher than those of the corresponding ICEVs or even HEVs. The total costs of ownership is also higher. Such vehicles could be afforded only by richer people who are a lot lower percentage of the total human population.

Almost the whole world is moving towards greener technologies and this is expected to lead to very high demand for such and surely to at least initial insufficient supply. All the prices are driven from the laws of demand and supply. At least initially, the rising economic tensions and broken supply chains are expected to reinforce the trend leading to more expensive green technologies, including batteries. This is expected to make the EVs with bigger batteries even less competitive in the short term, but the HEVs with their small batteries are competitive now. The history shows that usually only economically viable products become widespread.

Nowadays, there is no proven and established economically viable technology for the lithium battery recycling. This leads to many ecological problems in the short term and could lead to high level of stored lithium battery garbage. The easy availability of raw materials used in manufacturing batteries at a lower costs as compared to the recycling costs is the prime factor to impede the battery recycling market growth, but it is expected to grow by 2030 anyway due to rising use of the EVs [16]. At the same time the HEVs have small batteries, which could be of the proven NiMH type, which are also with very low flammability risk compared to the lithium ones.

All the mentioned problems are going to stop or considerably slow down the greener more ecological transport initiatives. It is necessary that the obstacles standing on the way of the widespread use of HEVs to be eliminated. They are the cleaner and more competitive transitional vehicle which will support a greener transport system, at least for the next 10 years. Their purchasing and usage must be stimulated until better, the real-life proven and economically viable technology appears. The conclusions are confirmed by study, estimating that only about 30 % of the worldwide passenger vehicle fleet will be the EVs in 2032. However, results also display vast differences between countries, which can particularly be attributed to divergences in governmental support [17].

7 Discussion of options and solutions for the transport pollution

All the suggested solutions are product of the experiences and many investigations done during the years.

The main problems of the EVs are the expensive batteries, which have comparatively low calendar and cyclic lives and the limited run per battery charge. The battery problem is expected to be solved in the up-coming years because a lot of money are invested for the development of battery technology. There are already breakthroughs in the field. The NMC532 lithium battery cell has been projected to have 100 years of lifetime for 20 °C work temperature [18]. The real lifetime is expected to be lower, but this is amazing achievement considering that the current lithium battery technology allows 15 years of calendar lifetime. It will take time for this technology to be applied and tested in real life.

A proper initial solution could be the PHEVs with big enough batteries for certain run entirely in electric power for city usage. Our experience points out that 20 - 40 km run is enough for most of the small and medium size cities, but different configurable options could be created for different cities, based on investigations. The idea is the battery to be with comparatively low capacity for the lower driving costs but with enough capacity for the daily needed electric city driving. Such a car would be versatile and economically viable and will help a lot for the timely ecological problem solution. Current HEVs are with very small batteries, about 1.3 kWh, which is enough for only about 5 km run and they cannot be charged from the grid. The PHEVs are usually with larger batteries than necessary. Often, they have batteries with about 8 kWh capacities. We suggest that in most cases the PHEVs with battery capacities of about 4 - 5 kWh are enough. This will allow for comparatively lower total ownership costs and for greener inter city transportation.

Figure 4 *The Sion - the car that charges itself [19]*

The problems with the overcharged power grids and insufficient or conventional power generation could be partially overcome by integration of photovoltaic systems on the outside of the car bodies. The company Sono Group N.V. have already created such vehicle. They have seamlessly integrated 456 half photovoltaic cells into the body of the car, that can add 112 km, on average and up to 245 km per week, of driving range to the car's battery, through the power of the sun, Figure 4. This creates full self-sufficiency on short distances [19].

Certain recent developments in internal combustion engines could also become a solution, but every new development takes time to be applied in practice. For example, a team from the University of New South Wales has retrofitted single-cylinder diesel engine to run on 90 % hydrogen which led to 85.9 % CO_2 reduction and 13.3 % indicated mean effective pressure/efficiency increase [20]. The main problem with hydrogen is that it is highly explosive and it could harm many in the case of a road incident. Our view is that hydrogen can be used as alternative fuel only when the production technology has developed sufficiently to allow efficient real-time production in the vehicle. Moving vehicles with hydrogen tanks are practically moving explosives.

The fuel and energy consumptions of all types of electric vehicles could be improved by better utilization of inertia. The previous research led to the conclusion that from 6 to 15% improvement of the run per battery charge is possible. This could be achieved with comparatively simple change of the vehicle control. It is suggested the gas pedal to be used only for acceleration and the stop pedal to be used only for two levels of regeneration and stopping with the brake pads. When neither one of the pedals is pressed the vehicle should move in automatic neutral gear. This will allow the driver unintentionally to better use the vehicle inertia because only the driver knows what is going to happen next on the road.

The governments should invest in a green and convenient public transport systems, which are often cheaper than the private vehicles for city use. A study analyzes the synergy and co-benefits of reducing the CO_2 and air pollutant emissions by using electric private cars, taxis and buses in Shanghai. The results show that electric buses provide the highest co-benefits. Thus, replacing traditional fuel vehicles with electric buses can simultaneously reduce air pollution and CO_2 emissions [21]. The public transport systems from smaller settlements to the near big cities should also be improved. They are rather poor in Bulgaria. The proper solutions are electric trains, trams, buses and trolleybuses. The battery technology is expected to offer lithium batteries with very high cyclic lives soon.

The smart traffic light control based on current traffic measurements and the creation of green light waves could also help a lot. In this regard the tendency the speed limits in urban areas to be lowered should be discontinued. The too low speed limits are bad for ecology because all the vehicle types use more energy for their movement. Speed limits of 30 to 60 km/h are a good balance between safety and vehicle economy. A study concludes that CO_2 emissions are minimum at 75 km/h for the ICEVs, at 38 km/h for the BEVs and at 50 km/h for PHEVs [7]. Better maximum speed control should be applied for the higher urban transport safety instead of lower speed limits.

In USA often there is a permission for right turn on red traffic light, which helps in some cases for easing congestions.

Safe bicycle and electric scooter transport networks should also be developed in cities, as well as between them. In Ruse city such has been created recently and it seems that more and more people are using bicycles or scooters. Such bicycle road networks should also be created from the smaller settlements to the big cities, because almost all the people living there travel daily for work. If there are safe and good road conditions many will start using greener and better for their health transport means.

Another option are the affordable short period rentals of electric bicycles, electric scooters as well as electric cars for the city or close to city use. Study concludes that 13 % of the daily car trips, corresponding to 2 % of the car kilometers in Germany, are suitable for replacement. At the same time, the E-scooters are estimated to have twice lower greenhouse gas emissions than EVs for their lifetime [22]. Mass uptake of e-bikes could make a significant early contribution to transport carbon reduction, particularly in areas where conventional walking and cycling do not fit journey patterns and bus provision is relatively expensive [23]. Research concludes that electric bicycles are the finest development in our ever congested world and provide an easy solution to daily commute woes. They save a lot of fuel and keep the environment clean, but also help people develop good health with little pedal exercise [24].

The extra urban riding speed limits of electric bicycles and scooters should be 50 km/h, the same as that of mopeds. The problem is that 40 km/h can be maintained with a high quality road bicycle on an even road for a long period of time; 50 km/h are also easy to achieve, but for short periods of time. This is the reason why mopeds are limited to 50 km/h. If such speeds could be achieved easy with regular bicycles and they are not dangerous then they should be possible for extra-urban driving and they will stimulate the wide spread use of the greener two-wheeled vehicles. The 25 km/h speed limit is good for city uses on bike lanes, but if the electric bicycles must share the road with cars, then the city speed limits of the automobiles (maximum 50 km/h) should apply in these cases because riding with speeds close to those of the other vehicles is safer.

The high ownership price of electric vehicles and the other problems related to batteries could be overcome with affordable shared use of rented EVs. In such cases the price will also be shared. The batteries will not be allowed to get older and their live cycles will be better used because the vehicles will be constantly used by someone. The prices for all ownership taxes will also be shared. In this case, the maintenance costs could also be lower. Better electricity rates can also be negotiated by the rental company. This would also solve the problem with the home charging of the flammable lithium batteries. This will lower the usage costs of the shared EVs and is expected to make them cheaper for driving compared to the expenses related to ownership.

All the measures are expected to have a strong ecological effect.

8 Conclusions

The HEVs and PHEVs with smaller batteries are the only economically viable solutions of the transport pollution problems today and their usage should be stimulated instead of limited. They can help for the solution of the rising ecological problems and those related to rising energy prices now. This is not expected to change in the next 10 years although there are some new breakthroughs in the battery technology.

Today, the BEVs are not economically viable and possess many drawbacks, mainly due to their big batteries. They will become cleaner and viable alternative only when the energy production shifts to predominantly renewable sources, when enough energy could be produced and distributed, when longer lasting batteries are designed and when a good charging network is created. Due to the rising world conflicts and tensions, it is expected energy prices to rise and energy production processes temporarily to regress towards conventional energy sources. This means that in the near future the BEVs may not become neither affordable nor cleaner solution. Their only advantage today is that they could lower the local air and noise pollution in urban areas. A study concludes that from the local point of view the electric vehicles can contribute to reduction of CO concentration in densely populated areas. However, from the global point of view, using the electric vehicles does not weigh in on slowing down the global warming [25].

The conclusion is that the HEVs, PHEVs and BEVs ownership and usage should be equally stimulated. Low emission city zones could be created, but HEVs, PHEVs and BEVs should have equal access to them, or a convenient green public transport system must be created together with the cheap enough short term BEV rental services. There are many solutions to the ecological and energy problems and all the decisions in this regard should be well balanced and should be based on what is possible and appropriate today.

Further country-based research is needed on the actual local pollution and competitiveness of the BEVs, depending on their energy mix. In terms of public transport, a local comparison of the pollution and competitiveness of electric trains, trams, buses and trolleybuses is also needed. There are still shortcomings in the control of electric vehicles and further research and improvements are needed in this regard. Battery technology is evolving rapidly and a continuous search for less flammable batteries with longer calendar and cycle lives is needed. For example, the Lithium Nickel Manganese Cobalt Oxide batteries are widely used in EVs today because of their high specific energy, but they are with higher flammability risks too. The Lithium Iron Phosphate batteries are with close characteristics, with a little lower specific energy, but with considerably lower flammability risks and for that reason they are the safer solution today. Considering the EVs, there are many issues that need to be explored for better solutions.

Grants and funding

The author received no financial support for the research, authorship and/or publication of this article.

Conflicts of interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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ANALYSING THE GENERATIVE DESIGN OF PAYLOAD PART FOR THE 3D METAL PRINTING

Tamás Markovits[1,*], László Dániel Erőss[1], Ármin Fendrik[2]

[1]Department of Automotive Technologies, Faculty of Transportation and Vehicle Engineering, Budapest University of Technology and Economics, Budapest, Hungary
[2]Lead R&D engineer, Mould Tech Systems Ltd., Zalaegerszeg, Hungary

*E-mail of corresponding author: markovits.tamas@kjk.bme.hu

Tamás Markovits 0000-0002-3778-9792, László Dániel Erőss 0000-0003-4430-0112

Resume

Additive manufacturing provides the possibility to print complex generative designed bodies. The research deals with redesigning a payload part of a camera holder using generative design for selective laser melting. The possibility of replacing the original polymer component with a metal printed component of a greater strength and the effect of different parameters of generative design were investigated. By comparing the generative design results obtained in several phases, the goal was to find a solution that can be used to replace the previous part and become printable with 3D metal printing. The internal stress values for each case and the amount of weight reduction that can be achieved were determined.
With the results obtained, the parts were prepared for printing. It is the key aspect of the industrial application of generative optimization.

Article info

Received 27 July 2022
Accepted 26 October 2022
Online 1 December 2022

Keywords:

generative design
additive manufacturing
laser powder bed fusion
Ti6Al4V
weight reduction
stress analysis

Available online: https://doi.org/10.26552/com.C.2023.010

ISSN 1335-4205 (print version)
ISSN 2585-7878 (online version)

1 Introduction

In developing the vehicle components, processes and methods that provide a unique, targeted solution to a specific challenge are becoming more widespread. These processes also include generative design and the 3D printing technology [1]. By combining the two methods, new component solutions can be developed that did not exist before [2].

Generative design is a powerful tool for product optimization in Additive Manufacturing (AM) [3]. One of the reasons for using the topology optimization and generative design is the creation of new constructions that can be designed with less material and less weight [4]. The need for weight reduction [5] in vehicles is self-evident [6]. It is also important in the aircraft industry [7], but it may be needed in the building industry [8], in medical applications [9] as well as in many other areas [10].

Due to the rapid development, metal 3D printing technology has also appeared in component manufacturing. Applying additive manufacturing can replace previous component designs with new design solutions, which is also greatly aided by generative design [11]. One of the main application areas is the production of customized components, where complex component geometries with smaller pieces can be made with a shorter lead time [12]. The spread of advanced solutions within the vehicle industry in competitive sports started some years ago [13-14].

The research aim was to develop the methodology and a unique titan alloy component using the generative design that provides an additional competitive advantage over a specific component, with lower weight, higher safety factor and higher load capacity than the original polymer component.

2 Experiments

The component included in the investigation is a drone (or UAV) payload camera's moving bracket from polyamide (PA12) polymer of a weight of 223 g. The replacement of this component from titanium (Ti6Al4V) material was investigated by generative design in the PTC Creo 7.0.2.0. software. Figure 1 shows the original polymer model.

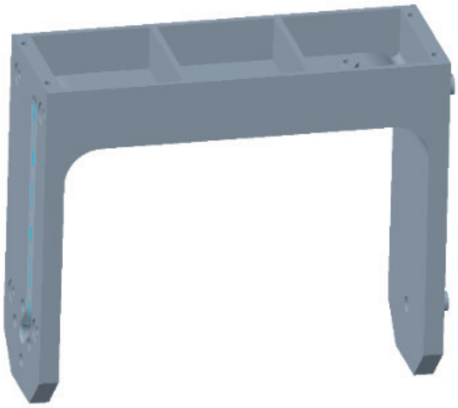
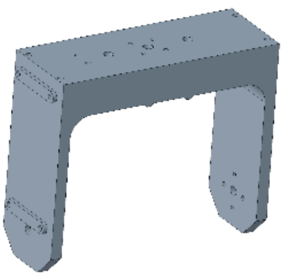
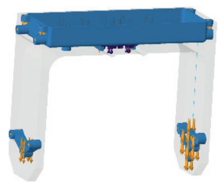
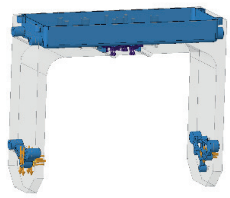
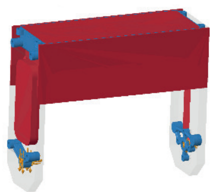


Figure 1 *The original polymer bracket part*

Table 1 *Illustration of design spaces in different phases of development*

Phase	Starting Geometry	Preserved Geometry	Excluded Geometry
A B C			
D			

The definition of a generative design study begins with modelling of the three main volumes. These are the starting geometry, the preserved geometry and the excluded geometry. The starting geometry is where the simulation can reorganize the structure. The preserved geometry contains the volumes what one would like to keep intact. It is essential to merge all the little geometry parts of the preserved geometries to bigger groups. If there were too many volumes that have a small size in the simulation, then the software would not be able to fine good solutions. In thiscase the simulation software will generate result with some separated volumes. In the Creo Generative Design application the preserved geometries must be part of the starting geometries. The excluded geometry is what the software must not use during the optimization process. The geometries used during the four development phases (A, B, C, D) are shown in Table 1. The starting geometry was the same in all the phases. The preserved and excluded geometries were the same in phases A, B and C. The preserved and the excluded geometries in phase D were modified. A lightweight preserved geometry and a much more complex excluded geometry were created to achieve the best result. This complex excluded geometry helped us to achieve the best form of the generated part with elimination of all the possible unacceptable geometries forms. The simplest possible starting geometry was produced due to authors' experience that the simpler starting geometry and the more complex excluded geometry provide the best results.

Then one must define the constraint(s) and load(s) of the part. The constraint of this part is a fixed constraint and the position of it is shown in Figure 2. In the case of this investigation only forces were used. The directions of these forces are shown in Figure 3. The magnitudes of the forces are shown in Table 2. Due to the weight of the carrier camera, a load of 100 N is expected. It is important to add some load to the separated preserved volumes. If there would be preserved volumes without load, then those volumes would not be the part of the solution. The software will leave those volumes intact and separated. However, for the simulation to create a favourable construct, more force had to be defined in the software and different values had to be applied.

After that, the definition of the case study is finished by setting the design criteria- and the fidelity

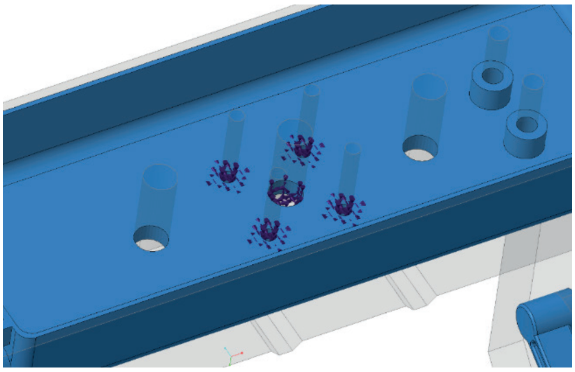


Figure 2 The constraint of the part

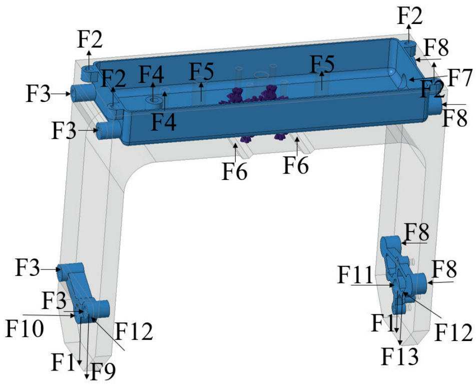


Figure 3 The applied forces

Table 2 Parameters of forces and generative simulation

Phase	F1 (N)	F2-F8 (N)	F9 (N)	F10 (N)	F11 (N)	F12 (N)	F13 (N)	Limit Volume (%)	Limit Mass (g)	Material Spreading (%)	Fide-lity (-)
A	100	1	-	-	-	-	-	30	-	80	5
B	1000	-	-	1000	1000	1000	-	19	-	90	5
C	20	-	-	20	20	-	-	18	-	80	5
D	-	-	1000	-1000	-1000	-	500	-	140	80	9

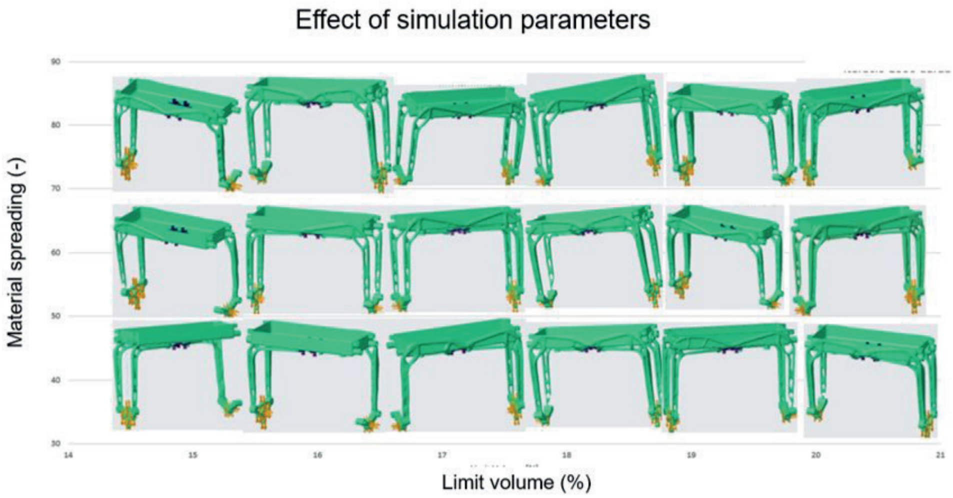


Figure 4 Effect of material spreading and limit volume parameters to the design

parameters. Those parameters can be seen in Table 2, as well. The limit volume or limit mass parameter sets the quantity of the reorganizable material. The percentage of the limit volume is related to the starting geometry. With this parameter the resulted weight can be predicted. If one wants to achieve lower weight, then one needs to decrease the lower Limit Mass value. If this parameter was too low, then the software would not be able to make an "unfinished" result. It is essential to see, that the preserved geometry mass will be a part of the Limit Volume. There is a certain point when the software is unable to make good result because there is not enough material to redistribute. The material spreading parameter sets the complexity of the result. This parameter can be set between 0 and 100. A lower material spreading value means a simpler result. The simulation with higher material spreading value will make more complex structures. To understand the relation between these two parameters different pairings were investigated. The output is the design change of the due to the simulation. This diagram can be seen in Figure 4. In this case it can be stated that higher material spreading value provide better result to us with lower limit value.

The fidelity parameter combines the element size and the iteration value. It can be set between 1 and 10. In the last phase of the development one simulation was 1000 iteration and the element size was 1.1 mm.

According to results from the previous simulation if one wants to lose as much weights as possible, one must set the higher fidelity value. The simulation with higher fidelity requires more time to finish. It is important to see that therefore we used high fidelity value only in the last phase when it was not avoidable.

After setting the simulation parameters, the simulation can be started. The data in the table contains the results of approximately 100 different test settings.

3 Results and discussion

As a result of the generative simulation, we obtained a design, stress distribution, deformation values and the mass of the formed design. The designs and stress states are illustrated in Figures 5, 6, 7 and 8. The simulation results can be sorted into four different development phases. Due to the difference in the force definition of the development phases (different directions and magnitudes), the maximum stresses to the original load were normalized to ensure the comparability of the results. The original stress results are shown in diagrams.

Development phase A results shown in the Figure 5. This was the preparation phase. There were several problems with these results. For example, the legs are too weak to resist side forces and the weight is more than the original plastic part. Other good example for the problems that the box part of the preserved geometry is missing in the stress distribution diagram, this means that it is not a part of the resulted body. The missing box also means some missing mass too. The main box part of the result geometry is thickened by the simulation. The thick wall is unnecessary and requires a lot of material. The lowest weight that could have been achieved in this phase was 297 g (without the box),and the highest stress was 9.5 MPa. It means that the structure was very over-designed because the yield strength of titanium alloy is 1000 MPa.

Development phase B is shown in Figure 6. This phase solved the leg weakness problem by redefinition of forces but did not solve the missing box problem. The magnitude of the new forces are bigger than the originals, but in this way, we could control the optimization process and significantly reduce the weights. We lose some weights with the elimination of the thick wall. The best result was 178 g (without the box) and the highest stress was 90 MPa. The maximum stress is also low, so we can decrease the limit mass further. With such parameters, further weight reduction has resulted solutions that are no longer technically acceptable, for example, 3-legged.

Development phase C is shown in Figure 7. In the third phase, the definition of the force was modified once again to further decrease the mass. This time we made simulation with smaller forces. The missing box problem was not solved in this phase. We achieved 172 g and the stresses decreased to 80 MPa. Below 172 g, the three-legged result appeared again. After that, we knew

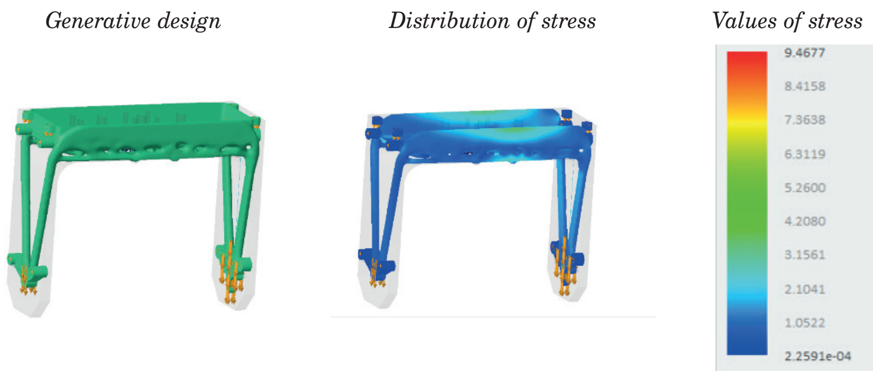


Figure 5 *Development Phase A*

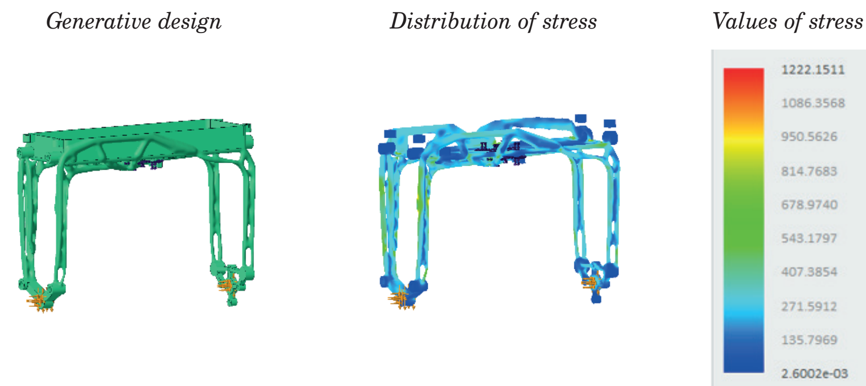


Figure 6 *Development Phase B*

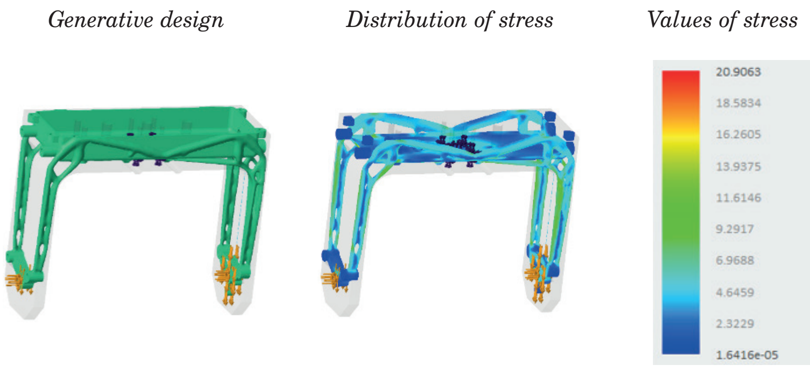


Figure 7 *Development Phase C*

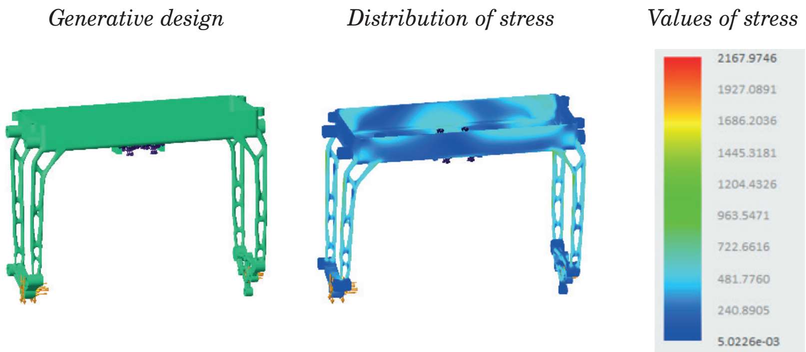


Figure 8 *Development Phase D*

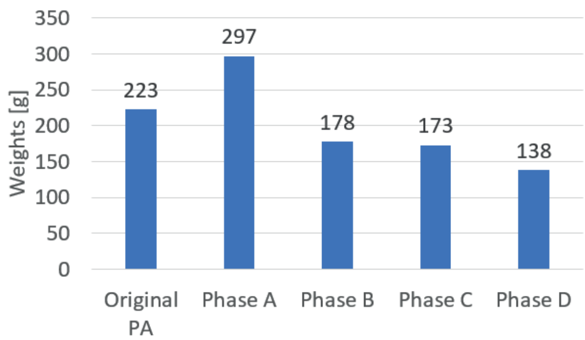


Figure 9 *Illustration of weight reduction in different development phases*

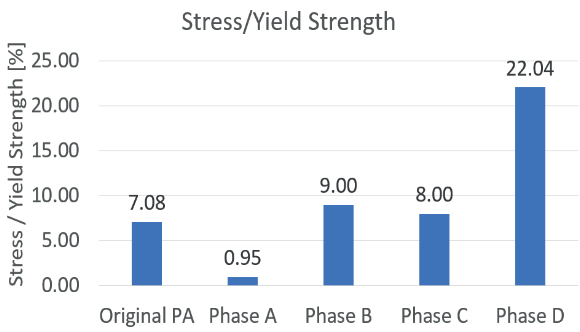


Figure 10 *Illustration of the stress rates in different development phases*

that the magnitude of the forces has a relatively small impact on results, but the direction of the force vector has a considerable impact. To avoid the three-legged according to this experience we have begun to develop the Phase D.

Development Phase D is shown in Figure 8. This phase was a long iteration phase. We constantly changed the excluded geometry, as complex as all the unnecessary structure parts have been erased. The missing box problem is finally solved. After these iterations, we achieved 138 g and the body remained a four-legged structure. We could achieve the highest stress (220 MPa), which meant that the better use of the load capacity of the material was done, but not yet entirely.

Figure 9 and Figure 10 show the component weights achieved during the different development phases (Figure 6) and the stress ratios relative to the yield point (Figure 10). In this diagram, the stress values were normalized for comparability. This was necessary because the magnitude of the applied forces was different during the simulation phases. Thus, the initial goal was partially achieved. In the current state of development, the component has 38% less weight than the initial polymer component. However, there are still large reserves due to the load capacity of the titan material, which will happen in the following development phase as we are planning.

4 Conclusions

With the investigation of the generative design possibilities, the following can be concluded:

- Generative design is a new tool for creating the complex structures for the 3D printing.
- Parameters used in generative software give very different solutions depending on the values set. The magnitude of the forces has a relatively small impact on the results, but the direction of the force vector makes a difference. Simpler starting geometry and more complex excluded geometry provide a better solution than inverting.
- It is necessary to lead the software to the desired solution. It is not yet fully automatic.
- In the case of the specific component, the polymeric material can be produced with a generically designed titanium material of a smaller weight and higher load capacity.

Acknowledgment

The project is funded by the National Research, Development and Innovation (NKFIH) Fund of Hungary. Project titles: “Development of multi-purpose fixed-wing drone based on innovative solutions and the creation of necessary competencies”. The application ID number: 2019-1.1.1-PIACI-KFI-2019-00139. The authors want to express their thanks for the financial support.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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INFLUENCE OF THE TECHNICAL CONDITION OF THE RUNNING SYSTEM OF ARTICULATED BUSES ON STABILITY OF THEIR STRAIGHT-LINE MOTION

Volodymyr Sakhno[1], Victor Polyakov[1], Igor Murovanyi[2], Oleksii Timkov[1], Liudmyla Mialkovska[2], Pavlo Popovych[3,*], Liubomyr Poberezhnyi[4]

[1]National Transport University, Kyiv, Ukraine
[2]Lutsk National Technical University, Lutsk, Ukraine
[3]West Ukrainian National University, Ternopil, Ukraine
[4]Helmut Schmidt University / University of the Federal Armed Forces, Hamburg, Germany

*E-mail of corresponding author: PPopovich@ukr.net

Volodymyr Sakhno 0000-0002-5144-7131,
Victor Polyakov 0000-0001-7042-3066,
Igor Murovanyi 0000-0002-9749-980X,
Oleksii Timkov 0000-0002-7925-7030,
Liudmyla Mialkovska 0000-0002-9044-1496,
Pavlo Popovych 0000-0001-5516-852X,
Liubomyr Poberezhnyi 0000-0001-6197-1060

Resume

Among the most important operational properties of articulated buses, ensuring their safety, it is necessary to note the course stability of traffic (CST), as often the loss of CST of a vehicle is accompanied by an accident. The parameters of the CST of a road train are closely related to the design of the running gear, in particular to the skew of the bus and trailer axles. The critical speed of rectilinear traffic was determined for different states of the articulated buses running system, which, in the absence of a bridge skew, was 32.1 m/s (116.6 km/h). The movement of the SSA is asymptotically stable. Under the action of perturbation, the stabilization time for lateral velocity is about 1 s and it increases to 2 s for the folding angle, but the amplitude of the backscatter of this angle is 10 times less than the initial perturbation, which indicates a stable asymptotic law of its change at small amplitude.

Article info

Received 10 October 2022
Accepted 10 January 2023
Online 19 January 2023

Keywords:

critical speed
lateral velocity
transition process
skew of the bridge
articulated buses

Available online: https://doi.org/10.26552/com.C.2023.019

ISSN 1335-4205 (print version)
ISSN 2585-7878 (online version)

1 Introduction

The modern development of public and freight transport leads to an increase in demand for large vehicles and city buses. This is justified by the arguments of economic savings, energy consumption conservation and pollution reduction due to the limitation of the number of vehicles and drivers needed to move a large number of goods and people. As a result, manufacturers of trucks and city buses are currently designing high-capacity structures in the form of articulated and multi-member vehicles. The use of hinged structures makes long vehicles flexible in use and allows mobility even in a chaotic (urban) environment [1]. We should also not forget about the corrosive effect of different aggressive chemical compounds on elements of vehicle metal structures, [2-6]. Improving the efficiency of modern freight and passenger trains involves increasing their movement speed and bringing the load level to the maximum.

Therefore, aims are to create the safe traffic conditions for these vehicles and improve their performance. In order to improve the situation in the field of passenger transportation, which has recently become very tense due to the increase in number of vehicles on the roads of megacities, there is an urgent need to improve it, namely - the unloading of city streets.

The appearance of new wheeled vehicles moving on specially designated lanes in large cities will be able to establish a system of passenger movement in the city district, which will primarily reduce the time of their movement from sleeping areas to the city center. This type of transport is the most promising at the moment because it carries passengers without delays during the peak and inter-peak periods. The basis of such a transport consists of two- and three-link articulated buses, the stability of which is affected by a large number of factors. Those are the design features of the layout scheme (load distribution on the axles of the bus and the towing link, the height of the center of mass, the control system, the type of supporting and coupling device and the construction of the running system). At the same time, the influence of each of the factors on the stability of the movement is ambiguous, since their operation is inextricably linked to the change in the characteristics of their structural elements, which cannot but affect the kinematic and stiffness properties of the chassis, in particular, the bus and trailer due to the skewing of their bridges, which can cause a deterioration in the traffic safety of public transport vehicles. However, the operation of articulated buses is inextricably linked with changes in the characteristics of their structural elements, which inevitably affects the kinematic and rigid properties of the chassis, in particular the bus and trailer and changes in distribution of reactions in the contact area of tires articulated buses with the road due to skew bridges, in particular. A large number of buses and articulated buses in operation have different technical conditions and, accordingly, different properties. In this case, there is a question of traffic safety of articulated buses with different technical conditions of the chassis of the bus and trailer.

It is obvious that even at the same technical condition of a running gear of the bus and the trailer at their manufacturing, after some period of operation it is possible to find out the various degree of wear of tires, elements of a suspension bracket of bridges of the bus and the trailer. It is known that the intensity of their wear is influenced by: the angles of the axle, the load on the wheel, lateral forces, tangential forces (traction and braking) and air pressure in the tires. Quantitatively, those factors are not identical for each of the axles of articulated buses. So, if there are different angles of installation of axles and various wear of a protector, it is possible to speak about the change of resistance to the lateral assignment of bridges and, as a result, parameters of maneuverability and stability of articulated buses, as a whole. The costs of maintenance and repair of the chassis are a significant part of the total cost of articulated buses, replacement of the entire set, in the case of extreme wear of one of the elements, is economically unreasonable. Therefore, a large number of articulated buses are operated with a chassis that has different technical conditions and, accordingly, different properties. In this case, there is a question about the stability and, as a consequence, the safety of the road train with the different technical conditions of the running gear.

However, the operation of articulated buses is inextricably linked with changes in the characteristics of their structural elements, which cannot but affect the kinematic and rigid properties of the chassis, including bus and trailer due to skew of their axles, which can lead to deterioration of articulated buses.

Given the fact that in Ukraine during the peak hours there is a significant overload of rolling stock, during its operation there may be deviations in the geometry of the chassis, which negatively affects the dynamics of articulated buses in different modes. Therefore, the question of taking into account the geometry of the axes of the links of articulated buses in the study of their stability is relevant.

2 Analysis of recent research

Among the most important operational properties of the road trains, including articulated buses, which ensure their safety, it is necessary to note the stability of traffic, as often the loss of stability of a vehicle is accompanied by an accident.

Maneuverability and stability of vehicles are in the focus of many researchers. Thus, in [1] a general method for modeling the kinematics of articulated vehicles, with different locations of the drive axle and different steering capabilities, is proposed. The main advantages of the method are its scalability (relative to a number of vehicle segments) and modularity, which allows direct (even automated) derivation of compact models that can be used in real time by relatively low energy computing devices.

In [6], a unified model is proposed, which includes the dynamics of rotation of any axis or articulation for any articulated bus. Comparative results by simulation prove that the approach applicable to any rotation scheme provides fairly high accuracy. In [7], is shown that the relationships between axles and between links of vehicles with several trailers can give rise to specific oscillating behavior of trailers during the vehicle maneuvers. The article shows that such oscillations are a direct consequence of properties of the vehicle kinematics, associated with the design of the traction coupling device. On the example of one pair of vehicle components, the patterns of its rotation are recognized, which then apply to a road train with any number of trailers. Numerical results, obtained for the kinematics of three uniaxial trailers, confirm the theoretical considerations that give a certain quantitative view of the problem.

In [8], a single-track dynamic model of articulated buses with a number of assumptions is considered, in particular, that the transverse accelerated front of the body and the angles of rotation of the steered wheels are insignificant. The kinematics and dynamics of articulated buses are considered in detail. The simulation results are functions of kinematic and dynamic parameters that allow determining the parameters of maneuverability and stability. In [9], a multivariate extension of the D2-IBC (Data-Driven - Inversion Based Control) method for determining the traffic parameters was considered and its application to control the stability of road trains was discussed in detail.

The equations of vertical and lateral dynamics of a road vehicle with 6 degrees of freedom are considered in [10], reduced to a matrix form. The motion of such a tool in the vertical and lateral planes is studied. It is shown that the developed method can be applied to analysis of the stability of the movement, in particular passenger trains. In [11], a simplified analysis of the maneuverability and stability of combinations of vehicles, such as a tractor in combination with one or two semi-trailers or a truck and a complete trailer. Car combinations are considered as linear dynamic systems with two degrees of freedom for each unit. The equations of motion are derived taking into account the effect of braking and acceleration and the characteristic equation for motion with constant speed is obtained. To improve stability, a new design of the saddle device for stabilization of the tractor-semi-trailer combinations is presented.

In [12], three-dimensional dynamic models of a car and a trailer were developed, based on which a dynamic model of a train was built. Based on the first-order approximation theory of ordinary differential equations and Hopf's bifurcation theory, the linear and nonlinear stability of each element and the road train as a whole, in rectilinear motion are studied. Numerical results show that for the nonlinear and linear models, the critical velocities differ little. At the same time, the costs of purchasing bridges and suspensions for articulated buses manufacturers are the highest, due to the fact that they mostly use air suspension with integrated longitudinal jet rods and a bridge beam.

From the above analysis of the approach to determining the parameters of maneuverability and stability of articulated buses, it follows that in each case it is necessary to develop a model that would meet the objectives of the study.

The technical condition of the trailer composition of road trains is influenced by a large number of factors, the degree of influence of which on different systems and components is not the same. The selection of the most significant factors, from the total number of defects and failures of components and parts, can be obtained using the mathematical and statistical method of expert evaluation (a priori ranking) [13]. According to this method, the least reliable components and systems are platform, drawbar, swivel and main frames and the brake system. These systems have the highest number of failures and damage to parts.

It is established that the suspension of the road train has the highest probability of failure. The skew of the bridges leads to uneven wear of the tire tread and in cases of difficult road conditions - a violation of controllability, stability of road trains. The main indicator of stability of movement is the critical speed V_{cr}.

In [13-15] a complex method of choosing the parameters of a road train was developed, based on mathematical models of its rectilinear and controlled motion, taking into account the angles of installation of the axles of a tractor and a semi-trailer. It is shown that the movement of a road train, consisting of a two-axle tractor and a three-axle semi-trailer, without the skew axles, is asymptotically stable. Increasing the skew of any axle of the semi-trailer and the second axle of the tractor in one direction or another leads to a decrease in the critical speed of the road train. The skew of the rear axle of the semi-trailer has the most significant effect. In this case, any combination of skew bridges causes a deterioration in the stability of rectilinear motion, due to fluctuations in the trailer link.

This technique can be applied to analysis of the stability of articulated buses.

The aim of the work is to study the influence of articulated bridges of articulated buses on their stability.

3 The results of the study

In the theory of the controlled movement of a road train, the following basic assumptions are considered to be quite justified in modeling [13]:

- the road train moves on a flat horizontal surface;
- unsprang mass is considered to be non-rolling;
- the controlling influence on the traffic parameters of the road train is carried out through the driven wheels of the traction vehicle, therefore the steering dynamics are not taken into account;
- the presence of gaps in the traction coupling device is not taken into account;
- the longitudinal speed of the road train is constant;
- the distance between the links of the road train does not change due to the smallness of the assembly angles;
- the constituent elements of the road train are absolutely solid bodies;
- the load on the road train is located so that the centers of mass of the towing vehicle and the trailer, as well as the traction-coupling device connecting them, are located in the vertical plane of symmetry of the link;
- the trajectory of the center of mass of the tractor is taken as the main trajectory;
- the interaction of the wheels with the supporting surface is expressed through the reaction of the road surface.

Since the stability of the road train in rectilinear motion is being considered, where the change in the normal reactions of the road bed to the wheels of one axis can be neglected, the plane-parallel movement of its links can be spread out when composing the cocks of the road train.

In [14], a system of equations describing the plane-parallel motion of an articulated bus was obtained. This system is written as:

- for the bus

$$\begin{aligned}
&m_1(\dot{v}_1 - \omega_1 v_1) = -X_1\cos\theta_1 - X_{1r}\cos\theta_{1r} - Y_1\sin\theta_1 - Y_{1r}\sin\theta_{1r} + (X_2 + X_{2r})\cos\psi_2 + (Y_2 + Y_{2r})\sin\psi_2 + X_S;\\
&m_1(\dot{u}_1 - \omega_1 v_1) = -X_1\sin\theta_1 - X_{1r}\sin\theta_{1r} + Y_1\cos\theta_1 + Y_{1r}\cos\theta_{1r} - (X_2 + X_{2r})\sin\psi_2 + (Y_2 + Y_{2r})\cos\psi_2 + Y_S;\\
&I_1\dot{\omega}_1 = (-X_1\sin\theta_1 + Y_1\cos\theta_1)(a_1 - \varepsilon\cos\theta_1) - (X_{1r}\cos\theta_{1r} - Y_{1r}\sin\theta_{1r})(a_1 + \varepsilon\cos\theta_1) +\\
&+(X_1\cos\theta_1 + Y_1\sin\theta_1)(h_1 + \varepsilon\cos\theta_1) - (X_{1r}\cos\theta_{1r} + Y_{1r}\sin\theta_{1r})(h_1 + \varepsilon\cos\theta_{1r}) -\\
&-X_2(h_2 - b_1\sin\psi_2) + X_{2r}(h_2 + b_1\sin\psi_2) - (Y_2 + Y_{2r})b_1\cos\psi_2 + Y_S(b_1 - c_1)a.
\end{aligned} \tag{1}$$

- for the trailer

$$\begin{aligned}
&m_2(\dot{v}_2 - \omega_2 u_2) = -(X_3 + X_{3r})\cos\psi_3 + (Y_3 + Y_{3r})\sin\psi_3 - X_S\cos\phi_1 - Y_S\sin\phi_1;\\
&m_2(\dot{u}_2 + \omega_2 v_2) = (X_3 + X_{3r})\sin\psi_3 + (Y_3 + Y_{3r})\cos\psi_3 - X_S\sin\phi_1 - Y_S\cos\phi_1;\\
&I_2\dot{\omega}_2 = (-X_S\sin\phi_1 + Y_S\cos\phi_1)a_2 + X_3(h_3 - b_2\sin\psi_3) - X_{3r}(h_3 + b_2\sin\psi_3) - (Y_3 + Y_{3r})b_2\cos\psi_3.
\end{aligned} \tag{2}$$

$$Y = \frac{k\cdot\delta}{\sqrt{1 + \left(\frac{k\cdot\delta}{\varphi\cdot G_\kappa}\right)}}, \tag{3}$$

where:

k - the coefficient of lateral deviation due to the tangent of the angle of inclination of the linear part of the curves;
φ - coefficient of adhesion between the tire and the support surface;
G_κ -the normal load on the wheel, N.

In the systems of Equations (1) and (2) the following notations are accepted: m_1, I_1; m_2, I_2 - respectively, the mass and central moments of inertia of individual modules are articulated buses; v_1, u_1 - longitudinal and lateral projection of the velocity of the center of mass of the i-th link on the axis of the movable coordinate system, invariably connected to the modules of articulated buses; ω_1 - angular velocity of the link; φ_1 - the angle of assembly of the road train; ψ_1 - skew angle i - axles articulated buses; X_i, X_{ir}, - longitudinal reactions of the road surface on the wheels i - their axles are defined as rolling resistance forces; Y_i, Y_{ir} - lateral reactions of the road surface on the wheels i - their axes are determined according to Rokar's axilmatics; i = 1,.., 3 - indices that belong to each of the axles of the road train; r - index indicating the starboard side of the links of the road train; a_1, b_1 - the distance from the center of mass of the bus to the front and rear axles, respectively; a_2, b_2 - the distance from the center of mass of the trailer to the point of coupling and the axis of the trailer, respectively; h_1 - the distance from the longitudinal axis of the bus to the axis of the pin; h_2 - the distance from the longitudinal axis of the bus to the axis of the rear wheel; h_3 - the distance from the longitudinal axis of the trailer to the axis of the wheel; ε - the distance from the axis of the pin to the axis of the front wheel; c_1 - distance from the center of mass of the bus to the coupling point with the trailer.

To solve the problem of stability of rectilinear motion of a road train it is necessary to make a system of equations of its perturbed motion. This system allows to determine the reactions of the links of the road train in a single disturbance (a sharp turn of the steering wheel of the tractor), as well as the critical speed of the road train. The theory of stability of motion of wheeled machines is based on the mathematical apparatus of research of differential equations developed by A.M. Lyapunov [13]. Steady motion, according to Lyapunov, is realized in a previously unknown region of initial perturbations, which is called the region of attraction of undisturbed motion. There is a problem of defining the boundaries of this area. The critical speed (CS) V_{cr} will be the speed at which at least one of the links of the road train loses stability. Stability means the ability of the road train to keep within the specified limits, regardless of speed and external forces, direction and orientation of the longitudinal and vertical axes in the absence of control effects from the driver [13, 15].

The system of equations of motion of a road train allows solutions $u_1 = 0$, $\omega_1 = 0$, $\omega_1 = 0$, ($\theta_1 = \theta_{1r} = 0$), which on the plane of the road corresponds to the movement of all points of the road train with speed v along the line θ = *const*.

The stability of the stationary solution $v_1^*, u_1^*, \omega_1^*, \varphi_1^*$ (in the case of rectilinear undisturbed motion, all these values, except for v, are equal to zero) is investigated next. At a constant speed of movement (v = const) and the linearity of the lateral removal forces, which are determined by the dependence of I. Rokar [4] Equation (3).

Let us investigate the stability of a stationary solution $v_1^*, u_1^*, \omega_1^*, \varphi_1^*$ (in the case of rectilinear undisturbed motion, all these values, except v, are zero). At a constant speed (v = *const)* and the linearity of the lateral deflection forces, determined by the dependence Rokar's $Y_i = k_i\delta_i$ [13], taking Equation (3) into account, one obtains:

$$
\begin{aligned}
&(m_1+m_2)\dot{u}+\dot{\omega}_1 m_2(b_1-c_1)+m_2a_2\big[(\dot{\omega}_1+\ddot{\phi}_1)\dot{\omega}_0-v_1\omega_1\big]=k_1\delta_1+k_1\delta_{1r}-m_1v_1\omega_1-\\
&-(X_2+X_{2r})\sin\psi_2+(k_2\delta_2+k_2\delta_{2r})\cos\psi_2+(X_3+X_{3r})\sin\psi_3+(k_3\delta_3+k_3\delta_{3r})\cos\psi_3;\\
&m_2\big[(\dot{u}-\dot{\omega}_1)(b_1-c_1)-a_2(\dot{\omega}_1-\ddot{\phi}_1)+v_1\omega_1\big]=I_1\dot{\omega}_1-(k_1\delta_1+k_1\delta_{1r})a_1-(X_1+X_{1r})(h_1+\varepsilon)+\\
&+X_2(h_2-b_1\sin\psi_2)-X_{2r}(h_2+b_1\sin\psi_2)+(k_2\delta_2+k_2\delta_{2r})b_1\cos\psi_2+X_3(h_3-b_3\sin\psi_3)+\\
&+X_{3r}(h_3+b_3\sin\psi_3)\cos\psi_3+(k_3\delta_3+k_3\delta_{3r})\sin\psi_3;\\
&I_2(\dot{\omega}_1+\ddot{\phi}_1)-m_2a_2[\dot{u}+\dot{\omega}_1(b_1-c_1)]-a_2(\dot{\omega}_1+\ddot{\phi}_1)+v_1\omega_1]=-(X_3+X_{3r})b_3\sin\psi_3X_3-\\
&-(k_3\delta_3+k_3\delta_{3r})b_3\cos\psi_3+X_3(h_3-b_3\sin\psi_3)-X_{3r}\sin\psi_3(h_3+b_3\sin\psi_3).
\end{aligned}
\tag{4}
$$

After solving these equations concerning the higher orderderivatives, one obtains:

$$
\dot{u}_1=-\frac{\begin{array}{c}m_2B0-m_2(b_1-c)+A0m_2C^2I_1+\\+m_2I_2a_2^2A0+A0+A0I_1I_2\end{array}}{m_2C^2m_1I_1+m_2I_2B^2m+m_2I_1I_2+m_1I_1I_2}, \tag{5}
$$

$$
\dot{\omega}_1=-\frac{\begin{array}{c}m_1m_2(b_1-c)B0+m_2I_2B0+\\+m_2I_2A0+I_1m_1B0\end{array}}{m_2C^2m_1I_1+m_2I_2B^2m_1+m_2I_1I_2+m_1I_1I_2}, \tag{6}
$$

$$
\ddot{\varphi}_1=-\frac{\begin{array}{c}m_2(b_1-c)m_1B0+m_2B^2m_1C0+\\+m_2C^2m_1B0+I_2m_2B0\end{array}}{m_2C^2m_1I_1+m_2I_2B^2m_1+m_2I_1I_2+m_1I_1I_2}, \tag{7}
$$

where:

$$
\begin{aligned}
&A0=2\Big(\frac{A2}{v_1}+(m_1+m_2)v_1\Big)\omega_1+\frac{A1u}{v_1}+A3\varphi_1-\\
&-\frac{A4\dot{\varphi}_1}{v_1};\\
&B0=2\Big(\frac{B2}{v_1}+(B+2C)v_1\Big)\omega_1+\frac{B1u_1}{v_1}+B3\varphi_1+\\
&+\frac{B4\dot{\varphi}_1}{v_1};\\
&C0\Big(m_2v_1C+\frac{C2}{v_1}\Big)\omega_1+\frac{C1u_1}{v_1}+C1\varphi_1+\frac{C3\dot{\varphi}_1}{v_1};\\
&A1=2(k_1+k_2+k_3);\\
&A2=2(k_1a_1-k_2b_1-k_3(B+C-c);\\
&A3=2k_3; A4=2k_3a_2;\\
&B1=2(k_1a_1-k_2b_1-k_3(a_2+B);\\
&B2=2(k_1a_1^2-k_2b_1^2+k_3(B+C-c)(B+a_2);\\
&B3=-2k_3(a_2+B); B4=-2k_3a_2(a_2+B);\\
&C1=2k_3a_2; C2=2[k_3a_2(-B-C+c);\\
&C3=2k_3a_2^2\cdot B=b+c; C=c+a_2
\end{aligned}
$$

The system of Equations (4) is reduced to the vector-matrix form:

$$
\|a_{ij}\|_1^3\cdot\begin{vmatrix}\dot{u}_1\\ \dot{\omega}_1\\ \ddot{\varphi}_1\end{vmatrix}+\|b_{ij}\|_{3,4}\cdot\begin{vmatrix}u_1\\ \omega_1\\ \varphi_1\\ \dot{\varphi}_1\end{vmatrix}=0. \tag{8}
$$

Then, for the partial solution of the system reduced to the vector-matrix form is sought, if and only if λ is the root of the characteristic equation

$$
D(\lambda)=A_0\lambda^4+A_1\lambda^3+A_2\lambda^2+A_3\lambda+A_4=0. \tag{9}
$$

Matrix of a characteristic equation, in the general form, is:

$$
\begin{aligned}
&\begin{vmatrix}a_{11}\lambda+b_{11} & a_{12}\lambda+b_{12} & a_{13}\lambda^2+b_{13}\lambda+b_{14}\\ a_{21}\lambda+b_{21} & a_{22}\lambda+b_{22} & a_{23}\lambda^2+b_{23}\lambda+b_{24}\\ a_{31}\lambda+b_{31} & a_{32}\lambda+b_{32} & a_{33}\lambda^2+b_{33}\lambda+b_{34}\end{vmatrix}=\\
&=\sum_{i=0}^{n=4}A_i\lambda^{n-i}=0,
\end{aligned}
\tag{10}
$$

where and b_{ij} - the corresponding coefficients, which depend on the geometric parameters of the road train, are obtained analytically in the program Maple 14.

According to the Rauss-Hurwitz stability criterion, a necessary but insufficient condition for stability is that all coefficients Ai be positive. The system will be stable if the determinant and its minors are positive. Analysis of the roots of the characteristic equation can characterize the state of the system.

In the general case, the following values of the roots of the characteristic equation are possible: λ is a real and a positive value - the system is unstable, the motion will be unstable; λ - real and negative value - the system eventually returns to a stable position. If the coefficient λ is a complex number, then its positive real part indicates the presence of increasing oscillations and the negative real part indicates the presence of attenuating oscillations.

Determinants of the Hurwitz characteristic Equation (9): first Δ_1 - is responsible for the presence of positive valid roots and the third Δ_3 - in the presence of a positive real part of the imaginary complex connected roots. From Equation (9) one obtains the factors on which the critical velocity depends:

$$
v_{kp}=f(m_1,m_2,a_1,c,k_1,k_2,k_3,\psi_1,\psi_2,\psi_3,\varphi). \tag{11}
$$

The uniform rectilinear motion can be analyzed by use of Equation (11), namely, to determine the value of the critical velocity of rectilinear motion of the road train and to identify the nature of the influence of factors, including the angles of the bus and trailer bridges [13].

The structure of the characteristic determinant in Equation (9) of the system in Equation (10), as well as the expressions of its coefficients a_{ij}, b_{ij} so cumbersome in an analytical form that in the following derivations, the general expressions of coefficients A_0, A_1, A_2, A_3, A_4, and the determinant Δ_3 of the characteristic equation are used Therefore, the required coefficients were calculated numerically using the computer simulation in Maple 14.

In the general case, the values of operational and design parameters of the road train, at which the determinant of the system A_4 = 0, are called critical and when $\Delta_3 = 0$ - fluttering. When considering the dynamics of the road train, taking into account the angles of the bridges, the main factor determining the stability of rectilinear traffic ν is the course speed of the vehicle.

Typical situations are:

$$A_4 = 0 \Rightarrow \nu = \nu_{cr}; A_4 > 0 \Rightarrow \nu < \nu_{cr};$$
$$A_4 < 0 \Rightarrow \nu > \nu_{cr}, \tag{12}$$

where ν - speed of the road train; ν_{cr} - critical speed of the road train;

$$\Delta_3 = 0 \Rightarrow \nu = \nu_0; \Delta_3 < 0 \Rightarrow \nu > \nu_0;$$
$$\Delta_3 > 0 \Rightarrow \nu < \nu_0, \tag{13}$$

where ν_0 - maximum speed of oscillating instability of the road train.

Since ν_{cr} and ν_0 are functions of the parameters of the road train, then in the space of these parameters of the equation $\nu = \nu_{cr}$ and $\nu = \nu_0$ determine the hypersurfaces on which the characteristic equation has one zero and a pair of complex roots.

The first equations of Equations (12) and (13) can be written as functions of the speed of the road train:

$$A_4 = f(\nu_{cr}, other\ factor)$$
$$\Delta_3 = f(\nu_0, other\ factor), \tag{14}$$

Thus, there are two characteristic values of the speed of the road train $\nu = \nu_{cr}$ i $\nu = \nu_0$, which can be obtained from Equations (14). However, their reduction to an explicit form due to the large size and number of input parameters is generally an unsolvable problem and does not allow the use of purely analytical research methods.

Those dependencies can be obtained using numerical methods of computer simulation. Since there are no explicit expressions for the solutions of Equations (14), it is necessary to find the dependences $\nu_{cr} = f(A_4)$ i $\nu_0 = f(\Delta_3)$ use the interval method [13]. This method allows to calculate any implicit dependencies. In the case of ν_{cr} and ν_0 for $A_4 = 0$ and $\Delta_3 = 0$ accordingly one has:

$$A_4 = (\nu, X_i) = 0;$$
$$\Delta_3 = (\nu, X_i) = 0; \tag{15}$$
$$i = 1 \ldots n,$$

where ν - current value of road train speed; X_i - road train parameters; n - number of parameters.

To find the critical velocity and the limiting velocity of the oscillating instability of the road train movement, one proceeds as follows, [13]. The initial velocity, at which condition in Equation (15) is satisfied, is chosen. Increasing the current speed of the road train ν from ν_{min} to ν_{max} by magnitude $\nu = (\nu_{max} - \nu_{min})/n$, in the range of ν_{min} to ν_{max} the conditions are checked at each step, $A_4 = 0$ or $\Delta_3 = 0$. If any of these conditions are not met, the current value ν is assigned to the corresponding of the extreme speeds ν_{cr} or ν_0. Thus, it is possible to obtain velocity dependences ν_{cr} and ν_0 from any of the parameters of the road train.

According to the selected layout of the road train, the critical speed is 29.8 m/s or 107.3 km/h.

As an example, Table 1 shows the values of the roots of the characteristic equation, which can determine the type of stability or instability of the road train.

As follows from Table 1, the first positive root appeared at a speed of 28 m/s, which can be considered the rate of oscillation instability and articulated buses. This speed is 6.28% less than the critical speed of rectilinear movement of the road train (v_{cs} = 29.8 m/s) and in the stability calculations, it is necessary to take this speed since when driving a vehicle in specially allocated traffic lanes (BRT system) movement at a speed of 25-30 m/s is allowed.

Figure 1 shows the effect of skew of the axle of trailer 1 and bus 2 articulated buses on the critical speed of rectilinear motion, provided that when determining the effect of skew of one of the axles, the skew of the other is absent.

Increasing the skew of any bridge in any direction reduces the critical speed of the road train. The skew of the trailer axle has the most significant effect. Thus, the skew of this bridge by 1 º reduces the critical speed of the road train by 4.6% and by 30 - by 15.2%, Further

***Table 1** The roots of the characteristic equation*

v_a, m/s	λ_1	λ_2	λ_3	λ_4
25.6	-26.15539534	-9.405998162	-1.250289683-3.017103424*I	-1.250289683 +3.017103424*I)
25.7	-23.53052177	-8.536488196	-0.6186081350-3.304419783*I	-0.6186081350 +3.304419783*I)
25.8	-21.51410109	-7.890250409	0.070258412e-1-3.454617665*I	0.070258412e-1 +3.454617665*I)
25.9	-19.91789858	-7.396702500	0.0356100428-3.531547024*I	0.0356100428 +3.531547024*I)
26.0	-18.62333016	-7.011559127	0.7068169155-3.565900596*I	0.7068169155 +3.565900596*I)

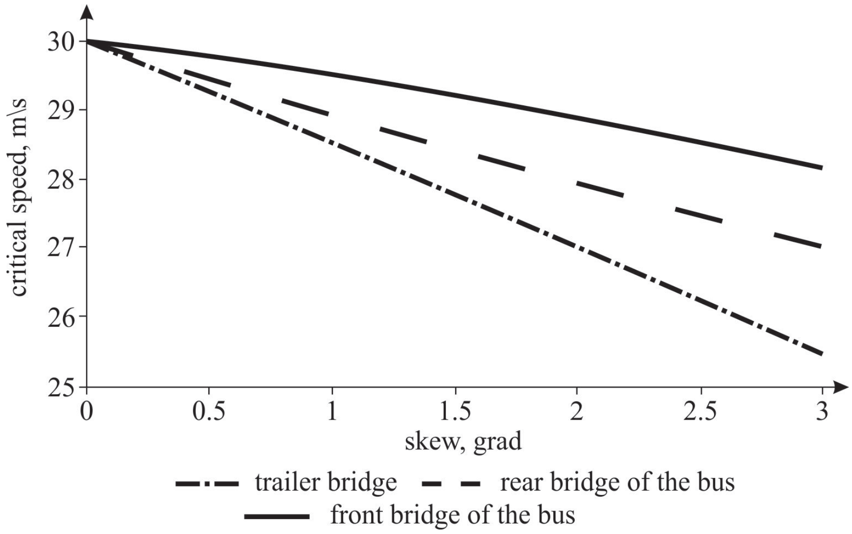


Figure 1 *Variation the critical speed of rectilinear articulated buses in terms of their bridges skew*

increase in the skew of more than 3 º leads to oscillating instability of the road train.

The combination of skew of different bridges articulated buses is a function of three variables, i.e. graphically $\nu_{cr} = f(\psi_1, \psi_2, \psi_3)$, impossible to represent.

The change in the critical speed of rectilinear motion, as a result of the simultaneous skew of different bridges, is considered only for typical schemes of bridge installation articulated buses, separate for articulated buses without skew axles, with an one-sided skew of all the axles and multi-sided skew of the bus and trailer drive axle, using the phase portrait method. For these bridge skew variants, the critical velocity was:

- in the absence of skew of the axles - 32.12 m \ s;
- for the one-sided skew of the bridges -25.61 m/s;
- for the one-sided skew of the rear axle of the bus and trailer - 26.95 m/s.

The method of phase portraits has long been used in mathematics and mechanics to analyze the behavior of systems described by systems of differential equations that have no analytical solution. Phase portrait is a graphical representation of ratios of the system state parameters that vary with time. Each point of the phase portrait (point of phase space) characterizes the state of the system at a particular time and the movement of the point along the line of the graph (phase trajectory) characterizes the change in the state of the system over time.

For analysis of the articulated buses movement stability, taking into account the skew of the bridges, phase portraits of lateral speed from the time are of interest $[t, u_1(t)]$, angular velocity from time to time $[t, \omega_1(t)]$, folding angle from time to time $[t, \varphi_1(t)]$, folding angle speed $[\varphi_1(t), \dot{\varphi}_1(t)]$, coordinates x and y of the center of mass of the bus from time to time $[x(t), y(t)]$.

Among the considered portraits the most informative are the portraits of the lateral velocity of the folding angle.

In the absence of skew of the road train bridges, it is established that the nature of the flow of both phase variable parameters of the road train is asymptotic. Figure 2 shows the dependences of phase variables on time at a speed of 32 m/s

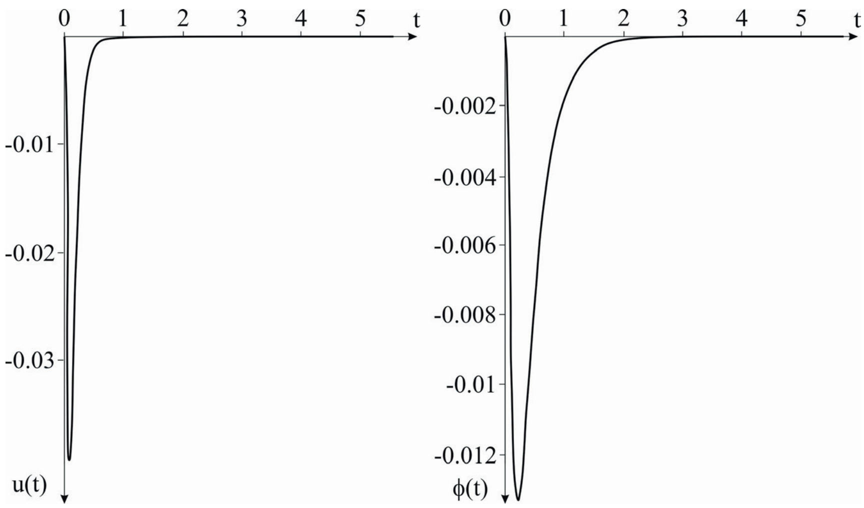
The results of the research have shown that the movement of articulated buses: without skew bridges is asymptotically stable. For the lateral velocity, the stabilization time is about 1 s, however, for the folding angle increases to 2 s, but the amplitude of the feedback is 10 times smaller than the initial perturbation (Figure 2b). The lateral displacement is initially about 5 cm per 12.5 m of the distance traveled, which is then eliminated.

Consider the three main options for skew bridges of road trains. The results for each option are presented in Figures 3 - 4. The sequence of drawings corresponds to the variant of skew of axles of articulated buses:

a) skew of the leading bridge of the bus,
b) unilateral skew of the leading bridge of the bus and the bridge of the trailer,
c) versatile skew axles of the semi-trailer.

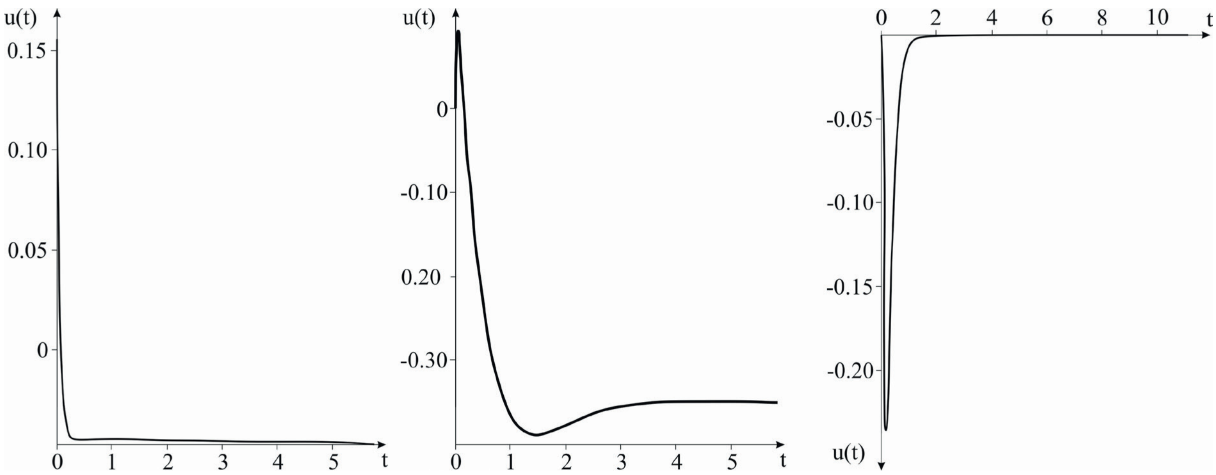
The motion parameters of articulated buses largely depend on their speed. If there is a skew of the leading axis of the bus, the critical speed of rectilinear motion is reduced to 30.2 m/s (without skew - 32.12 m/s). In addition, even at the correct angles of the bridges articulated buses there is a small lateral speed of the center of mass of the bus (Figure 3a). As a result, the driver must take corrective action by turning the steering wheel to the side by the amount of skew. Depending on the speed of movement, appearance of oscillating instability of the bus and, as a consequence, the occurrence of oscillations of the trailer link.

The results of the articulated buses, with a one-sided skew of the bridges, stability study are shown in Figure 4b. The critical speed for this mode is 25.61 m/s. There are modes of steady motion and oscillatory steady with a stabilization time of 2 s and unstable. When moving to critical speed, with a one-sided skew of axles



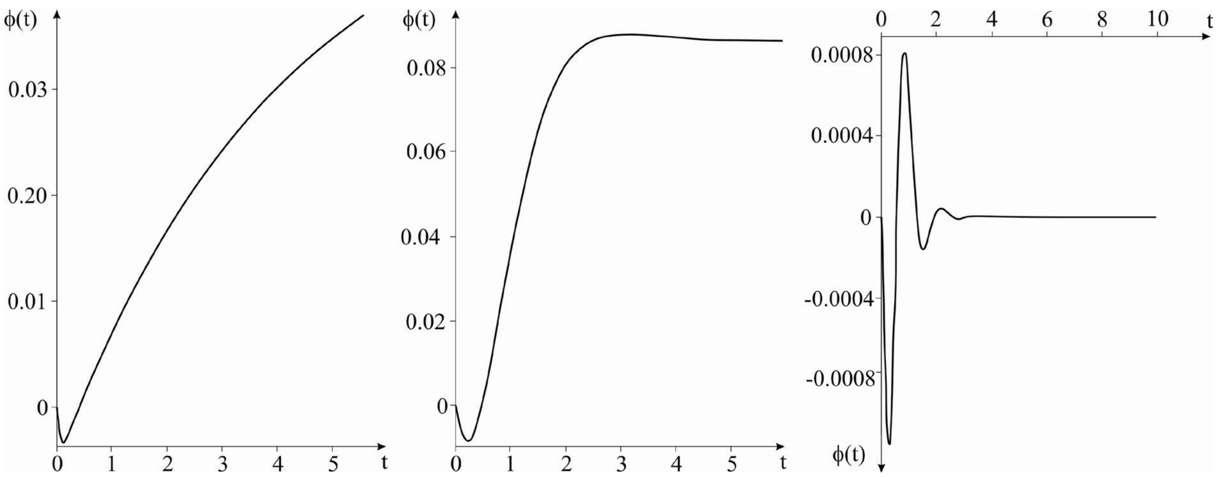
a) b)

Figure 2 *Variation of the lateral velocity a) and folding angle b) during the transition process, ν =32 m/s*



a) b) c)

Figure 3 *Variation of the lateral velocity during the transition process: a) ν =30.2 m/s, b) υ=25.61 m/s, c) ν =26.95 m/s*



a) b) c)

Figure 4 *Variation of the angle of addition during the transition process:*
a) ν =30,2 m/s, b) ν =25.61 m/s, c) ν =26.95 m/s

articulated buses there is a lateral speed of the center of mass of the bus, which exceeds the lateral speed for 4 times, in the case of a skew of the driving axle of the bus only (phase portrait of the folding angle in Figure 4b). When the maximum speed of the movement is = 25.61 m/s, the articulated buses become unstable. The trajectory of the center of mass of the bus with increasing speed is first slightly distorted, then there is movement at a significant angle to the initial direction and with further increase in speed, there is a loss of stability.

As in the case of skew of the bus drive axle, this type of skew can be overcome if the driver makes corrective actions with the steering wheel, but given the length of articulated buses, this will significantly increase its overall lane. Due to the divergence of the direction of movement of the axles, articulated buses on the plane of rolling of the wheels will have the lateral forces, which will lead to increased wear of the suspension elements and tire tread.

Results of the articulated buses, with a versatile skew of the bridges, stability study, are shown in Figure 4c. The critical speed for this case is 26.95 m/s. The zone of oscillating steady motion expands, the stabilization time increases to 3.5 to 4 s, which is quite long. In this case, the corrective actions of the driver may be to blame for the appearance of undamped oscillations, due to the long stabilization time of the system. The amplitude of oscillations exceeds the initial perturbation on the system by 1.7 to 2.5 times. The frequency of oscillations of phase variables increases to 1.5 to 3 Hz. (Figure 4 c). Phase portraits and the trajectory of the center of mass indicate an oscillating steady motion with damped oscillations, but with a large transition period.

Due to the misalignment of the axles of the semi-trailer, there is a force that forms the moment of rotation of the semi-trailer relative to its center of mass. As a result, the rolling resistance of the semi-trailer wheels increases, the wear of the tires and the wear of the suspension elements increase. All these indicate the need for periodic control of the angles of installation of articulated buses.

4 Conclusions

The critical speed of the rectilinear articulated bus has been determined, which in the absence of skew of its bridges was 32.1 m/s (116.6 km/h). In the case of skew of the leading axis of the bus, the critical speed of rectilinear movement decreases to 29.95 m/s. Increasing the skew of any bridge articulated buses, in one or the other direction, reduces the critical speed of the road train. The skew of the trailer axle has the most significant effect. Thus, increasing the skew of the trailer bridge by 1º reduces articulated buses; road trains by 4.6% and by 30 - by 15.2%. Further increase in skew over 3º leads to oscillating instability of articulated buses. It is shown that the movement of articulated buses; without skew bridges is asymptotic stable. Under the action of perturbation, the stabilization time for the lateral velocity is about 1 s and increases to 2 s for the folding angle, but the amplitude of the backscatter of this angle is 10 times smaller than the initial perturbation, which indicates a stable asymptotic law of its change at a small amplitude. The lateral displacement of the trailer is about 5 cm per 12.5 m of the distance traveled (part of a degree), which is then eliminated. This indicates the need to regularly check the angles of installation of bridges articulated buses.

Grants and funding

The authors received no financial support for the research, authorship and/or publication of this article.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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KOMUNIKÁCIE
COMMUNICATIONS

VEDECKÉ LISTY ŽILINSKEJ UNIVERZITY
SCIENTIFIC LETTERS OF THE UNIVERSITY OF ZILINA

ISSN (print version): 1335-4205

ISSN (online version): 2585-7878

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VEHICLE CABIN NOISE CANCELLATION MODEL USING PRE-FILTER FOR IMPROVED CONVERGENCE RATE AND BETTER STABILITY

Janak Kapoor[1,*], Ajita Pathak[1], Manish Rai[2], G. R Mishra[3]

[1]Department of Electronics and Communication Engineering, Amity University, Lucknow, India
[2]Electronics and Communication Engineering Department, FET MJP Rohilkhand University, Bareilly, India
[3]Physics and Electronics Department, Dr. RML Avadh University, Ayodhya, India

*E-mail of corresponding author: Janak_kapoor@rediffmail.com

Janak Kapoor 0000-0002-3726-4734,
Manish Rai 0000-0003-4220-6368,
Ajita Pathak 0000-0001-7294-4236,
G. R Mishra 0000-0003-1211-3558

Resume

Adaptive algorithms are used in updating the filter coefficients for active noise cancellation applications in reduction of vehicle cabin noise. The performance of the adaptive algorithms in low-frequency noise cancellation depends on how efficiently it alters the filter coefficient to minimize the difference between the approximated signal and the original one. Here is proposed an active noise cancellation model, using the low pass fixed coefficient filter before the adaptive filter, in order to improve the performance of the adaptive algorithm. Convergence rate, SNR and error vector magnitude are analysed for of adaptive algorithm in support of our research results.

Article info

Received 17 March 2022
Accepted 11 October 2022
Online 9 November 2022

Keywords:

active noise cancellation
adaptive algorithms
adaptive filtering
noise signal
convergence rate
SNR

Available online: https://doi.org/10.26552/com.C.2023.003

ISSN 1335-4205 (print version)
ISSN 2585-7878 (online version)

1 Introduction

Cabin noise in a moving vehicle is quite disturbing for the driver and co-passengers, long term exposure to this noise may increase stress level of the driver, increase fatigue and thus may lead to accidents. Conventional passive noise control techniques involve use of heavier insulating material for the low frequency noise reduction in cabin. This approach increases the overall cabin weight, thus resulting in decreased fuel efficiency [1]. Digital signal processing finds a solution to this problem by active noise cancellation techniques. Active noise cancellation methods use adaptive filters to estimate the noise and cancel it. Adaptive filters are based on algorithms, which are a set of mathematical formulations used to update the co-efficient of adaptive filters according to the variation of the input noise signal so that the adaptive filter approximates the noise signal. This approximated noise signal cancels the noise from original signal through destructive interference. The property of the adaptive algorithm to adapt with the time-varying input signal also finds application in echo cancellers, linear predictive coding, active noise cancellation systems for communication, creating spatial silence zones etc. Many algorithms, such as least mean square (LMS), recursive least mean square (RLS), filtered-x least mean square (FXLMS), normalized least mean square (NLMS) have been developed for optimizing the adaptive filter coefficients so that it may efficiently predict the variation in incoming noise. Major challenges involved in application of active noise cancellation system to vehicle cabin includes sensitivity of vehicles to the low acoustic excitation resulting from the low frequency vibrations caused by road surface [2]. Acoustics inside vehicle cabin depends on multiple noise factors, such as vehicle engine noise, outside traffic, wind flow, acceleration and inside sound of vehicle audio system, passenger noise etc. [3]. Impulsive noise produced inside vehicle cabin due to road bumps is of non-Gaussian nature, thus poses a major challenge

Table 1 *Notations*

Notation used	Description
n	Present time index
$s[n]$	Audio signal
$r[n]$	Noise signal
$w[n]$	Filter weights
$e[n]$	Difference between estimated signal and desired signal
$x[n]$	Input signal sample vector
$g[n]$	Gain vector
$d[n]$	Desired signal response
α	Leakage factor (0 to 1)
$s[n]$	Covariance matrix
μ	Step size
$Q[n]$	Filtered output
γ^{-1}	Exponential weighting factor
ϵ	Small positive constant

for active noise cancellation system [4]. Acoustic field complexity inside the vehicle geometry, convergence rate, stability, non-causality, inadequate spatial coverage, reflections, absorptions and high implementation cost often hinders the application of active noise cancellation system in the vehicle cabin [5]. A lot of research has been done in adaptive filtering, but the stated challenges are still the deciding factor in the implementation of adaptive filter design techniques to reduce the noise in moving vehicles. Many noise cancellation models using different adaptive algorithms, that are published in the literature have been tested to achieve higher stability, higher convergence rate and more accurate prediction, as well as cancellation. Cheer et al. [6] investigated the application of feedback controllers in attenuation of cabin noise in moving vehicles. Chen et al. [7] proposed the use of integrated loudspeakers in cancelling the noise field within area around the front seat passenger in a car cabin. An active head rest system model for reducing the road noise around passenger's ear in the vehicle cabin have been discussed by Jung et al. [8]. A comparative study of performance of different active noise cancellation algorithms have been done in [9] and an optimised weight filtered-x LMS algorithm for noise cancellation have been proposed for moving vehicles. This paper presents a noise cancellation model with a fixed coefficient pre-filter. Performance of the proposed model is analyzed by applying four different algorithms namely the least mean square (LMS), normalized least mean square (NLMS), sign-error least mean square (SELMS) and sign-sign least mean square (SSLMS) for the same input noise signal [10]. Higher computational complexity, convergence speed and poor numerical properties are the main factors associated with adaptive algorithms [11]. Martin et al. [12] proposed an inverter structure to reduce the computational load in the active noise control. Chiou et al. [13] presents a noise cancellation model to split the error signal by frequency separation so that adaptive algorithm needs to adapt the filter weights for same frequency component at a time. The purpose of this research work is to propose an active noise cancellation model by analysing the shortcoming of adaptive algorithms, tested against each other so that adaptive algorithms with better stability, high convergence rate with low mathematical complexity may be designed for application of active noise cancellation techniques in vehicle cabin noise reduction. The algorithms applied for analysis are the least mean square (LMS), normalized least mean square (NLMS), sign-error least mean square (SELMS), sign-sign least mean square (SSLMS) algorithms [14-16]. The detailed analysis of the algorithms used as given is presented in the following.:

1.1 Least mean square (LMS) algorithm

This is the basic and simplest adaptive algorithm used for active noise cancellation application. It is based on the principle of estimating the filter weights to minimize the mean square error between the filter output signal and the desired signal. Table 1 describes the notations used in computation Equations (1)-(8) of adaptive algorithms.

$$x[n] = s[n] + r[n], \tag{1}$$

$$y[n] = w^T[n-1]x[n], \tag{2}$$

$$e[n] = d[n] - y[n], \tag{3}$$

$$w[n] = w[n-1]\alpha + f(e[n]x[n]\mu), \tag{4}$$

$$f(e[n]x[n]\mu) = x^*[n]\mu e[n]. \tag{5}$$

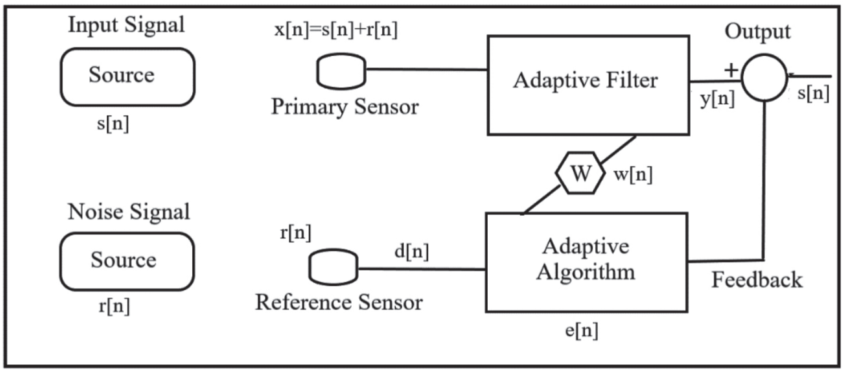

Figure 1 *Basic active noise cancellation model*

1.2 Normalised least mean (NLMS) algorithm

It is an advanced version of the LMS algorithm, it employs a variable step size as shown in:

$$f(e[n]x[n]\mu) = \mu[n]\frac{x^*[n]}{\epsilon + x^H[n]x[n]}. \tag{6}$$

1.3 Sign-error least mean square (SELMS)

It is more advanced form of LMS algorithm, it has added sign(e[n]) function for higher convergence rate, it has increased mathematical complexity with respect to the LMS algorithm as described in:

$$f(e[n]x[n]\mu) = \mu sign(e[n]x)*[n]. \tag{7}$$

1.4 Sign- sign least mean square (SSLMS)

This algorithm is also like the SELMS algorithm defined except for the two sign functions as shown in:

$$f(e[n]x[n]\mu) = \mu sign(e[n])sign(x[n]). \tag{8}$$

Figure 1 shows the basic active noise cancellation model. It consists of the input signal source, which is the primary signal or the signal of significance. The input signal is a pre-recorded 44100 Hz, 128 kbps mono audio human speech signal. The noise signal is also pre-recorded 44100 Hz, 128 kbps mono audio noise, generated by the vehicle engine. The primary sensor and reference sensors are input signal microphones for the desired audio signal and noise signal. The adaptive filter block consists of a combination of an adaptive filter and adaptive algorithm for updating the filter coefficients in response to the input noise signal. Filter weights w[n] determine the output characteristics of the adaptive filter, these filter weights also termed as filter coefficients are continuously updated by the adaptive algorithm based on the time varying noise signal, the adaptive algorithms tend to adjust filter weights in response to feedback signal until noise cancellation is achieved. Adaptive algorithm adjusts the filter weights to minimize the mean square error as defined as error vector magnitude between the desired response and the actual one [17]. In the case of multiple noise sources, the multiple channel reference signal is required for efficient active noise cancellation [18]. Variable step size adaptive algorithms are more robust, simple and offer better performance, as compared to conventional fixed step size algorithm [19]. Finite impulse response (FIR) digital filters are non-recursive, as compared to recursive nature of Infinite impulse response (IIR) digital filters; recursive IIR filters require shorter filter length [20]. Several hundred coefficients are required in cancellation of the low frequency road noise inside moving vehicle, resulting in the low convergence rate [21]. Convergence rate is thus an important factor of concern in performance of an adaptive algorithm. This paper covers all the major factors stated above and proposes a new approach of noise cancellation in the vehicle cabin aimed at achieving better cancellation without increasing algorithm complexity.

2 Proposed noise cancellation model

Simulink tool from MathWorks has been used for modelling and simulation work. Figure 2 shows the active noise cancellation model without the pre-filter. It consists of the input audio signal source, which is the primary signal as well as the signal of significance, the noise signal, an adder; noise signal is also used as a reference signal, adaptive filter and adaptive algorithm block. Figure 3 shows the proposed active noise cancellation model with an additional pre-filter block. The additional pre-filter is a direct form II, low pass IIR Butterworth filter. The filter order is 9, filter attenuation at the cut-off frequency is fixed at 3 dB, which is half the passband power. The application of the pre filter is to cut-off the undesired frequency components present in the noise corrupted signal at an earlier stage. This pre filter assists the adaptive filter in noise cancellation process. Figure 4 (a-d) shows the time domain plots of the input audio signal, noise signal, noise corrupted signal and the pre filter output signal. The reference microphone captures the noise signal,

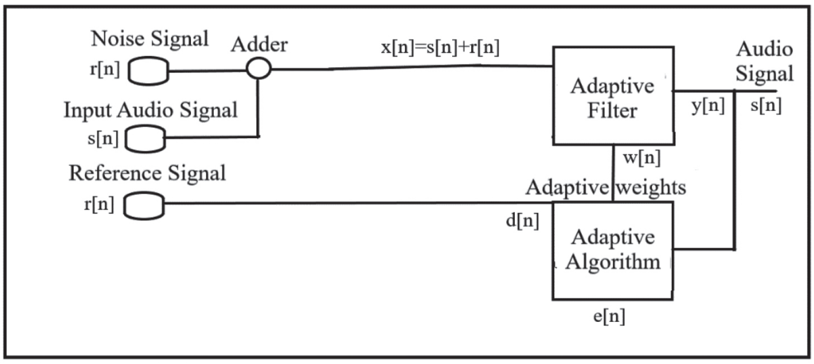

Figure 2 *Active noise cancellation model without the pre-filter*

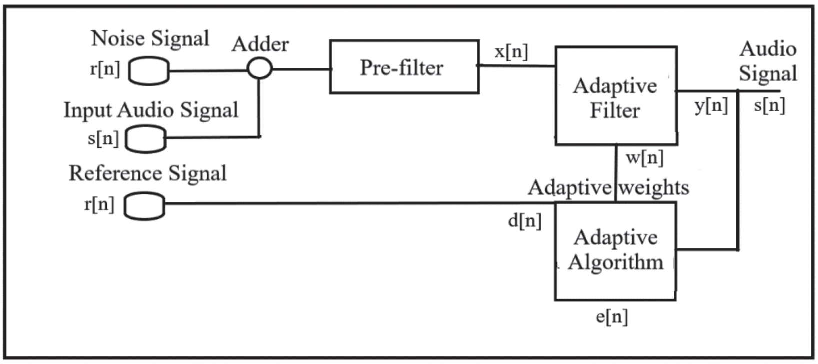

Figure 3 *Proposed Active noise cancellation model with the pre-filter*

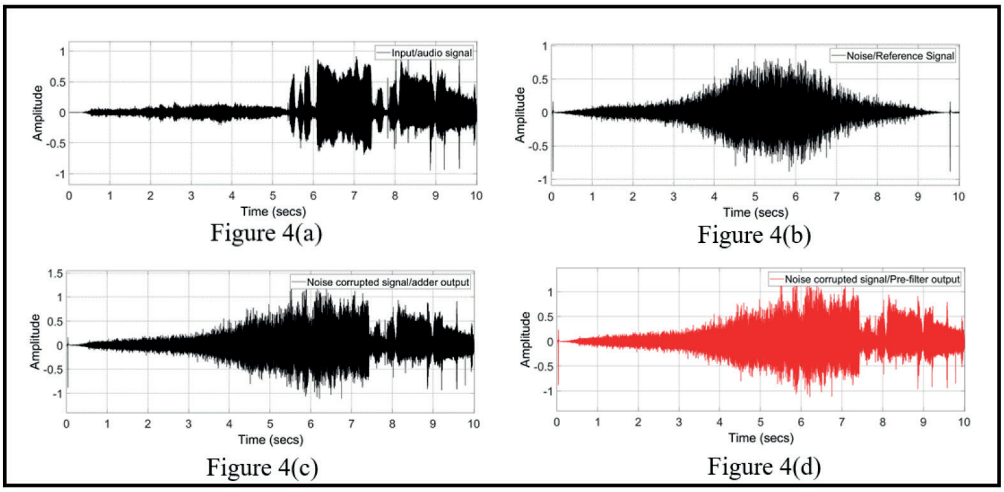

Figure 4 *Input audio signal, noise/reference signal, noise corrupted signal and the pre filter output signal*

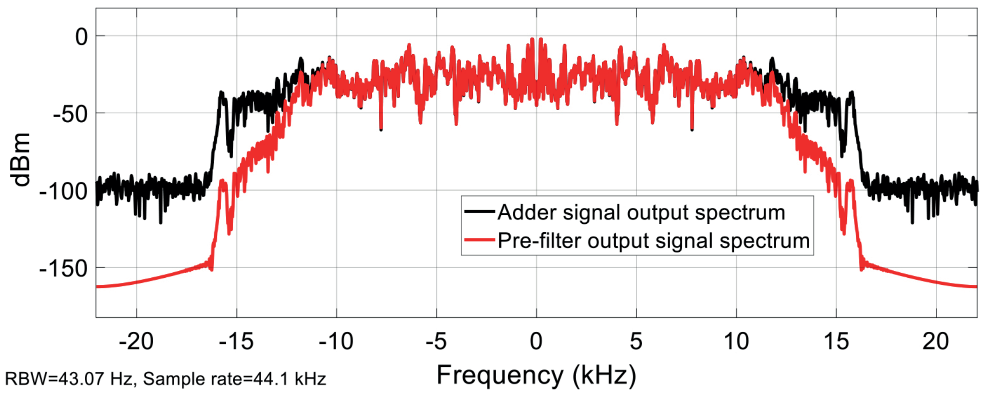

Figure 5 *Spectrogram of the noise corrupted audio signal with and without the pre filter.*

which is to be approximated and cancelled, thus, the input from the reference microphone is the same as the noise signal, denoted by r[n]. The spectrogram given in Figure 5 shows the frequency spectrum of the noise corrupted signal without pre filtering and compared with the pre filtered noise corrupted signal.

3 Results and discussion

The simulation results given in Figure 6 (a-b) show the time domain plot and frequency spectrum of the input audio signal, recovered signal using the pre filter and signal recovered without the pre filter. The effect of use of pre filter can be clearly observed in Figure 6, both in the time domain, as well as in the frequency spectrum. The recovered signal with the pre filter more closely overlaps the input audio signal both in terms of magnitude and frequency, whereas the signal recovered without using the pre filter is quite different from the desired input audio signal. Thus, it proves that the proposed model using the pre filter recovers the input audio signal from the noise corrupted signal more efficiently as compared to the conventional model. Sections 3.1- 3.4 show the effect of step size on convergence rate of adaptive filter for the Least mean square (LMS), Normalised least mean (NLMS), Sign-error least mean square (SELMS) and Sign- sign least mean square (SSLMS) algorithms. Figure 7-10 gives the array plot of magnitude of filter coefficients with respect to time. The filter coefficients amplitude varies in the range of -1 to 1 along the y-axis. The magnitude of adaptive filter coefficients tends to approach zero based on the feedback signal. The faster the filter coefficients approach zero, the higher is the convergence rate of the adaptive algorithm. The convergence rate of different algorithms is analysed for variable step size $\mu = 0.01$, $\mu = 0.001$ and $\mu = 0.00001$.

3.1 Least mean square (LMS) algorithm

The variation of filter coefficients generated by LMS algorithm with respect to time for different values of step size $\mu = 0.01$; 0.001 and $\mu=0.00001$ is given in Figure 7. It is observed that the best convergence rate and stability is achieved by LMS algorithm for step size $\mu = 0.00001$ and lowest convergence rate is obtained for the step size $\mu = 0.01$.

3.2 Normalised least mean (NLMS) algorithm

The variation of filter coefficients generated by NLMS algorithm with respect to time for different values of the step size is given in Figure 8. It is observed

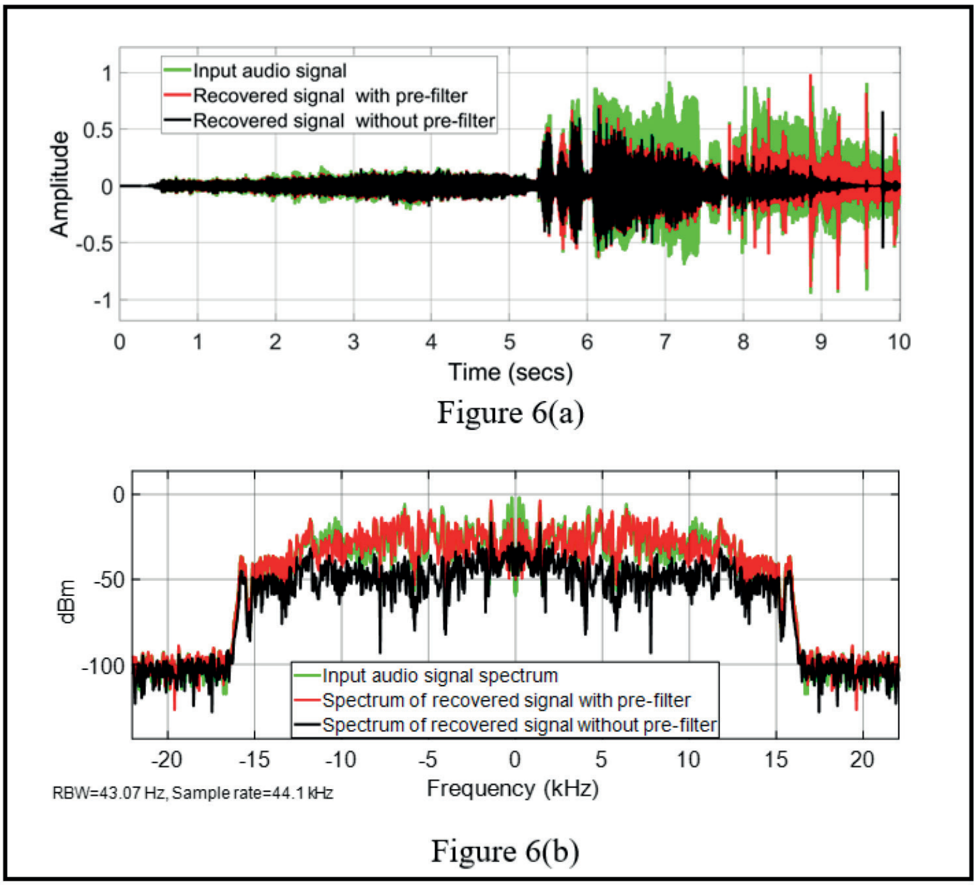

Figure 6 *Time domain plot and frequency spectrum of the signal recovered through the proposed model using the pre filter and without pre filter compared to the input audio signal*

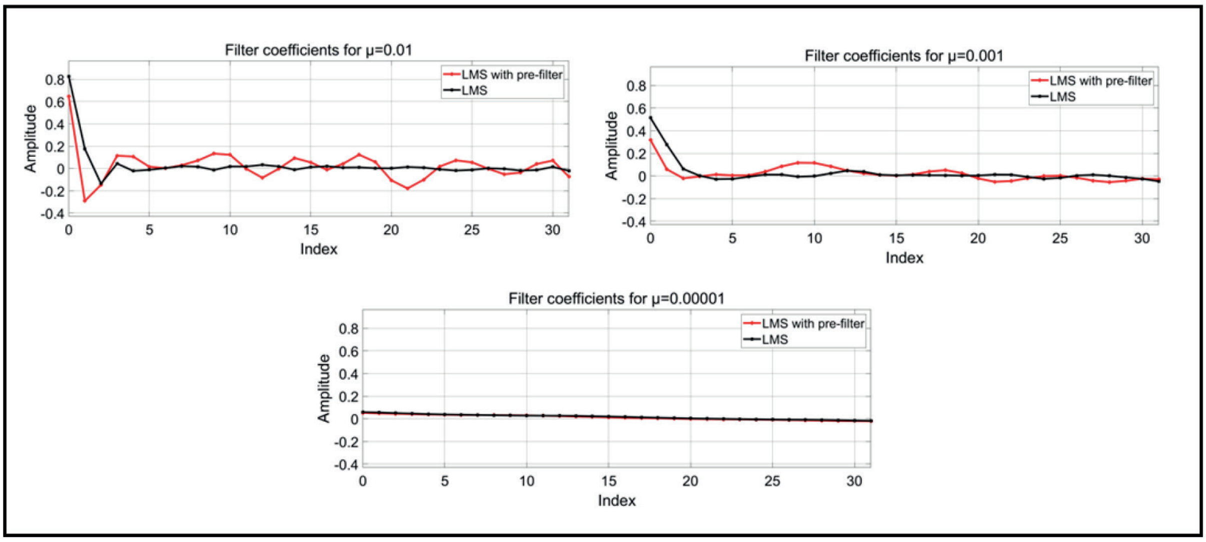

Figure 7 *Array plot of filter coefficients generated by the LMS algorithm for different values of step size*

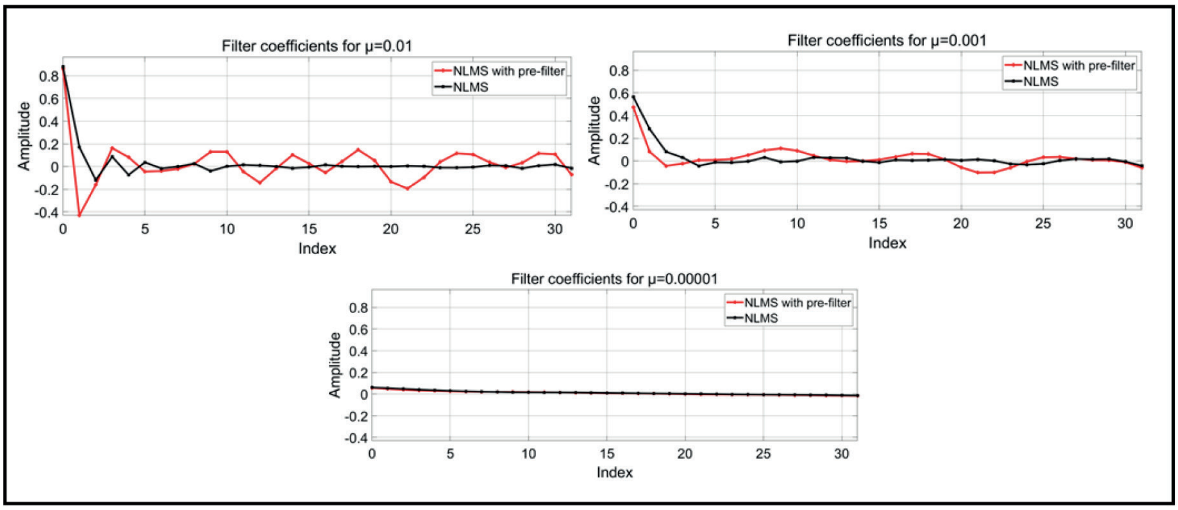

Figure 8 *Array plot of filter coefficients generated by the NLMS algorithm for different values of the step size*

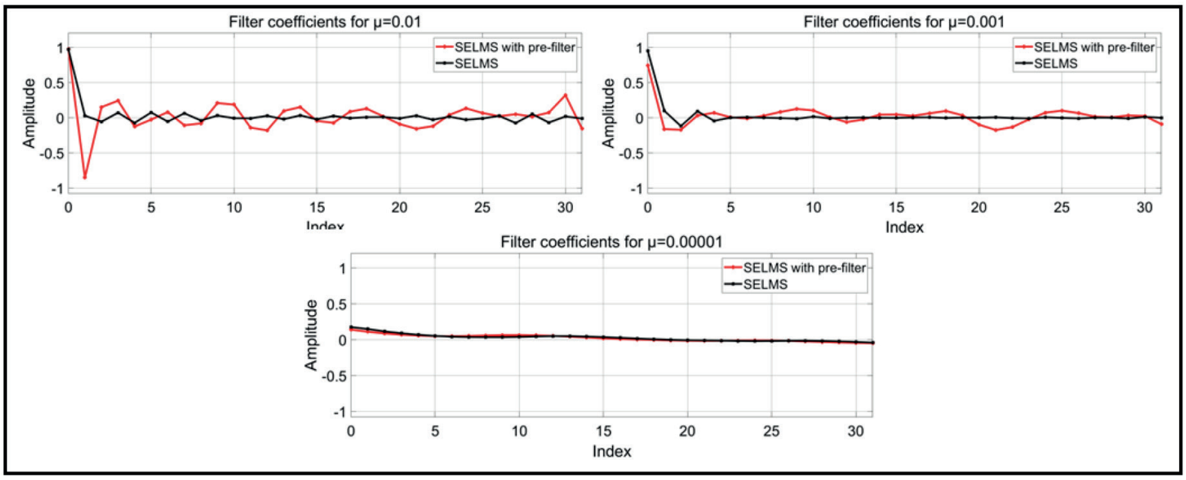

Figure 9 *Array plot of filter coefficients generated by the SELMS algorithm for different values of the step size*

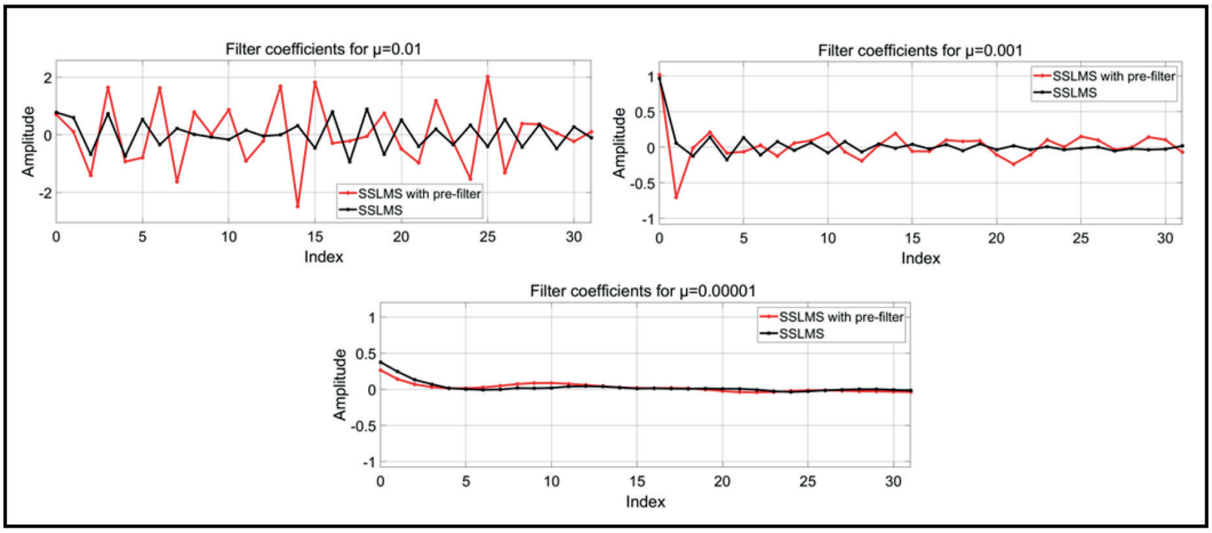

Figure 10 *Array plot of filter coefficients generated by the SSLMS algorithm for different values of the step size*

that the best convergence rate and stability is achieved by NLMS algorithm for step size μ = 0.00001 and lowest convergence rate is obtained for step size μ = 0.01.

3.3 Sign- error least mean square (SELMS)

The variation of filter coefficients generated by SELMS algorithm with respect to time for different values of the step size is given in Figure 9. It is observed that the best convergence rate and stability is achieved by SELMS algorithm for the step size μ = 0.00001 and lowest convergence rate is for step size μ = 0.01.

3.4 Sign- sign least mean square (SSLMS)

The variation of filter coefficients generated by SSLMS algorithm with respect to time for different values of step size is given in Figure 10. it is observed that the best convergence rate and stability is achieved by the SSLMS algorithm for the step size μ = 0.00001 and lowest convergence rate is for step size μ = 0.01.

Literature review states that improving the convergence rate of the adaptive algorithm has been a major factor of research in the concerned area of adaptive filtering. Many methods have been adopted for increasing the convergence rate and most of them adopted focus on modification of the adaptive algorithm [22]. This approach of modifying the adaptive algorithm suffers from the drawback of increased mathematical complexity of the adaptive algorithm. The increased complexity hurdles the practical applicability of the algorithm in noisy and highly unpredictable acoustic environment in a moving vehicle cabin, as it is learned from the previous studies that advanced adaptive algorithms, having high convergence rates, are much more mathematically complex as compared to basic LMS algorithms having low convergence. This paper presents an approach to increase the convergence rate, without modifying the basic algorithms, thus, achieving a higher convergence rate without increasing the mathematical complexity of basic adaptive algorithms. The proposed approach is to pre-filter the noise signal before adaptive filtering. The pre-filter used is a fixed coefficient Butterworth low pass IIR filter, the filter order is 9. The convergence rate of the adaptive algorithms, obtained after pre-filtering the noise signal, is compared to the convergence rate without pre-filtering. The comparative analysis is based on values of the filter coefficients generated by different adaptive algorithms to minimize the mean square error between the predicted signal and the actual signal. Filter coefficients are updated continuously to attain estimation, the faster they attain minimal values, the higher is the convergence rate. The lower range of variation results in higher stability [23-30]. Based on this criterion, Table 2 shows the values of the filter coefficients generated by the least mean square (LMS), normalized least mean square (NLMS), sign-error least mean square (SELMS), sign-sign least mean square (SSLMS) algorithms to cancel the noise signal. The values of filter coefficients are obtained for the step sizes μ = 0.01, \0.001 and 0. 00001. The range of variation of filter coefficients is considered to be from 0 to 0.008. Comparison of values of the filter coefficients values, generated after the pre-filtering on noise signal, depicts that an average number of 16 filter coefficient have magnitude greater than 0.002 for the pre filter LMS. This number is 21.3 for LMS without the pre filtering; similarly for NLMS with pre filter it is 15.3, NLMS without pre filter it is 20, for SELMS with pre filter it is 16.3; for SELMS without pre filter it is 16.3, for SSLMS with pre filter it is 17.6, for SSLMS without pre filter it is 17.3. Similar results are obtained for amplitude range greater than 0.006 and 0.008. From Table 2 is also observed that number of filter coefficients with amplitude greater than zero for all three-step size are 48 in case of LMS with pre filter, 62 in LMS without prefilter. This number is 50 in NLMS with pre-filter, 61 in NLMS without pre-filter. It is 51 in case of SELM with pre-filter and 53 without pre-filter. For SSLM with pre-filter this is 50 and for SSLMS without pre-filter it is 53. From these results is thus observed that the filter coefficients generated by adaptive algorithms for estimation of pre filtered noise is less in all the cases as compared to number of filter coefficients generated for estimation of noise without pre filtering thus these results prove that pre-filtering has increased convergence rate. The range of variation in amplitude of filter coefficients is also obtained to be less in case of pre-filtering than without pre-filtering this result shows improved stability of the adaptive algorithm for pre-filtered noise signal. Thus, simulation results prove that filter coefficients tend to converge at a faster rate and show a low fluctuation range in the case of the proposed pre-filter model as compared to the conventional non-pre filter model. Table 2 gives the mathematical values of filter coefficients shown in Figures 7 to 10. A comparative analysis is done for the values generated after pre-filtering of noise signal and the values obtained without use of the proposed pre-filter, moreover performance of various adaptive algorithms is also compared. Further, Error Vector Magnitude (EVM) and Signal to Noise Ratio of the recovered signal with respect to the input audio signal is calculated for different adaptive algorithms, which are applied with the pre-filter and without the pre-filter. These values are given in Table 3, which shows the error vector magnitude between the input audio signal, signal recovered after pre-filtering and that recovered without prefiltering. Numerical results clearly depicts that the error percentage is higher in case of signal recovered without pre filtering, which means the proposed model with pre filter is more efficient in approximating and cancelling the noise signal as compared to conventional model. Another parameter calculated for comparative analysis is the signal to noise ratio (SNR) of the recovered signal. SNR values of the recovered signals are higher in case of pre filter output justifying the fact further that the proposed model with pre filter cancels the noise more effectively. Figures 11(a-c) show the comparative histogram chart of the error vector magnitude and Figures 12(a-c) show the signal to noise ratio values obtained for variable step size applied to the four adaptive algorithms. Results show that the least error vector magnitude percentage of 26.01% for

Table 2 *Filter coefficients generated for the step size μ = 0.01, 0.001 and 0.00001 by different adaptive algorithms with and without the pre-filter*

Algorithm	Filter Coefficient, μ											
	0.01				0.001				0.00001			
	> 0.002	> 0.006	> 0.008	> 0	> 0.002	> 0.006	> 0.008	> 0	> 0.002	> 0.006	> 0.008	> 0
LMS	19	15	15	19	21	19	17	21	21	20	19	22
LMS with Pre-filter	15	14	14	14	16	16	16	16	17	15	14	18
NLMS	17	16	14	17	21	17	16	21	22	19	17	23
NLMS with Pre-filter	13	13	13	13	17	15	15	19	16	14	13	18
SELMS	17	15	15	19	13	12	11	13	19	18	18	19
SELMS with Pre-filter	16	15	15	16	18	18	18	18	15	14	14	17
SSLMS	16	16	16	15	15	15	15	16	21	21	20	22
SSLMS with Pre-filter	18	18	18	16	20	19	19	19	15	15	14	15

Table 3 *Error vector magnitude (EVM) and Signal to Noise Ratio of recovered signal with respect to the input audio signal calculated for the step sizes μ = 0.01, 0.001 and 0.00001 for different adaptive algorithms with pre-filter and without pre-filter*

Algorithm	EVM %			SNR in dB		
	μ = 0.01	μ = 0.001	μ = 0.00001	μ = 0.01	μ = 0.001	μ = 0.00001
LMS	92.48	80.13	37.75	0.6791	1.924	8.462
LMS with Pre-filter	62.44	58.91	33.08	4.091	4.596	9.609
NLMS	98.38	89.11	29.8	0.1421	1.002	10.52
NLMS with Pre-filter	69.15	68.37	26.01	3.205	3.302	11.7
SELMS	100	99.84	66.47	-0.0034	0.014	3.548
SELMS with Pre-filter	65.15	70.57	59.12	3.721	3.028	4.5666
SSLMS	103.2	100.2	80.57	-0.2743	-0.015	1.876
SSLMS with Pre-filter	91.38	70.92	66.05	0.7828	2.984	3.602

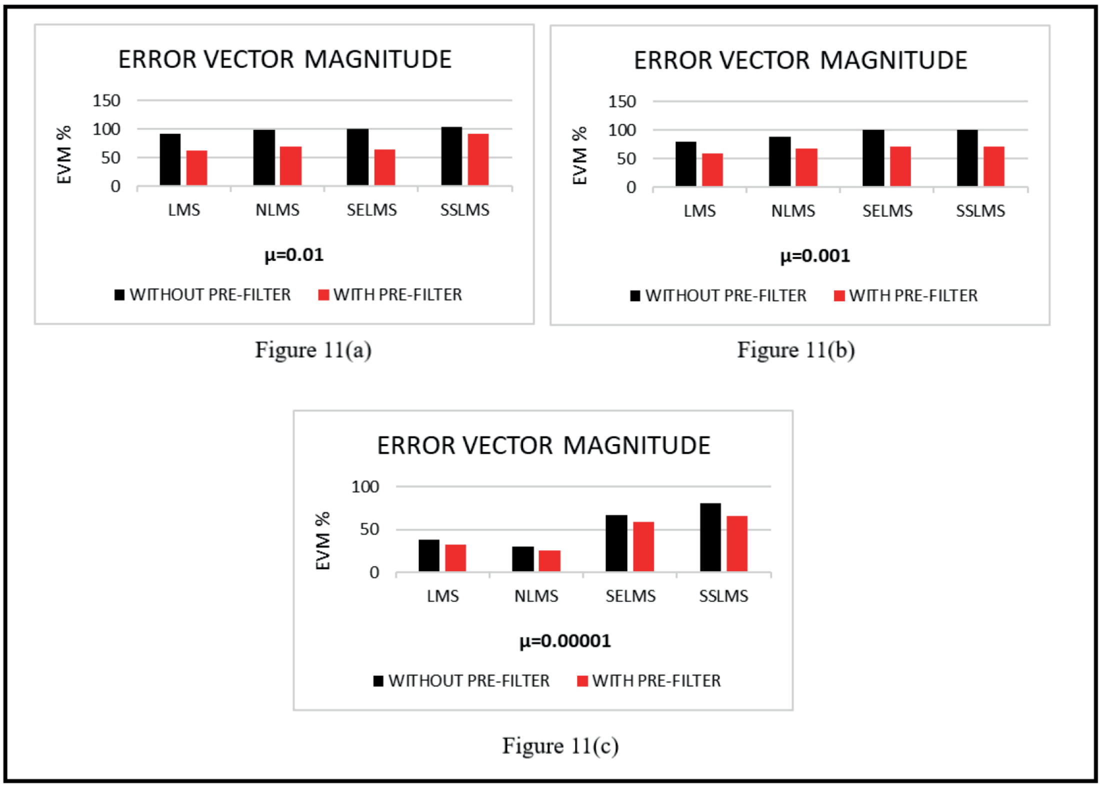

Figure 11 *Error vector magnitude of recovered signal*

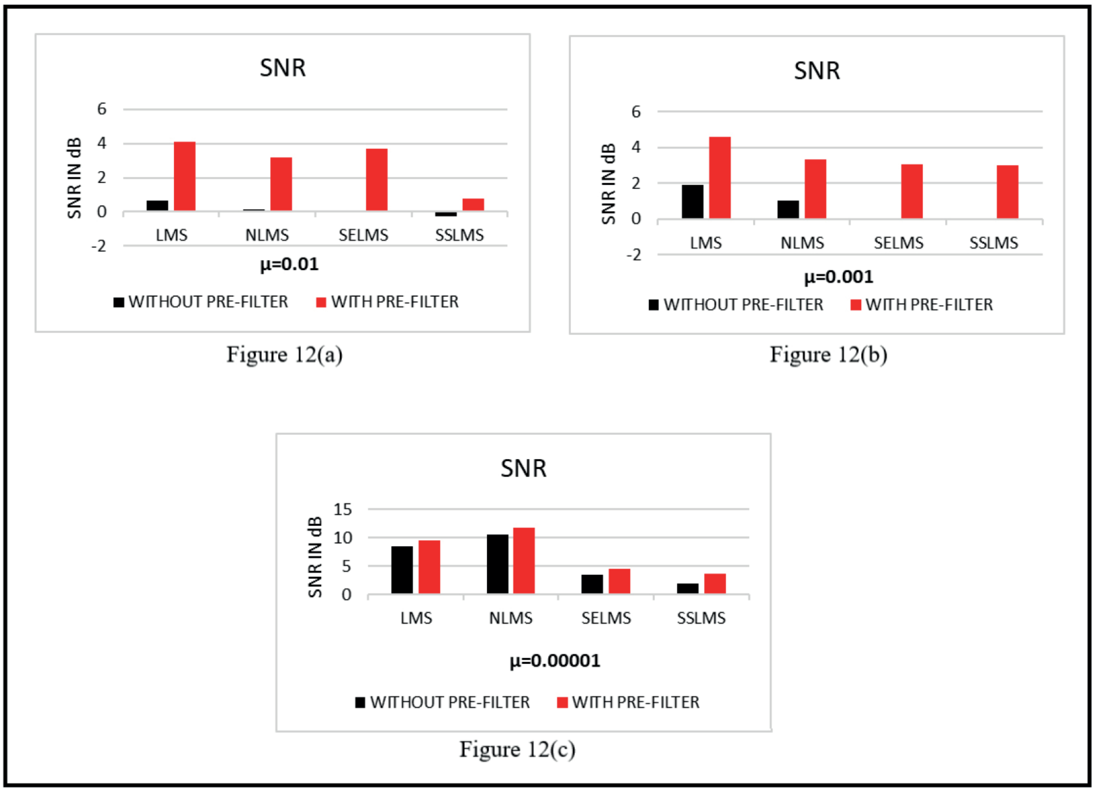

Figure 12 *SNR of recovered signal*

the NLMS algorithm for the step size μ = 0.00001. The highest signal to noise ratio (SNR) obtained is 9.609 dB by least mean square (LMS) algorithm for the step size μ = 0.00001. Given results thus prove that the proposed model has better convergence rate, higher signal to noise ratio, lower error vector magnitude and better audio signal recovery in presence of noise. These results are achieved without increasing the complexity of the adaptive algorithm.

4 Conclusions

This study develops an approach of pre-filtering the input noise corrupted signal before the adaptive filtering, so that many low frequencies noise components are pre-filtered and adaptive algorithms do not tend to adapt to these frequencies, thus increasing the convergence rate without increasing the mathematical complexity of the algorithm. The convergence time is inversely proportional to convergence rate. Increased convergence rate obtained in proposed model through quantitative analysis of filter weights, proves significant decrease in convergence time of adaptive algorithm in cancellation of engine noise inside the vehicle cabin. Precise calculation of convergence time is left for further research and may be covered in authors' next publication in near future. Based on the simulation results for four different algorithms on the proposed model, it is concluded that the increased convergence rate of adaptive algorithm, higher signal to noise ratio and lower error vector magnitude of the recovered signal can be achieved without increasing the complexity of the basic adaptive algorithm. Less complexity leads to practicability of the noise cancellation system for the vehicle cabin noise cancellation. Overall, results show better convergence rate and increased stability of adaptive algorithms in the proposed model. Higher stability and faster convergence rate lead to the more effective cancellation of cabin noise in moving vehicle.

Grants and funding

The authors received no financial support for the research, authorship, and/or publication of this article.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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MODELING OF ELECTRIC VEHICLES FLEET'S CHARGING USING PARTIAL DIFFERENTIAL EQUATIONS

Martina Kajanová[1,*], Peter Braciník[1], Michal Kralovič[2]

[1]Faculty of Electrical Engineering and Information Technology, University of Zilina, Zilina, Slovakia
[2]Stredoslovenska distribucna, a. s., Liptovsky Mikulas, Slovakia

*E-mail of corresponding author: martina.kajanova@uniza.sk

Martina Kajanová 0000-0003-4334-0200, Peter Braciník 0000-0002-8653-434X

Resume

With an increasing number of electric vehicles, their impact on electrical power systems is starting to be substantial. High deployment of these vehicles can even bring issues such as overloading the power transformers and power lines or loss of stability in the power system. Therefore, a suitable model, able to represent large groups or fleets of electric vehicles, is needed to prepare measures that can prevent these problems. The main contribution of this paper is the definition of a charging model representing a fleet of EVs using partial differential equations. This new approach enables meeting the accuracy of the commonly used battery charging models while significantly decreasing required computation times as shown in simulation results.

Article info

Received 6 September 2022
Accepted 26 October 2022
Online 28 November 2022

Keywords:

electric vehicle
charging
modeling
partial differential equations

Available online: https://doi.org/10.26552/com.C.2023.005

ISSN 1335-4205 (print version)
ISSN 2585-7878 (online version)

1 Introduction

Nowadays, there is an accelerating trend of global air and ocean temperature growth. The cause of this acceleration is the constant growth of society's consumption, which is associated with greenhouse gas emissions to the atmosphere. Transportation accounts for 30 % of total carbon dioxide emissions in the European Union, thereof road transport accounts for up to 72 % of these emissions. That is not a negligible share. Therefore, it will be necessary to reduce these emissions within several years, not only in the European Union but at the global level, as well [1].

The solution is to reduce mobility or replace internal combustion engines with a more environmentally friendly alternative. This alternative is usually assumed to be the electric motor drive powered by the accumulator. However, electric vehicle (EV) production and operation also produce carbon oxide emissions, but on a lower scale. Electric vehicle emissions are linked mainly with its production, especially batteries and emissions produced by the power generation for battery charging supply [2].

With deployment of electric vehicles, many questions and technical challenges arise. Among these challenges is the topic of electric vehicle charging. On the one hand, it is necessary to build more charging stations with the growing number of EVs and on the other hand, it is necessary to consider increased electricity consumption. From a global point of view, it is an uncontrolled load that is constantly changing and thus the necessary measures need to be taken to prevent overloading of the network or loss of a stability [3].

To define an appropriate measure to decrease the impact of EVs on the grid, it is necessary to predict the consumed power of the EVs charging. To be able to predict the consumed power of the EVs, the charging models and connection/disconnection times of the EVs need to be determined. Connection and disconnection times of EVs are related to behavior of the vehicle owners and this is not addressed in this paper. However, other works deal with this topic, e.g. in [4-6]. The model of EV charging is based on the battery parameters. There are many different types of battery charging models based on their application and required accuracy [7]. However, most of these models consist of one or more differential or nonlinear equations. It increases the computational complexity of these models, even more, if a group or a fleet of EVs is assumed.

Therefore, this work defines a charging model of a fleet of EVs as one unit using partial differential equations (PDE). A similar model, defined using PDEs, was already presented in [8], however, it assumes controlled charging or discharging of EVs. The presented model is more general and can be used to predict the consumed power of the charging EVs even if the charging is uncontrolled. Moreover, the comparison of the presented model with the commonly used electrical model for battery charging was carried out in this paper.

So, this paper is focused on definition of a charging model of a fleet of EVs, able to predict the consumed power of charging EVs and demonstrate its properties. Moreover, the defined model can be scaled from small EV fleets to fleets consisting of thousands or more of EVs without increasing the computation times. So, this definition of a charging fleet model allows to easily study the impact of EV charging on the power network, e. g. define hosting capacity for electric vehicles in a specific power network or increase in total consumption in a specific electric power system.

The contributions of this manuscript are twofold:

- a definition of a charging model representing the consumed power of a fleet of EVs with uncontrolled or controlled charging;
- a definition of a charging model that is able to scale from small EV fleets to large ones without increasing the computation times.

The rest of the paper is organized as follows. Section 2 presents the commonly used charging models and specifically the electric model that is later used for comparison with model defined in this paper. Section 3 defines the model of the EV fleet described with PDEs. The simulation of the created model and the comparison with the electric model are carried out in section 4. Section 5 concludes the paper and suggests future work.

2 EV charging models

The basis of the EV charging model is the battery charging model. There are many battery models and each has its advantages and disadvantages, so it is necessary to choose a suitable model to represent EV charging [7]. According to [9], medium-term battery models can be divided, according to different modeling perspectives and techniques, as follows [9]:

- empirical models.
- electrochemical models,
- physical, molecular models and
- electric models - equivalent circuits models.

2.1 Empirical models

The principle of operation of these models is to describe the battery charging function without using physical-chemical relationships. The basis of the models is the use of measured battery data. Empirical models are significantly simpler compared to other models; computations of these models are simpler and faster. They are used to simulate the state of charge and state of battery degradation in real time. The disadvantage is the lower accuracy of the output values [7, 10].

Empirical models include the universal model [10-11], the Nernst model [12], the Shepherd model [10] and the model of the equivalent circuit with polynomial equations [9].

2.2 Electrochemical models

Electrochemical models, based on the principle of internal phenomena in a battery, are very accurate. The electrochemical model of a battery is defined by several partial differential equations that describe the movements, concentrations of ions, and other chemical properties of a battery. The input data to these models are obtained by experimental measurement [12]. However, electrochemical models are difficult to compute, so simulations can take a long time. They are used when high accuracy of a battery model is required and to simulate battery behavior over a longer time horizon [7, 9].

2.3 Physical, molecular models

Physical and molecular models are extensions of electrochemical models. They describe phenomena in the electrolyte, chemical changes of the electrodes and many other phenomena. They express the charging process as a more complex process, taking into account the movements of particles in all directions. So, these models can be two or even three-dimensional. Computations of these models are demanding because of the large number of time- and space-varying variables described by PDEs. However, their accuracy is high and so they are often used as reference models. Physical models include a P2D porous electrode model, a P3D thermal model, a P2D strain and stress model and a P2D population balance model. The abbreviations 1D, 2D and 3D after P in the model's name represent the dimensions of the model [13].

2.4 Electric models

These models describe the electrical quantities of the battery, i.e. its volt-ampere characteristics. The models are based on the data provided by the battery manufacturer - nominal capacity, internal resistance, voltage, charging current, polarization voltage, the amplitude of the exponential zone and inverse time

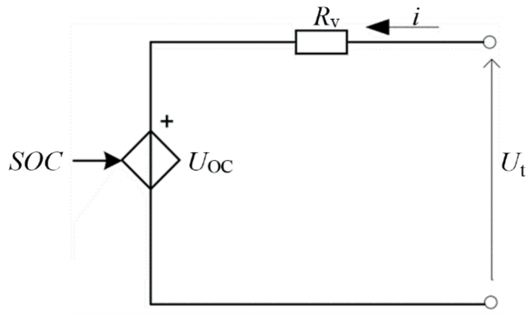

Figure 1 *Equivalent circuit of a battery cell*

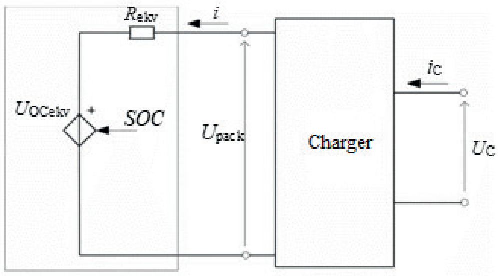

Figure 2 *Equivalent circuit of a battery*

constant of the exponential zone. Such a model is described in detail as it is used for comparison with the charging model of a fleet of EVs defined in this paper.

The basis of the battery model is a battery cell model and its equivalent circuit, as shown in Figure 1. This circuit consists of a controlled voltage source U_{OC} in series with the internal resistance of the battery cell R_v. The battery voltage is denoted by U_t [14].

The state variable of this model is the state of charge (*SOC*) of a battery, which is given by [14]:

$$SOC = \frac{Q}{Q_{nom}}, \tag{1}$$

where Q_{nom} is a nominal capacity of a battery (Ah) and Q is a current capacity of a battery (Ah).

Neglecting losses in the battery during charging, one can express the time change of the state of charge as [14]:

$$\frac{dSOC}{dt} = \frac{i}{Q_{nom}} \tag{2}$$

where i is a charging/discharging current (A).

The open-circuit voltage U_{OC} is expressed as [14]:

$$U_{OC}(Q) = U_K - \frac{K \cdot Q_{nom}}{Q_{nom} - Q} + A \cdot e^{(-B \cdot Q)}, \tag{3}$$

where U_K is a constant battery voltage (V), K is a polarization voltage (V), A is the amplitude of the exponential zone (V) and B is an inverse time constant of the exponential zone (Ah^{-1}).

Then, the battery cell voltage U_t can be easily derived by adding the voltage drop due to the internal impedance R_v [14]:

$$U_t = U_{OC} + R_V \cdot i. \tag{4}$$

The voltage drop is positive during charging and negative during discharging. Since we are examining the battery as a whole, it is necessary to convert cell voltages U_t, U_{OC} and resistance R_v to battery U_{pack}, U_{OCekv} and R_{ekv} as shown in Figure 2 [14].

The EV battery charging takes place in two phases. First, it is charged with a constant current, the voltage is slowly increased until the limit value is reached. The power consumed from the network P_{AC} and the power supplied to the battery P_{DC} are determined as [14]:

$$P_{AC} = U_C \cdot i_C, \tag{5}$$

$$P_{DC} = U_{pack} \cdot i, \tag{6}$$

where U_C is the network voltage (V) and i_C is a current consumed from the network (A).

Since U_{pack} is dependent on the SOC of the battery, then P_{AC} is dependent on the SOC, as well. The power consumed from the network can be expressed [14]:

$$P_{AC}(SOC) = U_C \cdot i_C(SOC), \tag{7}$$

$$P_{DC}(SOC) = U_{pack}(SOC) \cdot i, \tag{8}$$

while the relationship between the power consumed from the network and the charging power delivered to the battery is [14]:

$$P_{DC} = \eta \cdot P_{AC}, \tag{9}$$

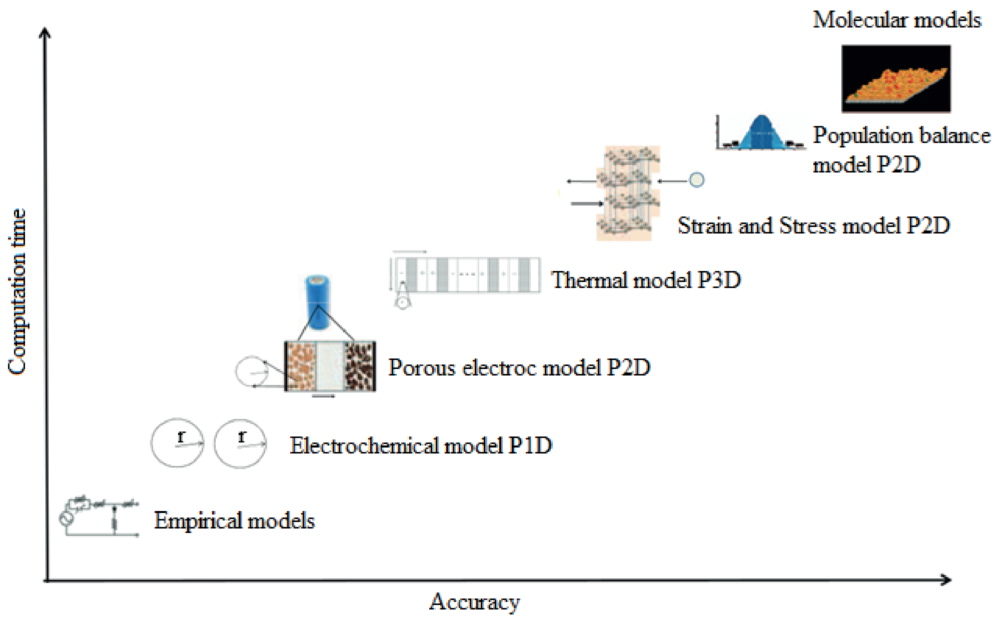

Figure 3 *The comparison of the presented types of battery charging models*

where η is a charger efficiency (-).

In the case of constant voltage charging, it is not possible to control the P_{AC} or i_C. The only controlled quantity is the voltage U_{pack}, which is kept at a constant value until the SOC level of 100 % is reached.

The comparison of the accuracy and computation time complexity of the presented types of models is shown in Figure 3.

3 Charging model of a fleet of EVs

The charging of one EV can be described by different models, as shown in section 2. However, modeling a fleet of several thousand EVs separately using these equations would represent a large computational burden. However, the relations describing the EV fleet can be simplified by an aggregation method [15]. A model using the aggregation method expresses a group of EVs as a whole and describes it by one or more PDEs. The EVs in such models are expressed as functions of their current SoC and time [16-17].

The simulation of the EV fleet is expressed using the two interconnected continuous PDEs. However, the EV fleet can acquire two discrete states [16-17]:

- charging, when the EV is charging and so represents a load for the grid,
- idle, when the EV battery is already fully charged but is still connected to the grid.

Individual discrete states are expressed using hyperbolic PDEs. These PDEs are interconnected using transition variables describing the transition of the EVs between individual discrete states, from the state of charging to the idle state and vice versa. The dynamic of these states is shown in Figure 4. The SOC of an EV is expressed in per unit (pu) and is represented by the variable x. The number of EVs that are in the charging state, with SOC equal to x at time t, is represented as u(x,t). The number of EVs that are in the idle state with SOC equal to x at time t is denoted as v(x,t) [16-17].

The EV transition between individual discrete states is determined by the variable σ. In the upper part of Figure 5, the EV transits from the idle state to the charging one is given by the variable $\sigma_{i\rightarrow c}$. At the bottom of Figure 4, $\sigma_{i\rightarrow po}$ determines the EV movement between the idle state and the state when the EV is disconnected from the charging station (EV arrival to/departure from the charging station) [16-17].

After connecting the EV to the charging station, the model assigns the EV automatically into the idle state. If its SOC is lower than 1, the EV is transited to the charging state. If SOC becomes 1, which means the EV is charged, the EV goes into the idle state unless it is disconnected from the charging station. By disconnecting from the charging station, an EV goes into an undefined driving state when the EV is being discharged. This condition is not modeled in the simulation, it is considered that EVs can be randomly connected and disconnected from the charging station [16-17].

3.1 Derivation of the model

The basis of the aggregated model is the EV battery charging model that was described in section 2.4. In this model, for simplicity, the SOC is denoted by x_i, where i expresses the ith EV [16-17].

The required energy for the EV fleet charging at the time *t* is given by [16-17]:

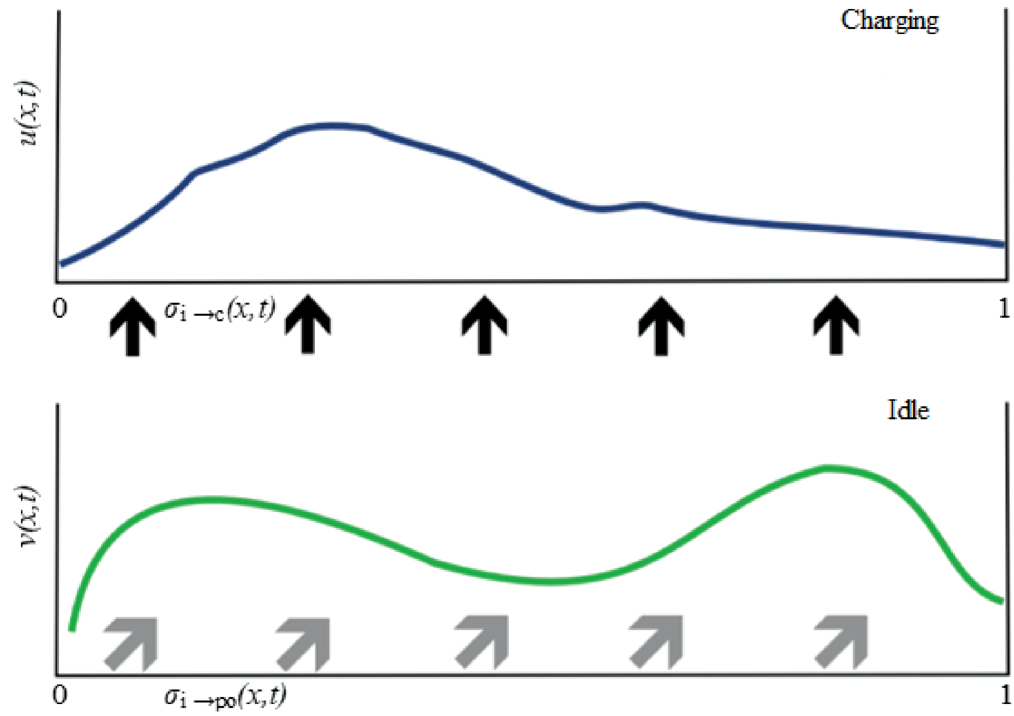

Figure 4 *The dynamic of the two defined discrete states*

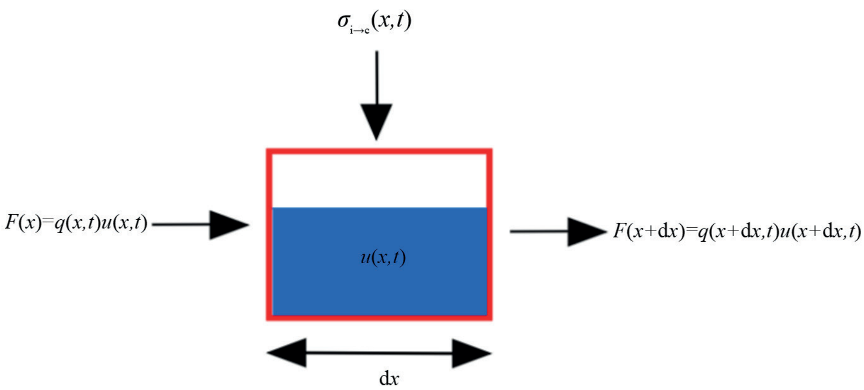

Figure 5 *The number of EVs in the charging state with SOC between x and x+dx*

$$P_c(t) = \sum_{x1=0}^{1} P_{AC} \cdot u(x,t). \tag{10}$$

The aggregation method can be used to express the PDE since dx/dt is linearly proportional to the charging power. In the model, the parameters of the battery and the efficiency of the charger η are assumed as homogeneous in the EV fleet.

The amount of EVs that are charged is denoted by u(x,t) and their SOC is x(t). The charging rate at x is noted as $q_c(x,t)$. Charging rate $q_c(x,t)$ is given by the change of the SOC over time, which is expressed by the battery charging model as in section 2.4. Simply, it can be expressed as [15, 17]:

$$q_c(x,t) = \frac{dx}{dt}. \tag{11}$$

To derive the model, the dynamics of the EVs charged in an infinitesimal segment between x and x+dx is considered. The flow of charged EVs at time t with SOC x is expressed through the function F(x,t) as [16-17]:

$$F(x,t) = q_c(x,t) \cdot u(x,t), \tag{12}$$

$$F(x+dx,t) = q_c(x+dx,t) \cdot u(x+dx,t), \tag{13}$$

where Equation (12) describes the incoming flow of EVs with SOC corresponding to x at time t and Equation (13) defines the outgoing flow of EVs whose SOC is already larger and corresponds to x+dx at a certain time t.

An additional increase in the number of EVs in this segment (dx) can also be given by the transition of EVs with SOC equal to x at time t, which come from the idle to the charging state, denoted by $\sigma_{i\rightarrow c}(x,t)$. Figure 5 shows the approximate amount of total number of EVs whose SOC at time t is between x and x+dx [16-17].

In an infinitesimally small time interval dt, the number of charged EVs can be expressed according to the conservation law as [8, 16-17]:

$$[u(x,t+dt)-u(x,t)]dx = q_c(x,t)\cdot u(x,t)dt - \\ -q_c(x+dx,t)\cdot u(x+dx,t)dt + \sigma_{i\to c}(x,t)dt. \quad (14)$$

If dt → 0 and dx → 0 are considered, then the PDE representing the time change of the number of EVs in the charging state is given by [8]:

$$\frac{\partial u}{\partial t}(x,t) = \frac{\partial}{\partial x}[q_c(x,t)\cdot u(x,t)] + \sigma_{i\to c}(x,t). \quad (15)$$

Equation (15) can be used to determine how many EVs have a certain level of SOC or how many EVs consume energy from the network, i.e. they are being charged.

Similarly, one can express the PDE determining the number of EVs in the idle state according to the following equation [16-17]:

$$\frac{\partial v}{\partial x}(x,t) = -\sigma_{i\to po}(x,t) - \sigma_{i\to c}(x,t). \quad (16)$$

The number of EVs with SOC equal to x at time t in the idle state depends on how many EVs are currently connected or disconnected to the charger $(\sigma_{i\to po}(x,t))$ and from the number of EVs that was transited from charging state to idle state $(\sigma_{i\to c}(x,t))$ and vice versa.

For the correct function of the model, it is necessary to determine the PDE boundary conditions representing the EV charging dynamics, i.e. for x = 0 at time t [16-17]:

- u(0,t) = 0, meaning SOC of EV cannot be lower than 0.

It is also important to determine the condition for the limit value of charging rate $q_c(x,t)$ when the EV is already charged [16-17]:

- $q_c(1,t) = 0$, after reaching x = 1, the battery is not charged any further.

The other conditions are defined within the model. If x is less than 1, then EVs are connected to the charger and they are in the charging state, until x does not take on the value of 1. EVs with x = 1 are not charged any further but are transited into the idle state [16-17].

4 Results

4.1 Simulation model

The mathematical model of EV fleet charging dynamics defined in the previous section consists of hyperbolic PDEs. The computation of these hyperbolic PDEs can be very complex. However, if a charging rate $q_c(x,t)$ is assumed to be constant over time, the quite simple Lax-Wendroff numerical method can be used to solve this model.

The Lax-Wendroff method is a numerical method, so it finds an approximate solution that solves the hyperbolic PDEs. It shows good accuracy and in the case of the second-order equations, it has an error rate of less than 3 %. The resulting equation of this method has the form of a Taylor series.

Using this method, the resulting equation expressing the number of EVs in the charging state is given as [16-17]:

$$u_j^{k+1} = u_j^k - \frac{a\cdot\Delta t}{2\cdot\Delta x}\cdot(u_{j+1}^k - u_{j-1}^k) + \frac{a^2\cdot\Delta t^2}{2\cdot\Delta x^2}\times \\ \times(u_{j+1}^k - 2\cdot u_{j-1}^k + u_{j-1}^k). \quad (17)$$

In Equation (17), u_j^k expresses how many EVs have a certain SOC corresponding to step j and time step k in the charging state [8, 16]:

$$u_j^k = u(j\Delta x, k\Delta t). \quad (18)$$

Variable a in Equation (17) denotes the constant charging rate. The charging rate is the same throughout the whole charging cycle. Δt determines the time of the discretization step of the function and Δx expresses the discretization step of SOC. Equation (17) thus defines the change in the number of EVs with SOC j at time k+1, based on the values at time k, the amount of EVs with j times Δx SOC and the amount of EVs with the surrounding values of SOC at j+1 and j-1 steps [8, 17].

The differential equation expressing the number of EVs in the idle state is derived only with respect to time and can therefore be solved numerically without modifications. The equation defines the number of EVs in the idle state in the next time step, which is determined by the number of vehicles in the idle state in the current time step and the transport variables σ. ${\sigma_{i\to po}}_j^k$ is the number of EVs moving from the idle state to the charging state in the current time step k and ${\sigma_{i\to c}}_j^k$ represents the number of EVs moving from the idle state to the driving state (disconnection from the charging station) in the current time step. The mathematical notation of Equation (16) in discretized version is [8]:

$$v_j^{k+1} = v_j^k - {\sigma_{i\to po}}_j^k - {\sigma_{i\to c}}_j^k. \quad (19)$$

Using Equations (17) and (19) and conditions set in section 3.1, the simulation model was created in Matlab R2020b. The simulation of EV fleet charging represents charging with constant power. From the model, it is possible to determine the time for EVs to charge, the number of charging vehicles at a certain time t and the number of EVs in the idle state at a given time. An important function of the model from the electrical grid point of view is the prediction of the consumed power from the grid for the fleet charging. The input variables to this model are the number and type of EVs in the fleet

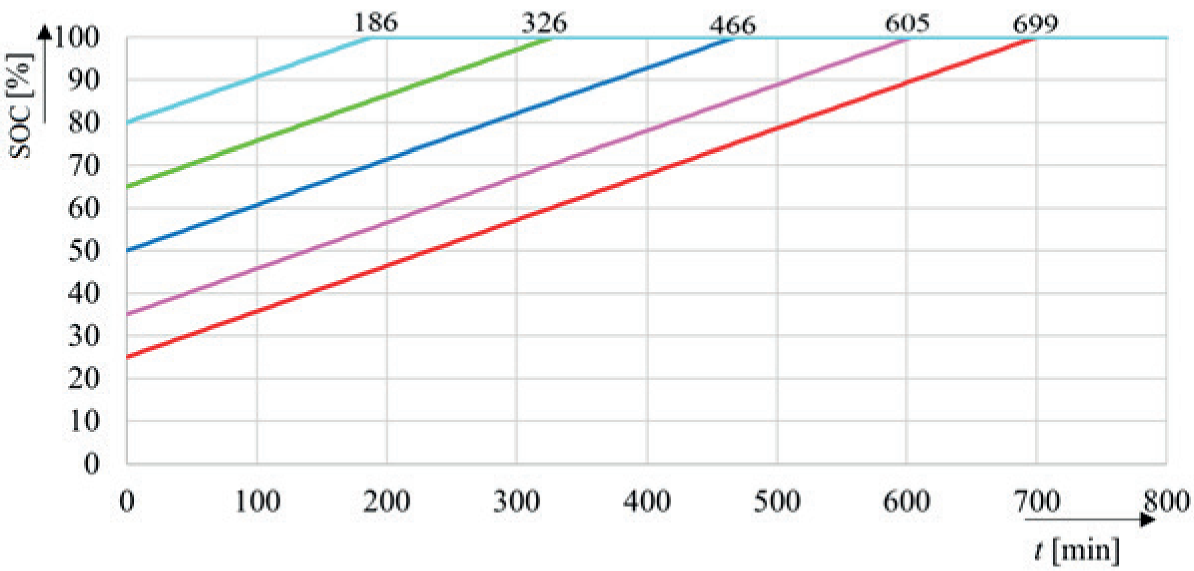

***Figure 6** Charging process of EV groups within the fleet*

with their initial SOC and defined constant charging rate.

4.2 Testing of the simulation model

To test the created simulation model, the following input values were used. We chose the maximum number of EVs in the fleet equal to 1000, with a nominal battery capacity of 50 kWh. Charger efficiency is assumed 87 %. The simulation time is set to 800 minutes. The length of time is chosen so that all the EVs have time to charge with charging power equal to 3.7 kW. The charging rate per time unit dt is then determined as:

$$dx = q_c = \frac{P_{nab} \cdot \eta}{Q_n \cdot 60} = \frac{3 \cdot 7 \cdot 0.87}{50} = 1.073 \cdot 10^{-3}. \qquad (20)$$

While x changes in the range 0 to 1 with a step dx, time takes on values from 0 to the selected simulation time with a dt step set to 1 minute.

In addition, it is important to determine the limits for Equations (17) and (19). If the SOC is lower than 1, the EV is automatically transited to the charging state from the idle state after being connected. If SOC is equal to 1, EV is transited into the idle state.

The initial conditions for these discrete equations need to be determined as well. In the idle state, there are no EVs in the initial state. All the EVs connected to the charging station are already in the charging state at the beginning of the simulation and they are divided into groups as follows:

- 300 vehicles with initial x corresponding to 25 % SOC;
- 200 vehicles with initial x corresponding to 35 % SOC;
- 100 vehicles with initial x corresponding to 50 % SOC;
- 200 vehicles with initial x corresponding to 65 % SOC;
- 200 vehicles with initial x corresponding to 80 % SOC.

The results from the simulation show the charging process of individual groups of EVs in Figure 6. The SOC of all groups increases over time and the duration of the charging process depends on the initial SOC.

After reaching x = 1, the vehicles are automatically transited into the idle state, as shown in Figure 7. The gradual increase of vehicles in the idle state, as soon as individual EV groups reach full SOC can be seen in Figure 6. Figure 6 also shows that EVs with the lowest initial SOC (25 %) are fully charged after 699 minutes. That corresponds to the time when the last group of Evs is added to the idle state (Figure 7).

The total consumed power is a function of the number of charging vehicles and the charging rate. So, the total consumed power at the time t is the sum of power consumed by all the Evs in the charging state. However, the number of vehicles in the charging state is constantly changing depending on their actual SOC. The power curve, therefore, evolves over time as shown in Figure 8. The curve corresponds to the initial condition of connecting all the vehicles to the charger and so their location in the charging state of the model. Therefore, the power takes on a value of 3700 kW, i.e. the power of the charger 3.7 kW multiplied by the number of vehicles 1000. As the Evs are charged and so transited from the charging to the idle state, the power gradually decreases. In addition, the trends in Figure 8 can be compared to Figures 6 and 7, where the EV group with an initial charge of 25 % reaches x = 1 after 699 minutes from the simulation start. The total power consumed at this time will drop to zero because all the vehicles are already fully charged and are in the idle state.

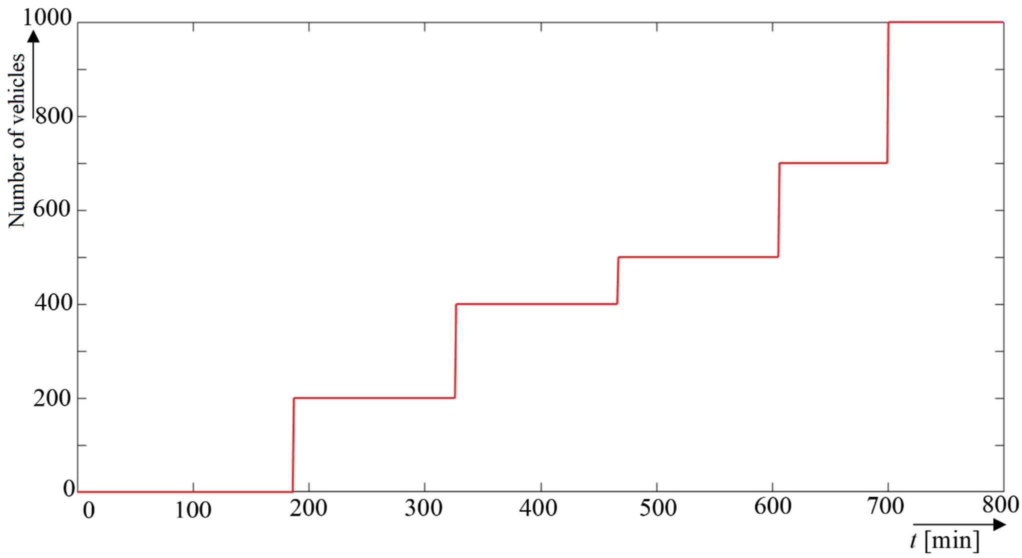

Figure 7 *The number of EVs in the idle state*

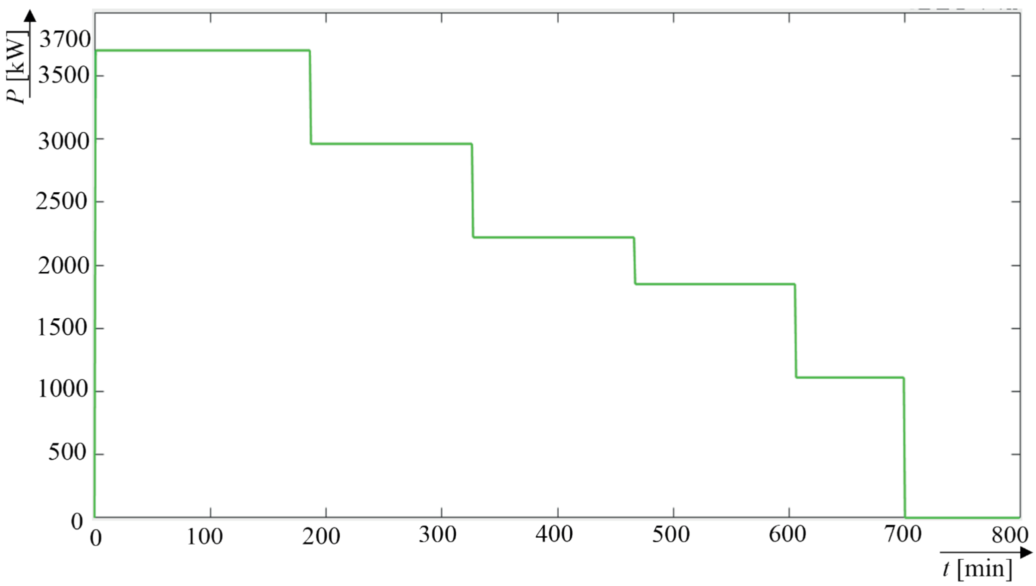

Figure 8 *The consumed power curve*

Table 1 *Evs parameters*

EV model	Nominal battery capacity	Charging time required for full charging from 20 % SOC by 22 kW charger
Tesla S85	85 kWh	3 hours and 29 minutes (209 minutes)

Table 2 *The initial state of charge*

EV	1	2	3	4	5
Initial SOC (%)	20	40	50	60	80

4.3 Comparison of the presented model to electrical model of battery charging

In this section, the EV fleet charging model defined using PDEs and the electric model of battery charging described in section 2.4 are compared. For such a comparison, the EV with parameters presented in Table 1 has been chosen. The charging rate of the charging point was assumed 22 kW. The manufacturer of a given EV type only defines the charging time for the maximal charging power of the EV. Therefore, we used an online calculator [18] that calculates the charging time of the selected EV as a function of the required charging energy and charging rate. The computed charging

Table 3 *Battery cell parameters*

Parameter	Value
Q (Ah)	3.1
U_K (V)	3.5
R_v (Ω)	0.01
K (V)	0.025
A (V)	0.2
B (Ah^{-1})	0.375

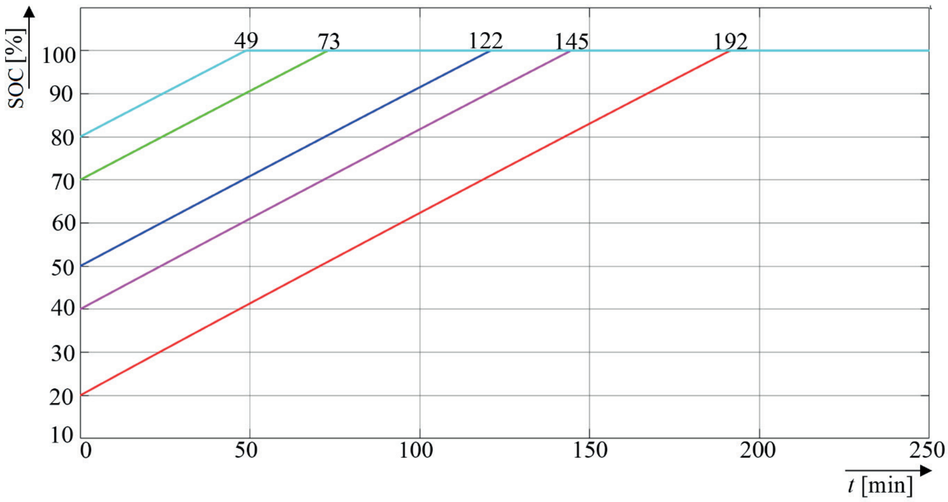

Figure 9 *The charging characteristics determined by the electrical battery charging model*

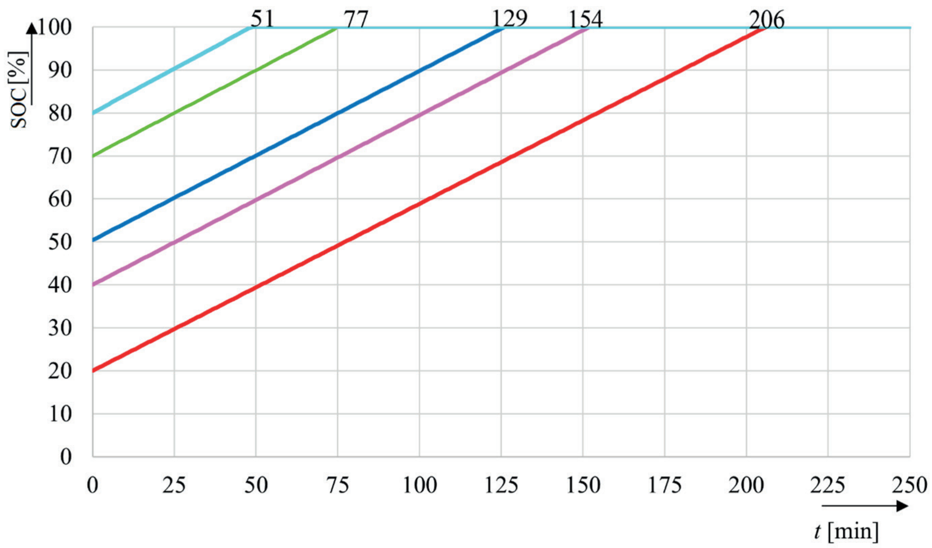

Figure 10 *The charging characteristics determined by the EV fleet model*

times of the presented charging model and the one from section 2.4 are compared, with the charging time from the online calculator presented in Table 1.

The full charging is represented by the charging window between 20 % and 100 % of the nominal battery capacity. The calculator has a preset charger efficiency value of 90 %, so the simulation models assume the same one. The charging process in a group of 5 Evs with different initial states of charge is monitored. The initial state of charge of individual Evs is presented in Table 2.

The battery charging model from section 2.4 calculates the battery charging time, current and voltage curves. The battery consists of battery cells, which are charged evenly in the battery and are assumed to be homogeneous. The parameters of the simulated battery cobalt blended lithium-ion cell are shown in Table 3.

Table 4 The average computation times

Number EVs in a fleet	Electrical battery charging model	EV fleet model with PDEs
5	37.25 s	0.188 s
10	73.68 s	0.180 s

The Tesla S85 vehicle battery is constructed from 16 modules connected in series. One module consists of 74 parallel-connected branches of 6 serial battery cells of type 18650. In one module, 444 such cells are connected. Based on this, the battery cell model was proportionally converted to the battery model. The resulting charging characteristics, determined using the electric battery charging model, are presented in Figure 9.

For the presented model of the fleet of EVs, it is also necessary to determine the discretization step dx the EV's data as:

$$dx = q_c = \frac{P_{nab} \cdot \eta}{Q_n \cdot 60} = \frac{22 \cdot 0.90}{85 \cdot 60} = 3.8824 \cdot 10^{-3}. \tag{21}$$

The simulation time was estimated from the expected charging time of the vehicle with the lowest initial charge according to the time given by the online calculator, namely 250 minutes. We kept the calculation step dt for 1 minute. The resulting charging characteristics are presented in Figure 10.

As can be seen in Figures 9 and 10, the character of the charging in both models is quite similar since the electrical battery charging model was used as the basis for definition of the EV fleet model. However, the charging window between 20 % and 100 % is 192 minutes, or 3 hours and 12 minutes in the simulation of the electrical model of battery charging, as shown in Figure 9. The reference charging time for this charging window (Table 1) is 3 hours and 29 minutes. In the EV fleet charging model, a full charge from the initial 20 % was achieved after 206 minutes, or 3 hours and 26 minutes, as shown in Figure 10. So, this second simulation case is closer with its charging time estimation to the reference one defined by [18] with a difference of only 3 minutes. However, the time difference in both models can be assumed small enough.

The main difference between the two models is their computation time. The average computation times for both simulation and for the case of an increase of EVs to ten within the fleet are presented in Table 4. As can be seen in Table 4, the computation time of the electrical battery charging model for 5 EVs in a fleet is much higher than the computation time of the EV fleet model presented in the paper. With the increase of EVs to ten within the fleet, the computation time of the electrical battery charging model increases even more. As can be seen in Table 4, the increase of the computation time is proportional to the increase of the EVs in the fleet and so utilization of this model, to represent charging of larger EV fleets, is not efficient. On the other hand, the computation time of the model defined in this paper is almost the same in both cases since the computation of PDEs defining the EV fleet model does not depend on the number of EVs. Therefore, this model can be computation time efficient for modeling large fleets of EVs, while keeping the accuracy of the model commonly used for battery charging representation.

5 Conclusions

Charging many electric vehicles represent an increased load on the power grid that changes unpredictably over time. Such uncontrolled charging of vehicles can cause problems with the stability of the grid or overloading of some of its parts. To study these impacts and implement measures to prevent them, modeling large EV groups charging is important.

Therefore, this paper defines a model suitable to represent the charging of the fleet of EVs that can vary in size without affecting the computation time. Simulation results show that the defined model meets the accuracy of the commonly used model representing battery charging while decreasing the computation time in comparison with these commonly used models.

The defined model can be used in future work in an analysis of the EVs' charging impact on the power system as a whole or its parts. Moreover, the model can be also utilized for the charging control system definition, where the EVs will be transferred between the charging and the idle states to meet the consumed power threshold or other requirements.

Grants and funding

The authors received no financial support for the research, authorship, and/or publication of this article.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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VEHICLE-TO-EVERYTHING COMMUNICATION

Zuzana Špitálová

Institute of Computer Engineering and Applied Informatics, Faculty of Informatics and Information Technology, Slovak University of Technology, Bratislava, Slovakia

E-mail of corresponding author: zuzana.spitalova@stuba.sk

Zuzana Špitálová 0000-0003-1865-1445

Resume

With an increasing number of vehicles, there is a need for reliable and secure communication between subjects participating in the dynamic traffic environment. This kind of communication is called V2X (Vehicle-to-Everything). It can also contribute to higher level of autonomous driving. The V2X model operation is enabled by use of the newest technologies and standards, defined by 3GPP Organization. In this paper, a review of the V2X communication models, available technologies and standards are studied.

Article info

Received 1 July 2022
Accepted 22 November 2022
Online 23 December 2022

Keywords:

VANET
DSRC-V2X
C-V2X
5G NR
IEEE 802.11bd

Available online: https://doi.org/10.26552/com.C.2023.017

ISSN 1335-4205 (print version)
ISSN 2585-7878 (online version)

1 Introduction

In the recent years, there has been a need for the V2X communication in the dynamic traffic environment. This communication ensures the safety and non-safety messages transmission. According to the subject, which is involved into communication, the last letter of the V2X model can change and define the models like:

- V2V (Vehicle-to-Vehicle) communication model
- V2I (Vehicle-to-Infrastructure) communication model
- V2N (Vehicle-to-Network) communication model
- V2P (Vehicle-to-Pedestrian) communication model.

Intelligent transport system

The first idea of monitoring the traffic was firstly formulated in Japan in the nineteen seventies. There was an intention to monitor the traffic information using telematics. It came to Europe in the nineteen eighties and there was the foundation of the ITS (Intelligent Transport System). The ITS supports the innovation services regarding the various traffic means and traffic management [1]. It helps to improve the safety and effectiveness of the traffic. This results in lower emissions. All the participants in the environment are the part of the ITS. Data generated by ITS system describe the real conditions on the road, traffic collision information or information about the planned journeys [2-3]. Seven groups of functionalities were defined, which should be covered by this system [3-4]:

- Travel and transportation management
- Travel demand management
- Public transportation operation
- Electronic payment
- Commercial vehicle operations
- Emergency management
- Advanced vehicle control and safety system.

The most known project, belonging to the ITS, is eCall [5], which enables to call emergency services in the European region in the case of accident.

There are also the organizations and partnerships, which define the conditions and standards for V2X, contributing to the ITS improvements. The most known is 3GPP (The 3rd Generation Partnership Project) Organization, founded in the year 1998 by the group of telecommunication associations [6]. This organization intended to create the standard for the 3rd generation of mobile telecommunication systems. Nowadays, it regularly works on releases, which define the supported technologies and functionalities for vehicular communication. Actually, they have been working on the Release 18 [6].

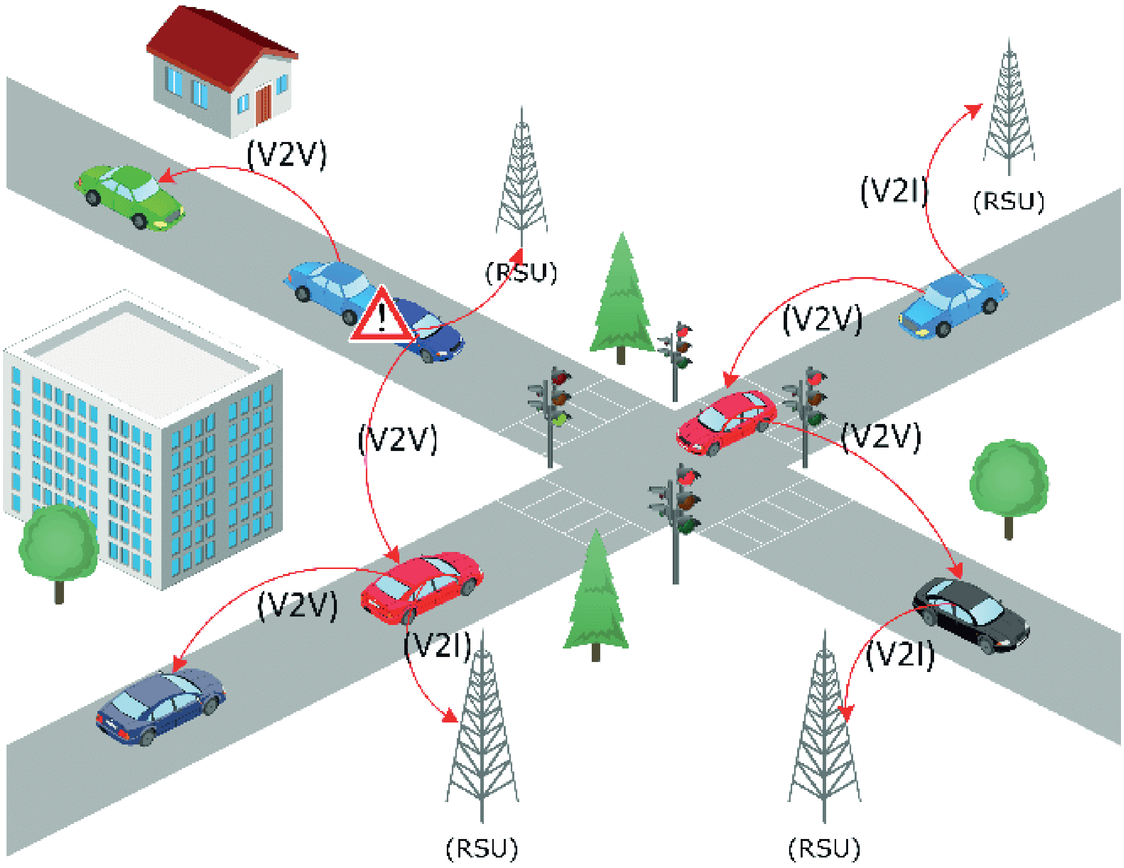

***Figure 1** The VANET environment with OBU and RSU units [14]*

VANET network and its components

The ITS operates in the vehicular network called VANET (Vehicular-Ad-Hoc-Network), which belongs to the subgroup of MANET (Mobile-Ad-Hoc-Network) networks. It is the network without the fixed infrastructure. That means, the communication between nodes is established spontaneously. The node can be any entity (vehicle, infrastructure, device) situated in this environment. The connection between nodes is enabled by the control units, like OBU (On-Board Unit) and RSU (Road-Side Unit). Both could be used like routers. An example of the VANET environment can be seen in Figure 1. Topology, created in the VANET network, is characterized by frequent changes and self-organization due to the high speeds of nodes. The connection is short and dependent on actual transport conditions [7-12].

VANET enables four communication types, unicast, multicast, geocast and broadcast. By unicast communication, the data packets are sent directly from source node to destination node. The multicast communication enables the group addressing of packets to nodes, which are located in the signal range of source node. By the geocast communication, the packets are sent to the nodes in geographical region. If the packets are received by the node from another geographical region, the data are damaged by the control electronics. By the broadcast communication, the data are sent from the source node to all the nodes in the network [9].

As it was mentioned, units OBU and RSU enable communication between the nodes in the network. The unit OBU is the hardware device integrated in the vehicle, together with another huge number of control units, creating the vehicle topology. It is used to establish the wireless communication. The received data are processed by this unit and resend to other units through the vehicular buses or to other nodes in the network [13]. The data sources are also obtained by vehicular telematics and vehicular technologies, like Head-up display, cameras or sensors. In addition to the received data, the OBU unit is able to transmit data, processed by vehicle itself.

The RSU unit is the hardware device equipped with the processor and antenna. It is able to establish wireless communication. However, it is equipped with the wire communication interface, as well. There are two types of these systems, static transport systems and smart transport systems. The first one works with the data from central systems, like information about weather or work on the road. The second one works with the actual data from the traffic system, obtained from cameras or from other nodes. As they are able to work like router, both can processed received data. The

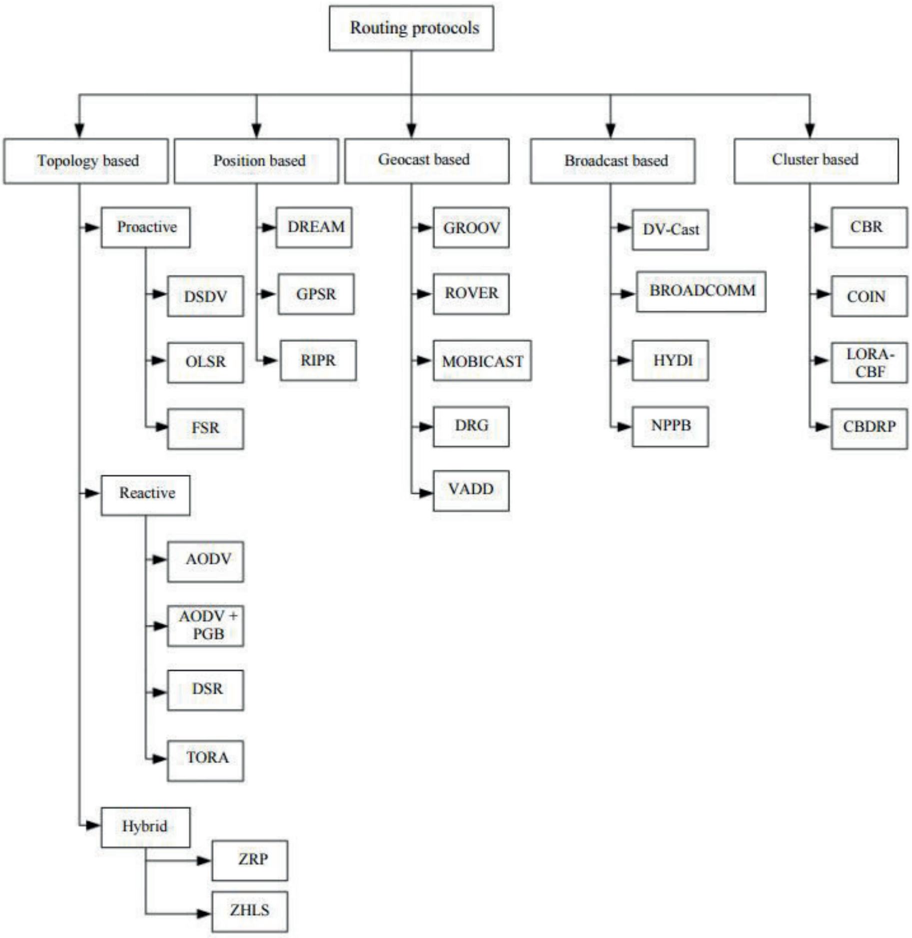

***Figure 2** Routing protocols [16]*

RSU units are normally located near to the main roads, highways, or gas stations [11, 13].

Routing protocols

As the topology of the VANET network is characterized by the frequent changes [15], there is a need for optimal creation of communication channels between the source and destination node. The optimal communication channel can be found using routing protocols, which could be classified like [9, 16-18]:

- Topology routing protocols: The idea of topology routing protocols is to find the shortest path between the source and destination node. Information related to route is stored into the routing table. According to the updating time, protocols are further divided into proactive, reactive and hybrid protocols [11].
- Position routing protocols: These protocols are based on the vehicle position or location from sources such as maps or GPS [16]. There is no need to maintain the topology information.
- Cluster routing protocols: Vehicles with similar characteristics, like velocity or direction can create a cluster with one cluster head. Cluster head is responsible for the communication with other clusters creating virtual infrastructure [11]. In the case of inside communication, the direct path is used.
- Geocast routing protocols: The information is forwarded between the nodes in the same geographical area. The packets are sent from source nodes to nodes in the same zone.
- Broadcast routing protocols: The information is shared between vehicles, which are outside the range of the source node [17]. It means that there is a flooding of information, shared via the nodes in the network. The information is related to emergency situations, road conditions or safety situations.
- Forwarding routing protocols: The information is transmitted via multiple hops between the nodes. This way is useful when the requested information is only in the interest of a few nodes [9].
- Beaconing routing protocols: This mechanism enables to store information, which are not time dependent and rebroadcast that with other incoming message.
- Delay-tolerant routing protocols: This scheme is used when the traffic density is low and the end-to-end routing is not possible, for example at nights.

In Figure 2, are shown the routing protocols mentioned above, which can also be classified into more subgroups.

***Table 1** Service requirements for V2X use cases [20-22]*

Service type	V2X applications	Description	Datarate [Mbps]		Latency [ms]	Comm. range [m]
			V2V	V2I		
Automated driving related services	Platooning	SAE J3016 Level 4/5 Platooning	65	50	20	80-350
Automated driving related services	Advanced driving	SAE J3016 Level 4/5 Automated driving	53	50	100	360-700
Safety related services	Extended driving	Collision warning	1000*	-	3*	50-1000
Automated driving related services Safety related services	Remote driving	V2X Data transfer	-	DL[1]:1 UL[2]:25	5	1000+

*- exclusive selection

[1]- Downlink, [2]- Uplink

Autonomous driving

With the increasing number of vehicles and used technologies enabling the vehicular communication, there is also the intention to increase the level of autonomous driving. In 2014, the levels were defined in the standard SAE J3016 [19] by the Society of Automobile Engineers (SAE). There are six of these levels:

- Level 0 - manual driving (No driver assistance systems.): The driver is fully responsible and permanently carries out all the aspects of the driving tasks.
- Level 1 - driver assistance (The system will perform one of the driving tasks.): The driver can delegate steering or accelerating/braking to the system.
- Level 2 - partial automation (The driver must permanently monitor the system.): The system will perform some of the driving tasks.
- Level 3 - conditional automation (In certain situations, the driver can turn attention away from the road, but must always be ready to take full control again.): The system can autonomously control the vehicle on defined routes.
- Level 4 - high automation (The driver can transfer complete control to the system and dedicate to other activities. However, he can take control at any time if he wishes.): The system is able to perform all the driving tasks.
- Level 5 - full automation (No driver needed): The system controls the vehicle autonomously under all the conditions.

V2X use cases and service requirements

Regarding to the V2X model, there are three groups of vehicle related services [20]. The first group, safety-related services, works with the real-time safety messages to decrease the risk of car accident. The second group, non-safety related services, makes the traffic flow effective. The last group, automated driving-related services, intends to increase the level of autonomous driving.

For each of the mentioned cases, there are requirements for quality of service [20-22]. These services mainly depend on maximal end-to-end latency and communication range. Very low latency (less than 10 ms) is required for V2X applications like collision warning or remote driving. As the communication range is also very important in these cases, the minimal one, which is needed to support some of the services, is 50 meters. The higher, the better, is the main requirement in these cases [21].

2 The V2X technology based on DSRC

There are several protocols and standards defining the communication between the nodes in VANET network, like WAVE protocol for North America and ETSI ITS protocol for Europe. Both define the standardization for the DSRC (Dedicated short-range communications). DSRC establish the communication via the OBU and RSU units [23-25].

WAVE protocol

This protocol is defined in the standard IEEE 1609 for the safety wireless communication. The communication model can be described with ISO/OSI model divided into four layers, as it can be seen in Figure 3.

Physical layer

Physical layer of the WAVE protocol is defined in the standard IEEE 802.11p. It supports different data rates using OFDM mechanism. The 75 MHz bandwidth in 5.9 GHz spectrum is divided into 7 smaller operation channels, each of 10 MHz bandwidth [2]. The channel 178 is the control one, channels 174, 176, 180 and 181 are used like service channels. Channels 184 and 172 are reserved for the future use. There was the channel

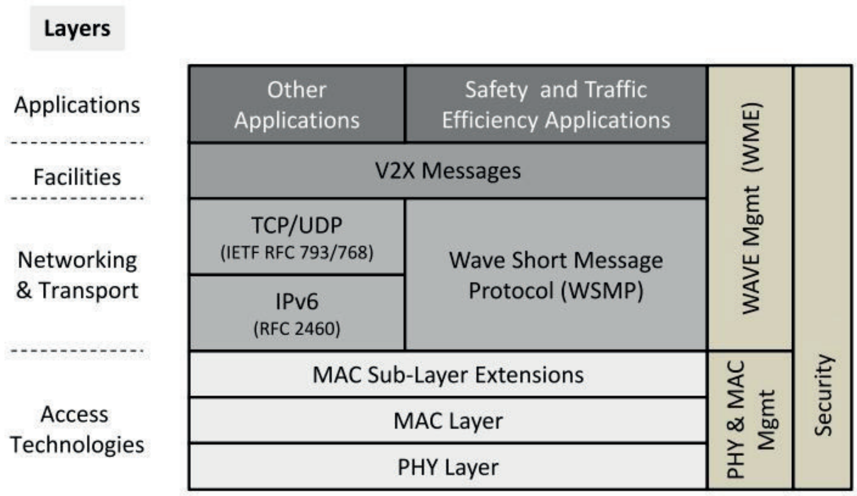

Figure 3 *Communication model for WAVE protocol [2]*

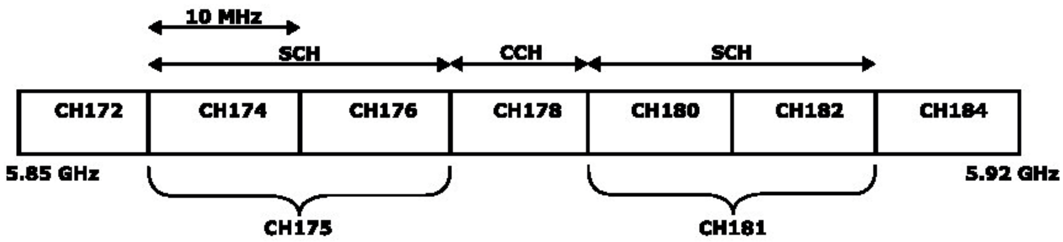

Figure 4 *WAVE frequency band [26]*

revision, which merged the channels 174 and 176 into the channel 175 and the channels 180 and 182 into the channel 181 [26]. The mentioned spectrum can be seen in Figure 4.

By devices with more than one physical layer, it is possible to use the control channel and minimal one service channel. By devices with one physical layer, there is a switch between the control and service channel. In this case, the devices are synchronized for monitoring and use the control channel [2].

MAC layer

The MAC layer of WAVE protocol is defined in the standard IEEE 1609.4. A typical reference model consists of two planes, data and management [27]. Data plane provides data service to the upper layer for incoming and outgoing data. Management plane provides synchronization and channel availability. The MAC sublayer provides channel switching for devices with parallel switching operation between the control and service channels [27].

WSMP protocol

The WSMP (WAVE Short Message Protocol) protocol allows applications to control features and parameters of physical layer [28]. It can be a number of a channel or receiver's MAC address. It is designed to have the minimal size.

BSM

The BSM (Basic Safety Message) protocol defines safety related messages, which are periodically sent by source node [29]. The destination nodes are all the entities in the signal range.

ETSI ITS Protocol

This protocol is similar to WAVE, just defined for the geographical region of Europe. In Figure 5, is shown the communication model described by ISO/OSI model divided into four layers, network and transport layer, access, application and facility layer.

Physical and MAC layer

Physical and MAC layer are defined by IEEE 802.11p standard. It is also called ITS-G5. It works in two frequency bands, 5 GHz using the OFDM mechanism. In the second case, communication works in the range of 5.9 GHz divided into smaller operation channels named from A to D. Version A works with the frequency of 30 MHz for safety messages, version B with the frequency of 20 MHz for non-safety messages and version C works

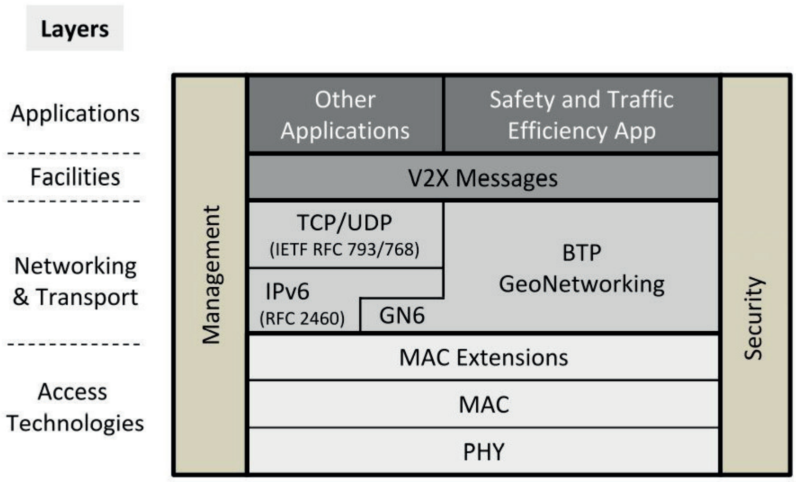

Figure 5 *Communication model for the ETSI ITS protocol [2]*

in the frequency band for radio access [2, 30].

GeoNetworking protocol

This protocol uses geographical coordinates for transmitting the safety related data. All the nodes, located in the geographical region of the source node, are able to receive the data. After processing the information, they forward the message in the range of the region.

CAM

The CAM (Cooperative Awareness Message) is safety related message with information about vehicle state, like position, direction or velocity. It is periodically sent by source node to destination nodes in the network to proceed the critical traffic situations [31-32].

DENM

DENM (Distributed Environmental Notification Message) messages are classified as safety related. They operate in the geographical region, which the source node is located in [32]. They are sent in the case of any change, not periodically.

Standard IEEE 802.11p

Standard IEEE 802.11p is based on its forwarder IEEE 802.11a for the WLAN network. In the traffic environment, it supports the communication between moving nodes up to the speed of 252 kmph, as it is seen in Table 2. Latency time is 100 ms and the communication range is about 1000 m. The transmission reliability is just 78% due to the noise effects [33-34].

Physical layer uses the OFDM (Orthogonal Frequency Division Multiplexing). The main difference is the carrier spacing and bandwidth, which are reduced by the factor of two (10 MHz of bandwidth and 156.25 kHz sub-carrier spacing). It uses BCC (Binary Convolutional Coding), which loses its capability to recover defect messages when the modulation and coding schemas are extended in a high communication range (more than 50 m) [14, 33, 35].

MAC layer uses EDCA (Enhanced Distributed Channel Access) method. This method uses CSMA/CA (Carrier Sense Multiple Accesses with Collision Avoidance) with no exponential back-off and no message acknowledgement [33].

Standard IEEE 802.11bd

Standard IEEE 802.11bd is based on the standard IEEE 802.11ac (Wifi 5). The standard "bd" is able to support double performance of "p" version. Regarding to the latency and communication range, one can expect the values < 100 ms and > 1000 m [33]. It supports the communication up to the speed of 500 kmph with double communication range of IEEE 802.11p. The used bandwidth channel is 20 MHz [14]. According to [33], the transmission reliability is just 88%.

The MCS (Modulation and Coding Scheme) profile enables to reach 256-QAM and MIMO (Multiple Input, Multiple Output) antenna helps to provide high throughput. The LDPC (Low-Density Parity-Check) coding mechanism and Midambles are used to establish the reliability in the environment of 500 kmph velocity [14]. In comparison with the "p" variant, which uses BCC, the supported velocity is double. More details there are seen in Table 2. There is also the standard IEEE 802.11bd^{DC}, which uses DCM (Digital Code Modulation) modulation to increase the communication range. It is based on the standard IEEE 802.11ax.

The MAC layer of "bd" variant uses EDCA method for channel access. With the frequency range of 20 MHz and 256-QAM MCS, it is possible to enable the message retransmission by sending each OFDM symbol over two different sub-carriers [33].

Table 2 *Comparison of IEEE 802.11p and IEEE 802.11bd standards [36]*

Feature	802.11p	802.11bd
Radio bands of operation	5.9 GHz	5.9 GHz and 60 GHz
Channel coding	BCC	LDPC
Re-transmission	None	Congestion dependent
Countermeasures against Doppler shift	None	Midambles
Sub-carrier spacing	156.25 kHz	312.5 kHz, 156.25 kHz, 78.125 kHz
Supported relative speeds	252 kmph	500 kmph
Spatial Stream	One	Multiple

3 The V2X technology based on C-V2X

C (Cellular)-V2X technology is good candidate for supporting the vehicular communication due to its coverage, security, mobile services and high network capacity.

LTE-V2X

The LTE (Long Term Evolution)-V2X communication mode is standardized by the 3GPP Organization supporting V2V, V2I, V2P and V2N communication models in the frequency band of 5.9 GHz [33].

Physical Layer

The physical layer of LTE-V2X technology is based on SC-FDMA (Single-Carrier Frequency Division Multiple Access) and supports the channels of 10 or 20 MHz. Each channel is divided into sub-frames, Resource Blocks, of 180 kHz (12 sub-carries each of 15 kHz). In terms of time, the channel is divided into sub-frames of 1 ms. Each sub-frame consists of 14 OFDM symbols with cyclic prefix (9 of them are used for data transfer and the rest of 4 are used for transport of demodulation reference signals, the last symbol is used for switching between the received and transmitted one via the sub-frames) [35].

The resource blocks are formed into sub-channels. Each sub-channel can consist of resource blocks just with the same sub-frame. The number of resource blocks for one sub-frame is variable and configurable. Sub-channels are used for transporting the data and control information. Data are formed into transport blocks and are transported via channel PSSCH (Physical Sidelink Shared Channel). Transport blocks contain the whole data packet and use QPSK, 16-QAM or 64-QAM modulation with turbo coding [21, 24].

Each transport block contains the SCI (Sidelink Control Information) message divided into two resource blocks, which are transported via PSCCH channel. The SCI message contains the critical information about received transport block, which is not able to be decoded. This data should be transmitted in one sub-frame [21, 36].

Transmission modes

By LTE usage, there are two transmission modes:

- LTE-Uu mode: This mode is applicable for short distances. The information is firstly transmitted to the entity eNodeB (also named eNB) via the uplink channel by source node. After that, the information is transmitted via the downlink to destination node [24]. The entity eNodeB is able to transmit the information to other nodes in the network using eMBMS (enhanced Multimedia Broadcast Multicast Service) [36].
- LTE-PC5 mode: This mode supports the direct communication between nodes via the PC5 interface using sidelink channel. The presence of the entity eNodeB is optional [36]. This case can be seen in Figure 6, where the RSU unit represents the eNodeB. The two modes are defined according to this situation. If the entity is present, there is mode 3. If not, there is mode 4 [24, 36-38].

Depending on the mode, which is used for the data transmission, the requirement for the latency is in the range between 20-100 ms [39]. The communication range can reach the value >1200 m [40].

5G NR V2X

5G NR (New Radio) V2X communication mode supports the advanced V2X functionalities and higher level of autonomous driving [37].

Physical layer

By 5G NR V2X, there are two frequency bands defined:

- Frequency band 1 (FR1): from 410 MHz to 7.125 GHz
- Frequency band 2 (FR2): from 24.25 GHz to 52.6 GHz.

In both cases, the sidelink channel is supported. By data transmission, the OFDM method with cyclic prefix

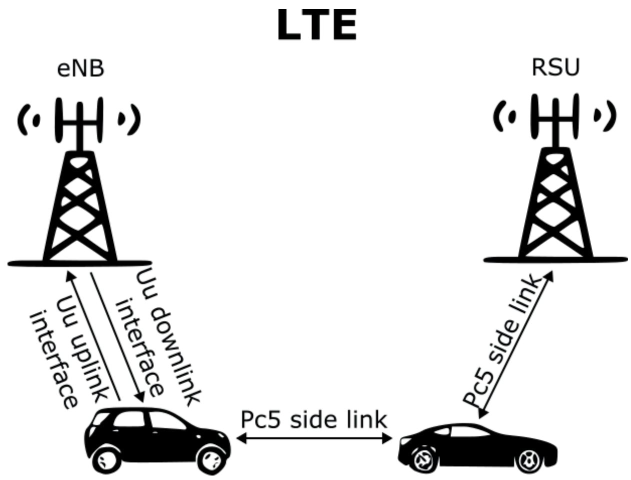

Figure 6 *LTE- communication model [24]*

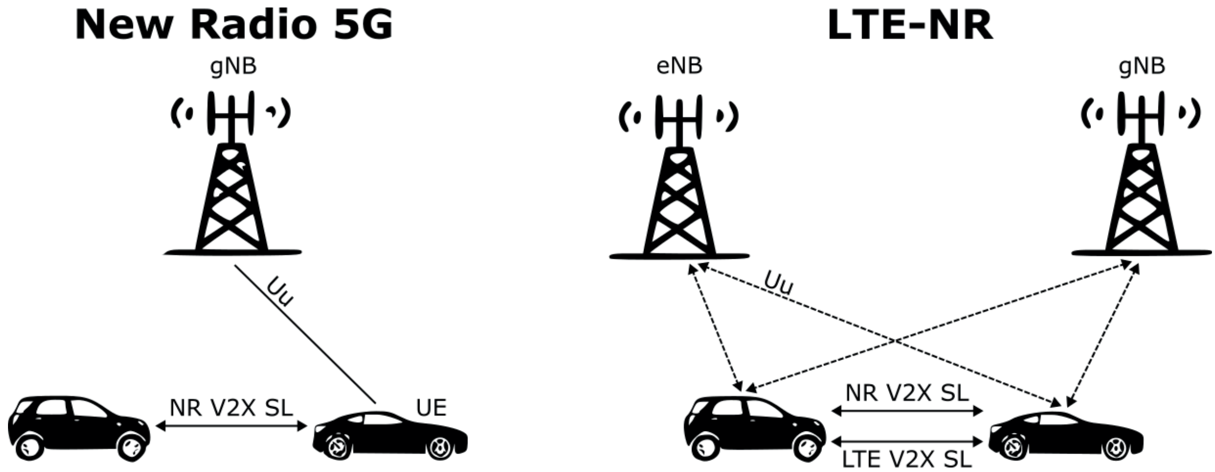

Figure 7 *Standalone (left) and non-standalone (right) 5G communication models [24]*

is used. The frame duration is 10 ms. Each frame is divided into 10 parts with duration of 1 ms. Sub-frames are organized into slots for data transmission. Sub-carrier spacing is defined for both, FR1 and FR2. For FR1, there are values 15 kHz, 30 kHz and 60 kHz. For FR2, there are values of 60 kHz and 120 kHz [21, 41]. In the terms of modulation, 16-QAM and 64-QAM are used [36]. More details, there are in Table 3.

Transmission modes

There are two transmission modes defined:

- Mode 1: This mode uses the interface PC5 supporting sidelink V2X communication for NR.
- Mode 2: This mode uses Uu interface supporting uplink and downlink channel in standalone (SA) and non- standalone (NSA) modes. In the standalone mode, the direct communication between vehicles or towards the entity gNB via sidelink channel is supported. It can be seen in Figure 7, left-hand side. In non-standalone mode, the data are transmitted firstly towards the gNB entity and forwarded to destination node [21, 24]. This can be seen in Figure 7 on the right-hand side. This model includes the possibility of the LTE usage, as well. For sidelink channel usage, there are four sub-modes defined [36]:
- Mode 2 (a): Each node (user) selects its resources autonomously.
- Mode 2 (b): Each node (user) is able to assist to other nodes (users) by resources selection.
- Mode 2 (c): In this sub-mode, the node (user) uses pre-configurable channel sidelink for data transmitting.
- Mode 2 (d): The node (user) selects the resources for another node (user).

Depending on the mode, which is used for the transmission, the requirements for the communication range is between 50-1000 m and 3-500 ms for the latency [39].

4 Conclusion

In this paper is described the V2X communication, which supports the data transmission between subjects in the traffic environment. Regarding to the latency and communication range, it compares C-V2X and DSRC-

Table 3 *Comparison of LTE-V2X and 5G NR V2X [36]*

Feature	LTE-V2X	5G NR V2X
Comm. types	Broadcast	Broadcast, Groupcast, Unicast
MCS	Rel. 14: QPSK, 16-QAM Rel. 15: 64-QAM	QPSK, 16-QAM, 64-QAM
Waveform	SC-FDMA	QFDM
Re-transmission	Blind	HARQ
Feedback channel	Not available	PSFCH
Control and data multiplexing	FDM	TDM
DMRS	Four/sub-frame	Flexible
Sub-carrier spacing	15 kHz	sub-6 GHz: 15, 30, 60 kHz mmWave: 60, 120 kHz
Scheduling interval	one sub-frame	slot, mini-slot or multi-slot
Sidelink modes	Modes 3 and 4	Modes 1 and 2
Sidelink sub-modes	n/a	Modes 2(a), 2(d)

Table 4 *Comparison of DSRC-V2X and C-V2X regarding to V2X use cases [33, 39-40]*

Parameters	IEEE 802.11p	IEE 802.11bd	LTE-V2X	5G NR V2X
Latency [ms]	100	< 100	20 - 100	3 - 50
Communication Range [m]	1000	> 1000	> 1200	50 - 1000
V2N Service Support	No	Yes	Yes	Yes
Supported V2X Use Case	Advanced driving (SAE J3016 level 3)	Advanced driving, Platooning (SAE J3016 level 3)	Advanced driving Platooning	Advanced driving Platooning Collision warning (partially) Remote driving (partially)

V2X communications referring to the V2X use cases in Table 1. In Table 4, are mentioned the V2X use cases in the column of the type, which is able to fulfill the requirements.

Comparing IEEE 802.11p and IEEE 802.11bd, the "p" version is able to fulfill partially the requirements for advanced driving. The problem is the transmission reliability, which is just 78%. For advanced driving of the SAE level 4 or 5 that is not enough. The IEEE 802.11p is just suitable for the cases of the level 3. The version "bd" fulfills the requirements of advanced driving and platooning with the reliability 88%. Thus, that is not enough for the SAE level 4 or 5.

Regarding to C-V2X communication, the LTE-V2X fulfills the specifications for platooning and advanced driving of SAE levels, which are higher than 3. For the use cases like collision warning and remote driving, that is not enough regarded to the latency. In the case of communication range, the LTE is suitable just partially. The 5G NR V2X is able to fulfill the requirements for the use cases of platooning and advanced driving. For the other cases, it fulfills the specifications just partially. By collision warning, the latency is on its lower limit and by remote driving, the communication range is not enough.

To summarize the data, the C-V2X seems to be a good candidate for vehicular communication regarded to extended functionalities. In cooperation with vehicular telematics and with higher functionalities of 5G NR V2X, which are still under research, there is a big potential to reach the higher (4 or 5) SAE level of autonomous driving.

Grants and funding

The author received no financial support for the research, authorship and/or publication of this article.

Conflicts of interest

The author declares that she has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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FEM MODELLING OF THE TEMPERATURE INFLUENCE ON THE STRESS-STRAIN STATE OF THE PAVEMENT

Alexandr Shimanovsky[1], Abdujabbor Karabayev[2], Iryna Krakava[1], Volha Tsyhanok[1], Ibragim Sodikov[2], Abduvokhid Yunusov[3,*]

[1]Department of Technical Physics and Engineering Mechanics, Belarusian State University of Transport, Gomel, Belarus
[2]Department of Urban Roads and Streets, Faculty of Highway Engineering, Tashkent State Transport University, Tashkent, Uzbekistan
[3]Department of the Traffic Engineering and Management, School of Engineering, Kimyo International University in Tashkent, Tashkent, Uzbekistan

*E-mail of corresponding author: abduvokhid.yunusov@gmail.com

Alexandr Shimanovsky 0000-0001-8550-1725,
Abdujabbor Karabayev 0000-0002-9880-8547,
Iryna Krakava 0000-0002-8750-1806,
Volha Tsyhanok 0000-0001-8032-2285,
Ibragim Sodikov 0000-0002-2595-288X,
Abduvokhid Yunusov 0000-0002-5569-4172

Resume

The highways that are used in the countries with a sharp continental and a hot climate operate in the conditions when the pavement temperature changes along its height. This fact can lead to a significant increase in stresses in the layers of the road structure. In this paper is suggested an approach to solution of the joint problem of the pavement deformation and the heat propagation in it by a finite element modelling technique. The ANSYS software package was applied to solve the described problem. It is shown that an increase in the road surface temperature leads to a significant increase in the von Mises-equivalent stresses in the asphalt concrete upper layer and that is the cause for the ruts formation. Computational results also showed that at low temperatures of the road surface, the significant tensile stresses arise in its upper layers and that leads to formation of cracks.

Article info

Received 18 July 2022
Accepted 15 November 2022
Online 12 December 2022

Keywords:

road pavement
asphalt concrete
temperature
stress-strain state
finite element modeling

Available online: https://doi.org/10.26552/com.C.2023.011

ISSN 1335-4205 (print version)
ISSN 2585-7878 (online version)

1 Introduction

When vehicles pass through the highways, the roads are under the action of cyclic loads. Large flows of vehicles of various masses lead to accumulation of the residual deformations in various elements of the pavement; this subsequently causes damages of its surface. Climatic conditions have a significant impact on the strength of roads, as well. Seasonal fluctuations in air temperature throughout the year, as well as its jumps due to sharp changes in weather conditions for several days, lead to a change in the stress-strain state of the pavement layers [1-2]. The climate of Uzbekistan is sharp continental and it is characterized by a dry hot climate. The summer in Uzbekistan is dry and hot, the average temperature in July in the flat part of the country is +26 °C to +30 °C and in the south of the country it reaches +31 °C to +32 °C. The absolute maximum of the air temperature in Tashkent is +44 °C, in Termez - +50 °C. The surface of the asphalt concrete pavement is heated up to +75 °C to +80 °C. In this regard, it becomes necessary to assess the effect of uneven temperature distribution in the road structure on stresses in it and its deformations. The similar analysis is also in demand in other countries, including the European ones, due to the climate changes [3-5].

Nowadays, the significant number of experimental studies, related to the analysis of the temperature distribution along the pavement height, have been carried out. The authors of the paper [6] present the results of measuring the temperature and moisture of the pavement upper layer on the island of Bali (Indonesia). It is shown that during the day the change in the temperature of the surface layer can reach

35 °C. In the article [7] there are presented the results of experiments performed in order to determine the temperature, moisture, stresses and strains in the pavement of an experimental road section in Lithuania. The above information shows that during the calendar year the range of temperature changes in the road surface layer is more than 65 °C. At the same time, the temperature difference at the surface and at the base of the pavement at a particular point in time can reach 20 °C or more. The measurement results also showed that the stresses in the upper layer of the road surface during the passage of cars do not, as a rule, exceed 250 kPa. In the paper [8] there are presented the experimental results of the determining the temperature in the layers of the pavement in Slovakia. In [9], a two-layer pavement was modeled to determine the effect of ambient temperature in summer on an asphalt concrete pavement, taking into account the traffic load.

In the paper [10] there are investigated the factors that determine the temperature value on the pavement surface. The dependences demonstrating the effect of thermal conductivity on the pavement temperature are given. A technique that allows to calculate the pavement temperature depending on the meteorological conditions typical for Sweden at different times of the year is described in [11]. The authors of papers [12-13] propose a method for determining the temperatures in pavement elements based on parameters that determine the meteorological situation in the place under consideration.

The authors of [14] provide an overview of studies on determining temperatures in the pavement and present various empirical models and analytical dependencies that make it possible to establish the distribution picture for the physical, mechanical and geometric temperatures for different road parameters and environmental conditions.

In [15], a simplified model is proposed to describe the thermo-viscoelastic deformation of the road surface under the action of a moving load from tires. Comparison of the calculation results to the experiment demonstrated a satisfactory accuracy of the obtained results. It is noted that for a more precise determination of the maximum deformations, a detailed investigation of the base deformation features is required.

In the work [16] there are analyzed the distribution patterns of temperature, moisture, stresses and strains in the pavement and subgrade of a highway located in the northern part of Kazakhstan during one year, in particular, during the cold period. The distribution of temperature and the moisture was studied experimentally using special sensors. It is shown that in the winter the elasticity modulus of the asphalt concrete layers and the upper part of the subgrade increases significantly: up to 18,000 MPa and 10,000 MPa, respectively. Stress and strain calculations were performed using a mathematical model of an elastic multilayer half-space. It has been established that all the stress and strain components at the points of the pavement and subgrade change significantly during the annual cycle. Similar results were obtained by Lithuanian scientists [17].

In recent research, there are many investigations performed by scientists from different countries where the stress-strain state of the road surface and the formation of various defects in road structures are studied. In [18], it was considered a multilayer system as one- or two-layer and the author established the depth where the stresses from the load action are almost unchanged. The authors of the article [19] used the Drucker-Prager model of the material elastic-plastic deformation to establish the effective equivalent stresses and strains in the coating at maximum operational loads. The problem was solved using the finite element model in the ANSYS software package. The results of the developed and optimized compositions of a complex organic binder based on Dzharkurgan oil, viscous bitumen and gossypol resin with structure-forming additives are given in [20-21]. These compositions ensured the latter's strength in the range of 1.1-1.5 MPa.

The authors of paper [22] demonstrate the results of determining the allowable temperature gradients for a cement concrete pavement that do not allow formation of microcracks on their surface. The finite-difference method implemented in the PARUS software was used to study the stress state. The analysis used a strength criterion based on the process of formation and development of microcracks in concrete. Similar studies were carried out in [23]. In investigations [24-25] there were considered the peculiarities of the non-elastic deformation of the materials of the asphalt-concrete surfaces, as well as the approaches that are supposed to take into consideration the found effects at the process of computer simulation. However, those calculations did not consider the effect of the load from a passing car.

The stress-strain state analysis of the pavement system under moving aircraft loads is performed in investigation [26]. It is demonstrated that the Mises model allows to obtain the stress results that are the closest to the experimental data. The finite element method is applied for determining the stresses in asphalt pavements due to action of the moving load in papers [27-28]. It is shown that this method allows to get the results that are close to the experimental ones.

In papers [29-30] there are demonstrated the results of the finite element modeling of the stress-strain state of the cement concrete pavement under the action of passing vehicles for various temperatures of the pavement.

Thus, the performed analysis allows to obtain a large amount of information on the experimental determination of temperatures, stresses and deformations in the road surfaces. In addition, the methods for calculating temperatures in the road material were developed in sufficient details. However, no investigations were found with calculations of the

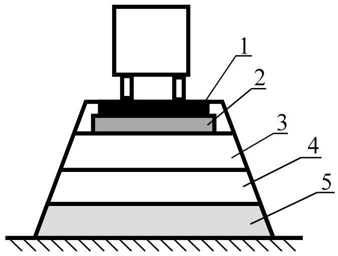


Figure 1 *Estimated model of the road surface: 1 - dense asphalt concrete, 2 - porous asphalt concrete, 3 - highly porous asphalt concrete, 4 - gravel mixture, 5 - dusty sandy loam*

Table 1 *Physical and mechanical properties of pavement layer materials*

Layer Number	Thickness layer (mm)	Density (kg/m^3)	Young modulus (MPa)	Poisson's ratio	Coefficient thermal expansion (1/K)	Specific heat (kJ/kg·K)	Thermal conductivity (W/m·K)
1	60	2300	3200	0.30	10^{-5}	1.65	1.40
2	90	2300	2000	0.25	10^{-5}	1.65	1.25
3	120	2000	2000	0.25	10^{-5}	1.65	1.00
4	400	1700	205	0.15	10^{-5}	1.00	0.64
5	-	1600	46	0.35	1.18×10^{-5}	1.10	0.62

pavement stress-strain state under the loads from moving vehicles, taking into account the peculiarities of the temperature distribution along the pavement height.

The purpose of the presented paper is to determine the influence of temperature distribution in the pavement on its stress-strain state. In this case, the algorithms developed earlier [31-32] are used to solve other technical problems.

2 Finite element model

As an example of the model the section of the first category road (according to the scale used in Uzbekistan) is considered, the corresponding scheme is shown in Figure 1. The used type of pavement includes four layers, which are made from various materials. The physical, mechanical and geometric characteristics of the layers used for the calculations are shown in the Table 1. The physical and mechanical parameters are taken from [33]. The thickness of the base (of the layer 5) was assumed to be 830 mm. The investigation demonstrated that in this case, it is possible to determine the stresses and deformations in the road surface with a sufficient degree of accuracy, therefore, no increase in its thickness was required.

The standard method for calculating the road surface assumes application of uniformly distributed pressure from the tires to the road section. When the vehicles move along the road, it is affected by several tires at the same time. Taking into account the periodicity of load application along the length and width of the pavement, a structural element containing a section that includes ¼ of the load application area is selected. Thus, a parallelepiped is taken as the calculation area, which includes several layers of the road surface with different physical and mechanical characteristics. The resulting geometric model is shown in Figure 2.

The finite element model of the selected pavement structural element was created using the ANSYS Mechanical software. To conduct a complex static and temperature analysis, the pavement layers were modeled by a 20-node Brick-element Coupled Field 226, which allows to consider the features of multiphysics analysis. The finite element mesh was created in a semi-automatic mode, the number of finite elements of the model was about 7000.

A uniformly distributed pressure of 600 kPa was applied to the model surface circle quarter of the 140 mm radius, this load simulated the force acting on the road from the tires. A symmetry condition is imposed to all the side surfaces of the parallelepiped as bonds; vertical movement is prohibited for the lower surface of the lower layer. In addition, for the pavement upper layer the different temperatures T_t were set from the range from - 20 to + 50 °C relative to the constant temperature of the lower surface of layer 5, which was assumed to be 0 °C. The selected range of temperature changes corresponds to the conditions of Uzbekistan, which is located in the sharply continental climate zone. In this paper, the change in Young's modulus depending on the increasing temperature is neglected. Therefore, for example, at the base temperature T_0 = 20 °C the real surface temperature of 70 °C corresponds to the T_t = 50 °C.

During the calculation, the solution of the coupled

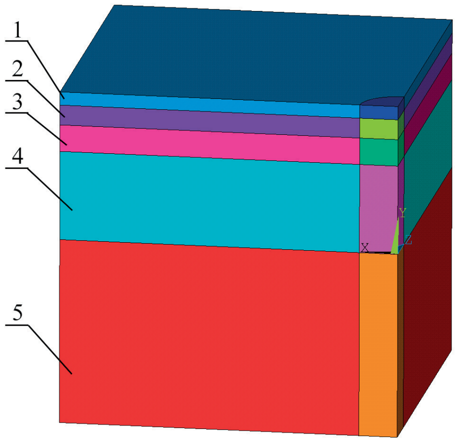


Figure 2 *Structural element of the pavement. The layers of the material correspond to the pavement layers shown in Figure 1*

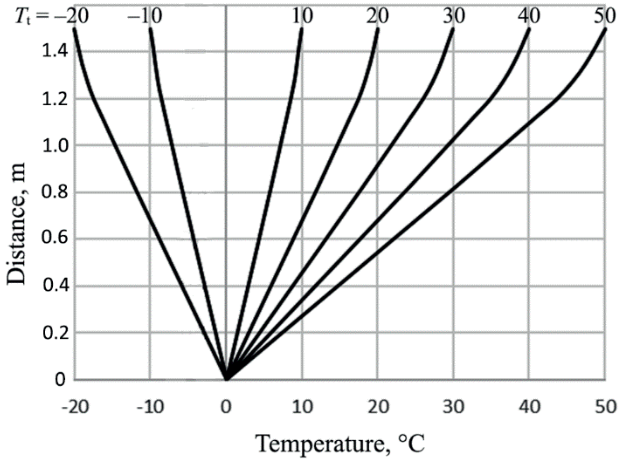


Figure 3 *The obtained temperature changes in the pavement layers at different surface temperatures T_t.*

thermoelastic constitutive equations [34] was performed:

$$\{\varepsilon\} = [D]^{-1}\{\sigma\} + \{\alpha\}\Delta T, \tag{1}$$

$$S = [\alpha]^T\{\sigma\} + \frac{\rho C_p}{T_0}\Delta T, \tag{2}$$

where: $\{\varepsilon\}$ - total strain vector; $[D]$ - elastic stiffness matrix; $\{\sigma\}$ - stress vector; $\{\alpha\}$ – vector of the thermal expansion coefficients; ΔT - temperature change relative to the reference temperature (it was assumed 0 °C); S - entropy density; ρ - density of a material; C_p - specific heat at constant stress; T_0 - absolute reference temperature (K).

3 Calculation results and their analysis

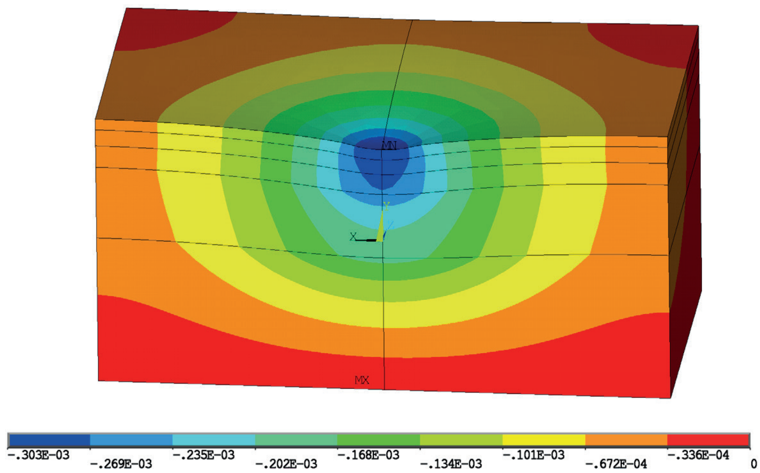
During the calculations, the distributions of temperature, stresses and strains in the pavement layers were obtained.

Figure 3 shows graphs demonstrating the calculated temperature changes along the road height at different temperatures of its surface. Their comparison to the experimental dependences presented in [16] shows a fairly good agreement.

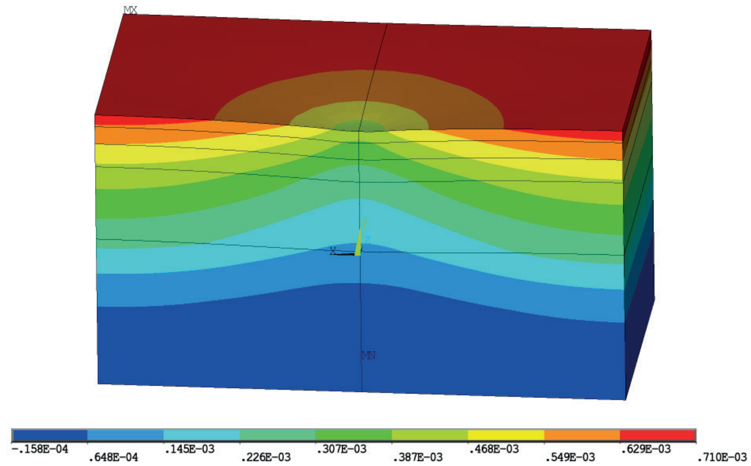
Figure 4 shows the distribution of deformations along the cross section of the road near the place of the load application. Under the applied load action, at the same temperature at all the points of the road surface, all the road surface layers are displaced downwards, as shown in Figure 4, a. When the pavement is heated, its thickness increases due to the thermal expansion. The application of the load from the tire weight leads to a decrease in deformations caused by heating and the total movement of the four upper layers of the pavement at high heating temperatures remains positive, i.e. they do not return to their original position.

There should also be noted that the difference between the largest and the smallest displacements of the model points in the case of pavement heating increases and for the temperature T_t = 50 °C the ratio is 2.4 times in comparison to the case of the not heated pavement, that fact indirectly indicates an increase in the uneven distribution of stresses over the volume.

Comparison of the von Mises equivalent stress patterns (Figure 5) confirms the conclusion presented



a)



b)

Figure 4 *Pavement deflections at temperatures: a - T_t = 0 °C, b - T_t = 50 °C*

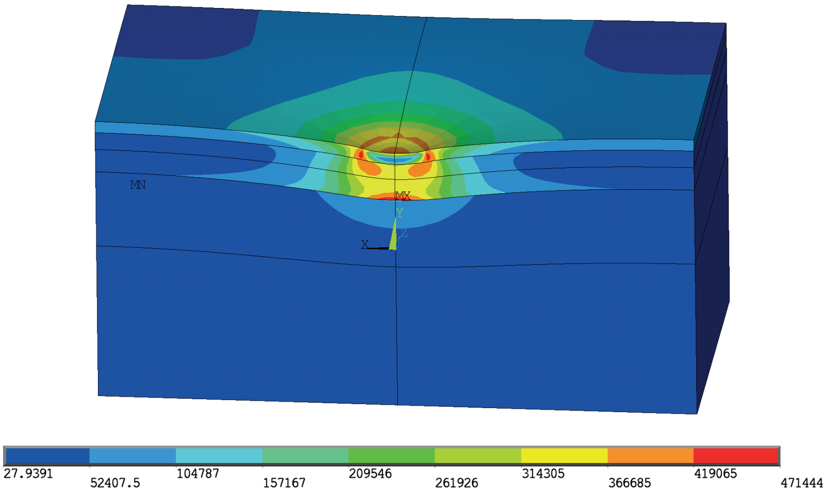
earlier in the strain analysis. At the same temperature of the road layers, the stresses in the three upper layers are distributed fairly evenly, so, it can be assumed that they work like a three-layer plate on an elastic base (Figure 5, a). In the case of the road upper layer heating the greatest stresses are concentrated in the upper layer of the road (Figure 5, b). The maximum stress values increase by a factor of 5.7 compared to the case without heating (up to 2.7 MPa). This causes formation of the ruts in the places where the tires pass. It should be noted that the presented calculation did not take into account the decrease in the asphalt concrete stiffness with an increase in temperature, which is observed in practice. Consequently, the track appears on the road not only due to a change in the mechanical characteristics of the road surface upper layer, but due to the redistribution of stresses due to the temperature deformations, as well.

Figures 6 and 7 show how the displacements and stresses in the layers of the road surface change when the heating temperature of its surface changes and the pressure force of the car tire is taken into account. The presented figures show that the greatest deformations are observed in the first and the second layers at a temperature of about 30 °C. At the same time, at temperatures above 20 °C, the base is practically not deformed. However, the greatest modulus values of deformations are observed when the air temperature decreases.

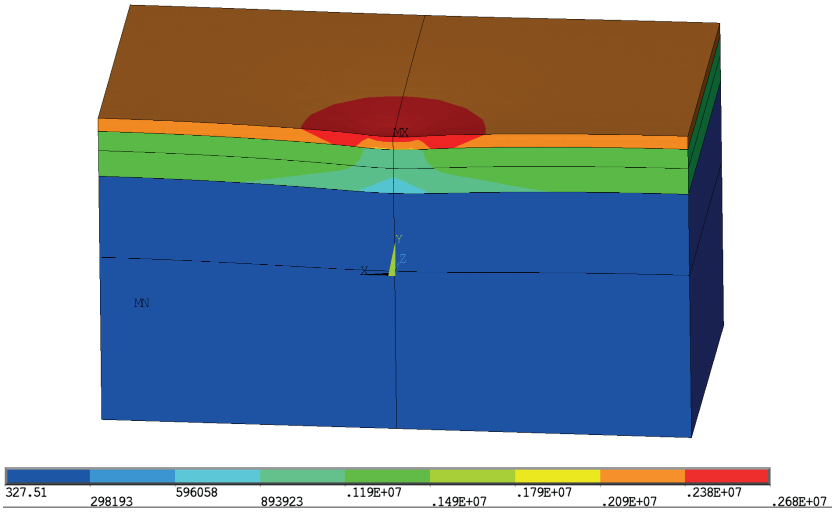
Graphs of the von Mises equivalent stresses changes demonstrate a significant increase in their values in the layer 1 material both with an increase and a decrease in the temperature. In the first case, this can lead to the formation of a rut and in the second case - to the road surface cracking.

4 Discussion and conclusions

The paper considers a technique for the finite element modeling of thermal elastic deformation of a road surface using an element that implements the possibility of the Coupled Fields analysis. Taking into account the actual distribution of temperatures in the pavement made it possible to establish that the presence of a temperature gradient leads to a significant increase



a)



b)

Figure 5 *Distribution of the von Mises equivalent stresses in the pavement layers at temperatures: a - T_t = 0 °C, b - T_t = 50 °C*

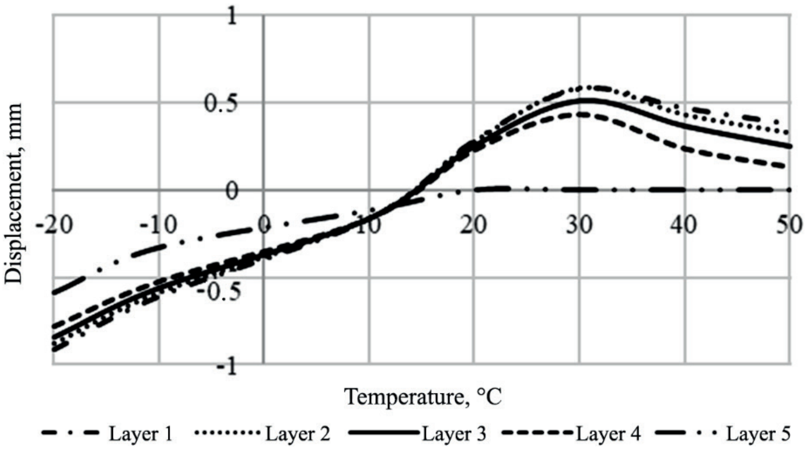


Figure 6 *Change in the maximum displacements in the layers of the road under the center of the contact area between the wheel and the road surface depending on the temperature of the upper layer T_t.*

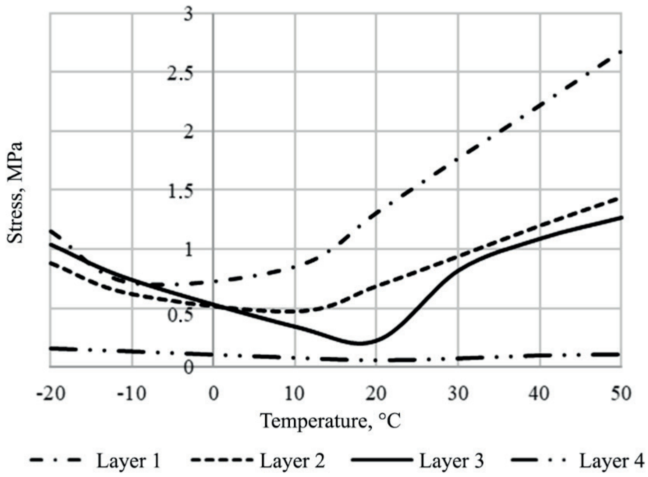


Figure 7 *Changes in the maximum von Mises equivalent stresses in the wheel-road contact zone depending on the temperature of the pavement top layer*

in the asphalt concrete pavement upper layer stresses. When the pavement surface is heated to 50 °C the maximal stresses in the upper layer of the road surface increase by 4 times compared to the case when the temperature of all the layers is the same. This fact is one of the reasons for formation of the ruts on the road at high air temperatures. At a low pavement surface temperature the most unfavorable situation is observed in the third layer of the pavement where the stresses are doubled. This leads to the pavement cracking at low temperatures.

The results presented in the paper were obtained for the model that does not consider the dependence of the materials mechanical characteristics on temperature. A decrease in the elastic modulus due to the temperature increase would lead to some decrease in the road surface upper layer stresses. To perform an appropriate quantitative analysis, the use of nonlinear equations for the deformation of materials is required and this kind of investigation is planned to be performed in the further work.

The proposed method for the pavements' calculation can be applied to the optimization of the geometric and physical parameters of pavements.

Grants and funding

The authors received no financial support for the research, authorship, and/or publication of this article.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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THE ROLE OF TRANSPORTATION COSTS ON AFFORDABLE HOUSING FOR LOW-INCOME CLASS

Mohammad Mehdi Khabiri[1,*], Saeed Nemati Pour Ghasem Abadi[2], Zohreh Ghafori Fard[1]

[1]Civil Engineering Department, Yazd University, Yazd, Iran
[2]Art University of Isfahan, Isfahan, Iran

*E-mail of corresponding author: mkhabiri@yazd.ac.ir

Mohammad Mehdi Khabiri 0000-0003-3434-7603, Zohreh Ghafori Fard 0000-0002-9084-982X

Resume

This research was conducted to investigate the current state of transportation, as well as the transportation costs of the residents of towns with affordable residential houses, by preparing and presenting a questionnaire to these residents. In this questionnaire, things like housing costs, the amount of travel to the city center, satisfaction with public transportation services and its variety, easy access to public transportation and required places, the amount of use of public transportation and private vehicles were examined and solutions to reduce transportation costs were presented. Although the price of housing in the towns is lower than in the city center; the costs of transporting the residents of these towns are significant. In addition, the state of public transportation and access to needed places is unfavorable, so that about 60% of the interviewees were dissatisfied with public transportation services.

Article info

Received 3 August 2022
Accepted 22 November 2022
Online 19 January 2023

Keywords:

AM
affordable housing
low-income
public transportation
transportation costs
transportation of settlers

Available online: https://doi.org/10.26552/com.C.2023.020

ISSN 1335-4205 (print version)
ISSN 2585-7878 (online version)

1 Introduction

Housing and transportation are the two biggest categories of household expenses; Hence, they are the focus of majority of affordability analyses. However, since the transportation and land use have a close relationship with each other, it is not possible to create affordable housing without paying attention to transportation costs and the cheapness of land; because the cheap housing is usually in towns far from the city center and, if no measures are taken for transportation, the residents of these towns will bear huge transportation costs and finally, living in towns with cheap residential houses far from the city will not be economical due to transportation costs. Transportation constitutes the main spatial structure of cities and has fundamental effects on the shape and direction of urban development. Cities have complex transportation systems and these transportation systems give strength to cities. Therefore, paying attention to its affordability is of particular importance [1-2]. Affordability of goods or services means people's ability to buy basic goods and services. In recent research, it has been suggested that, to deal with the challenges of providing affordable public transportation services to poor urban residents at a cost that does not harm the financial-economic sustainability of the urban transportation system, city officials can set fares at "cost recovery" levels. appropriate, determine and target for the majority of the population and give subsidies to those who need them the most[3]. On the other hand, in 2010, transportation was the fourth category of household consumption (6.9%) for people who were in the lowest consumption sector (after food and beverages (41.5 %), housing (14.7%) and energy (8.1 %)), [4]. Lack of affordability can be the most important factor for the lack of access of the low-income class of the society to special transportation [5-6]. The affordability of transportation can be defined as the ability to make essential trips to work, school, health and other social services and to meet other family members or other urgent trips without restrictions resulting from economic issues [7]. Providing a definition of transportation poverty requires combining sub-concepts such as transport affordability, mobility poverty, accessibility poverty and exposure to transport externalities (Figure 1) [8].

In this regard, studies have been conducted in recent years; for instance, according to the research of Bagnoli et al., determining the affordability of transportation is

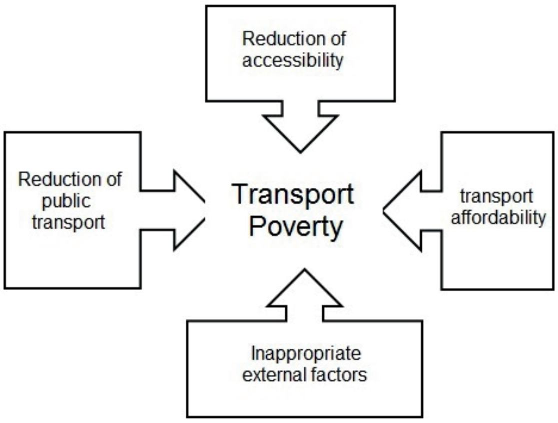

***Figure 1** Interrelationships between the dimensions of transportation poverty [8]*

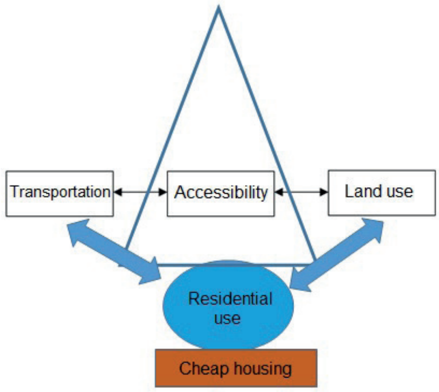

***Figure 2** Mediated accessibility between land use and transportation*

a complex process because while transportation needs are individual, income is a family characteristics, [9]. On the other hand, it is not possible to define a definitive criterion for determining affordable transportation for all the countries; although Srivastava [10] suggest that this criterion should be considered 15 to 20% of household income for countries with developing economies. Guarda et al. in a 2016 study [11], stated that in the field of measuring transportation costs, the affordability of transportation for low-income groups may not show for the two reasons. First, there is more fare evasion in deprived areas. Second, poor people may avoid some motorized trips because they are too expensive. In this regard, authors found that fare evasion in Santiago is more frequent in bus stations located in low-income areas than in high-income areas, which shows that there is a relationship between fare evasion and inability to pay bus fare. On the other hand, the studies of Falavigna and Hernandez [12] and Behrens and Vente [13] show that in some poor parts of the city, walking accounts for 40 to 45% of all the trips by the low-income people, while this value is 10 to 20% for the higher income groups. These findings are important for designing transportation policies that benefit low-income groups. Rodriguez et al., in a study on the experiences of Latin American cities in promoting bicycles as a means of daily transportation [14], state that the main goal of affordable policies is that people can make all the necessary trips to access education, health, work and social services without forcing them to ignore essential activities. In fact, affordable policies have two main effects on mobility patterns. First, they can encourage greater use of public transportation. Second, they can facilitate switching from walking to public transport over long distances, although this effect is often small. In other words, to the improve transportation conditions for poor people, the authorities should invest in walking, cycling and public transportation facilities. It should be noted that public transportation has a special place [15], because public transportation systems have the greatest impact on urban development and provide the possibility of providing a situation for "combination of land use" and "public transportation".

Transportation and housing have a close relationship with each other [16-17]; accessibility is a fundamental concept that expresses the basis of the relationship between the land use and transportation (Figure 2) and refers to the ease of moving between places; because when transportation becomes cheaper in terms of money and time, access will increase [18-19]. The person's accessibility is usually measured by counting the number of activity places (opportunities) that are available at a certain distance from the person's home and multiplying that number by the distance (Equation (1)) [20-21]. This capability can be calculated for all the kinds of opportunities from shopping, work, training etc. In fact, it can be said that the four main components of accessibility include land use, transportation, time and the needs and abilities of community members (Figure 3). In addition, this relationship can be presented in the form of Equation (2) [22].

$$A_i = \sum_j O_J d_{ij}^{-\beta}, \tag{1}$$

$$A_{total} = \frac{1}{N(N-1)} \sum_{i \neq j}^{N} \sum_{j=1}^{N} \alpha_{ij}, \tag{2}$$

where is:

A_i: The accessibility of person I,

O_J: The number of opportunities at a distance d from the person's home,

d_{ij}: A measure to measure the size of the separation between i and j,

β: A fixed value that is obtained by paying the model,

A_{total}: access to different places,

α_{ij}: travel time between two places i and j are in this relationship.

Therefore, nowadays planning for affordable housing with development policies that include the effects of transportation is very important and since housing is the biggest expense of most households, the importance

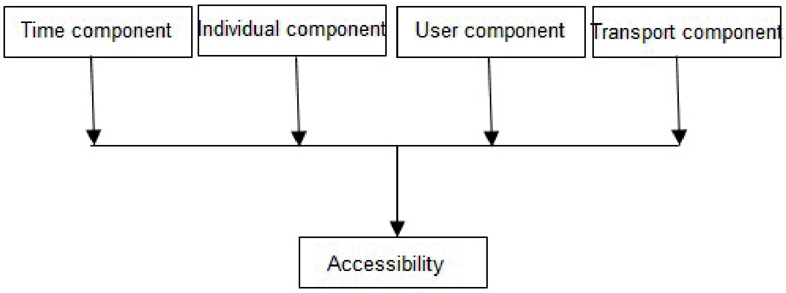

***Figure 3** Components of accessibility*

of this issue is doubled. Considering the general goals of providing affordable housing in areas with proper access and transportation options, there is a need to reduce unnecessary costs caused by the possible overestimation of car travel and its related effects [23] .Determining the affordability of housing is a complex process, just like determining the affordability of transportation. Housing affordability was initially defined as households not spending more than 30% of their budget on housing; but since the costs of housing and transportation are interdependent, many experts recommend that housing affordability is defined in such a way that the housing and transportation costs of a household are at least 45% of their budget. This shows that a cheap house is not really affordable if it has a high transportation costs. In this regard, experts suggest a more compact and multifaceted development of the city by reducing the distance between destinations and improving the options of non-motorized modes of transportation and modes of public transportation, which improve the overall accessibility, especially for pedestrians or public transportation passengers and as a result, living in a central urban neighborhood increases the variety of services and activities available at a given time and financial budget and in addition, it saves travel time and travel costs [24]. In this regard, Newmark et al. in a research in the field of affordable housing [25], state that the provision of affordable housing is influenced by proper location because the provision of affordable housing is influenced by the transportation costs. In fact, for the construction of affordable housing, high-efficiency neighborhoods, that is, places that meet the needs of residents with the lowest transportation costs, should be selected or created. High-level efficient places enable residents to drive less by making shorter trips or by using cheaper transportation modes such as walking and biking and as a result, residents' transportation costs are significantly reduced. In a 2020 study, Xiaohong et al. [26] also stated that social justice can potentially be improved by well-designed transportation systems. However, this is despite the fact that transportation facilities and systems are usually lacking and weak in towns where the land and housing are cheaper, which imposes high transportation costs on this low-income group. Abd El-Hameeda et al. consider one of the transportation problems in Egypt to be the lack of attention to urban planning and transportation issues and transportation costs [27].

As mentioned, transportation costs have a significant impact on housing costs, so that it is not possible to create affordable housing without paying attention to the transportation costs and the cheapness of the land. Therefore, this study and investigation of the transportation situation of towns deals with the preparation and completion of the questionnaire, as well as with solutions to reduce transportation costs for the low-income people and to create cheap housing with low transportation costs are introduced.

2 Research methodology

As mentioned, it is impossible to provide affordable housing for low-income people regardless of transportation costs. It is possible that cheap housing is usually located on the outskirts of cities and towns adjacent to the city and is far from the city center; therefore, if a suitable plan to provide cheap transportation for these areas is not considered, the residents of these areas will have to pay huge costs to meet their needs and access to the city center. Therefore, to check the current situation of transportation of the residents of towns, a questionnaire was prepared and provided to the residents of towns. This questionnaire includes questions about the costs of housing, the amount of travel to the city center, satisfaction with public transportation services and its variety, easy access to public transportation and required places, the amount of use of public transportation and private vehicles. In order to analyze the factors affecting this research, a statistical test was performed using the KMO (Kaiser-Mayer-Okine) method, the results of which are presented in Figure 4 and Table 1. According to Figure 4 and Table 1, only four primary factors have the greatest effect and the rest of the variables have similar and small effects.

In continuation of the research, the answer sheets were evaluated using the SPSS software. In addition, in this research, the countries that were successful in this field are examined and finally, it offers suggestions in this regard. The countries investigated in this field include Turkey, Brazil, Taiwan, America, England, Egypt and Australia.

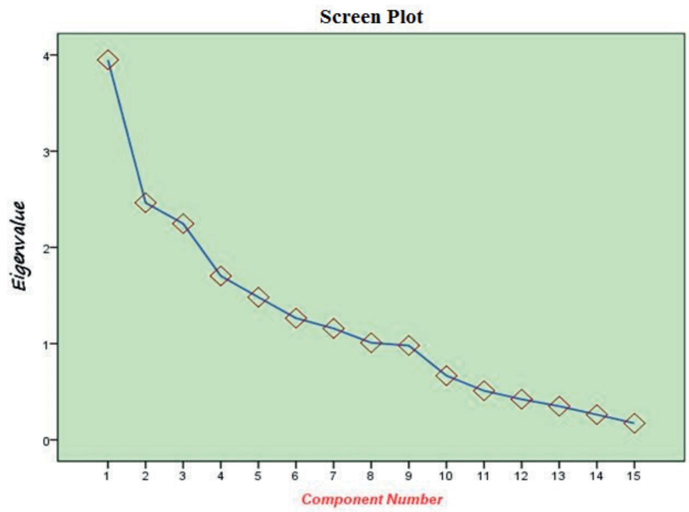

***Figure 4** Chart of specific values of the number of factors extracted in this study*

***Table 1** Extracted factors along with specific values, % age of variance and cumulative % age of variance*

Component	Question subject	Cumulative %	% of Variance	Total
1	Housing costs	21.190	21.190	3.949
2	The amount of travel to the city center	34.411	13.221	2.464
3	Transportation costs	46.466	12.055	2.247
4	Satisfaction with public transportation	55.604	9.138	1.703

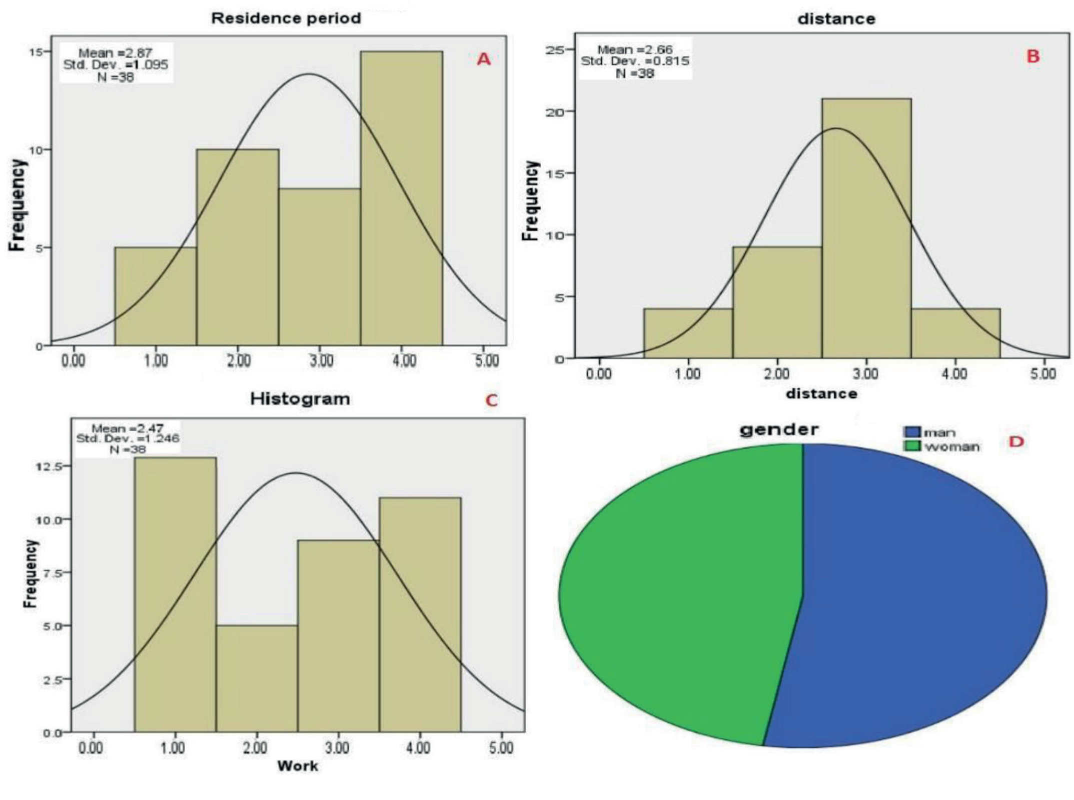

***Figure 5** Frequency diagram related to: a - Duration of residence in the town; b - The distance of the town from the city center; c - Type of work; d - Gender of people.*

3 Results and discussions

As mentioned, to check the existing transportation situation of the residents of towns, a questionnaire was prepared and given to the residents of towns and then the answers were evaluated using the SPSS software. In Figure 5, the graph of the frequency data related to the characteristics of the people completing the questionnaires and in Figure 6 and Figure 7 the graph of the frequency data of the answers are presented.

According to Figure 5, most of the people who participated in completing the questionnaires have been living for a long time (more than 8 years) in towns with more than 10 kilometers from the city center and most of them are employees. According to Figure 5-d, about 47.4% of people are women and 52.6% are men.

According to Figure 6, it can be seen that in the current situation, although the price of housing in the towns with affordable and low-costs residential houses is lower than in the city center; the costs of transporting the residents of these towns is significant and the public transportation and access to the required places are also unfavorable. For example, according to Figure 2-d, most of the residents were dissatisfied with public transportation services and according to Figure 2-i, most of the residents do not use public transportation due to dissatisfaction with transportation services.

In general, there are two ways to improve the transportation situation and reduce the transportation costs of the towns' residents. The first solution is to create places needed by the towns' residents, such as supermarkets, hospitals, etc. in the towns, which reduces the need to move to the city center. The second solution is to increase the variety of public transportation and improve their services, which is discussed in the next section.

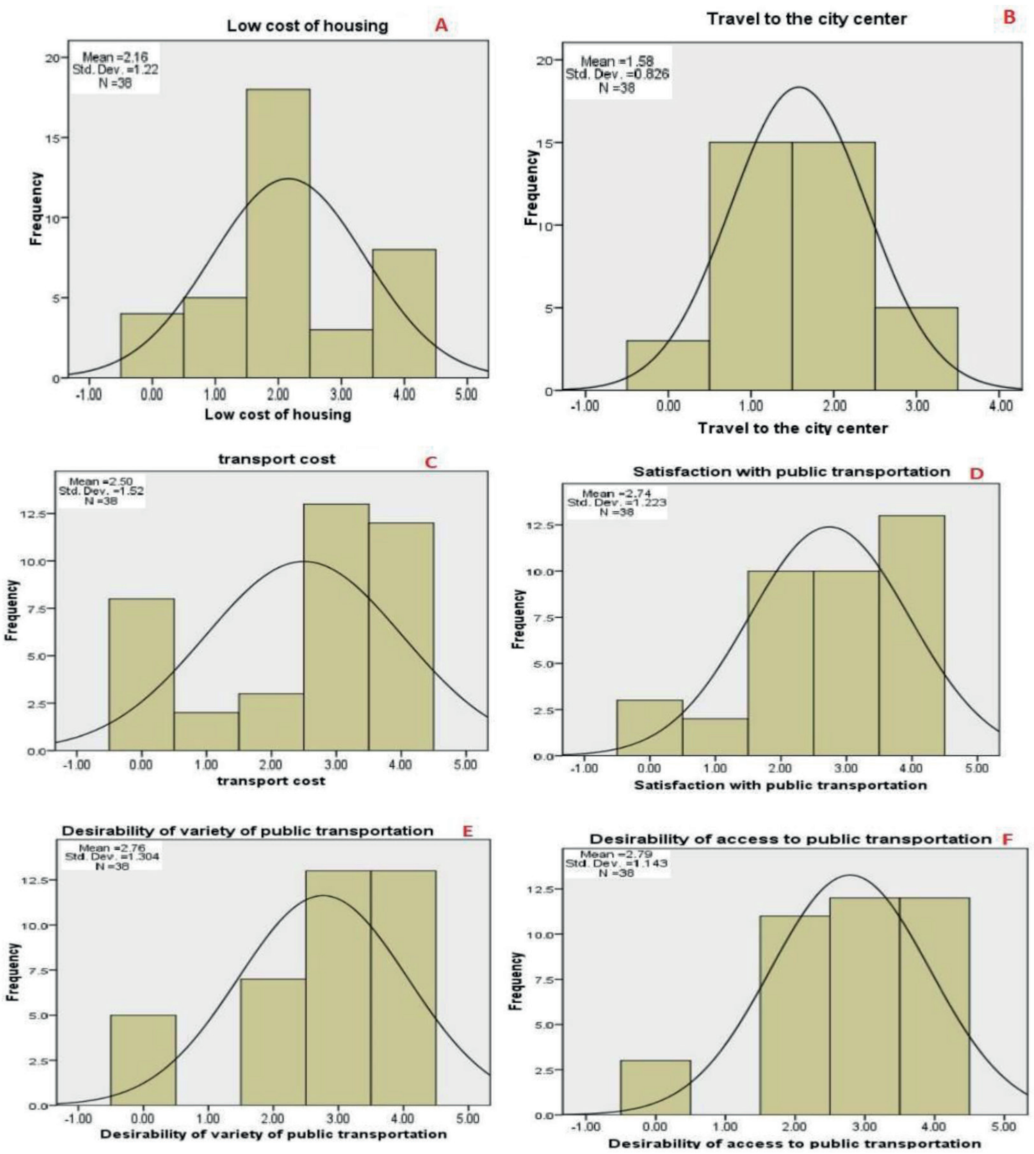

***Figure 6** Frequency diagram related to answer to:A - Question 1; B -Question 2; C - Question 3; D - Question 4; E - question 5; F - Question 6.*

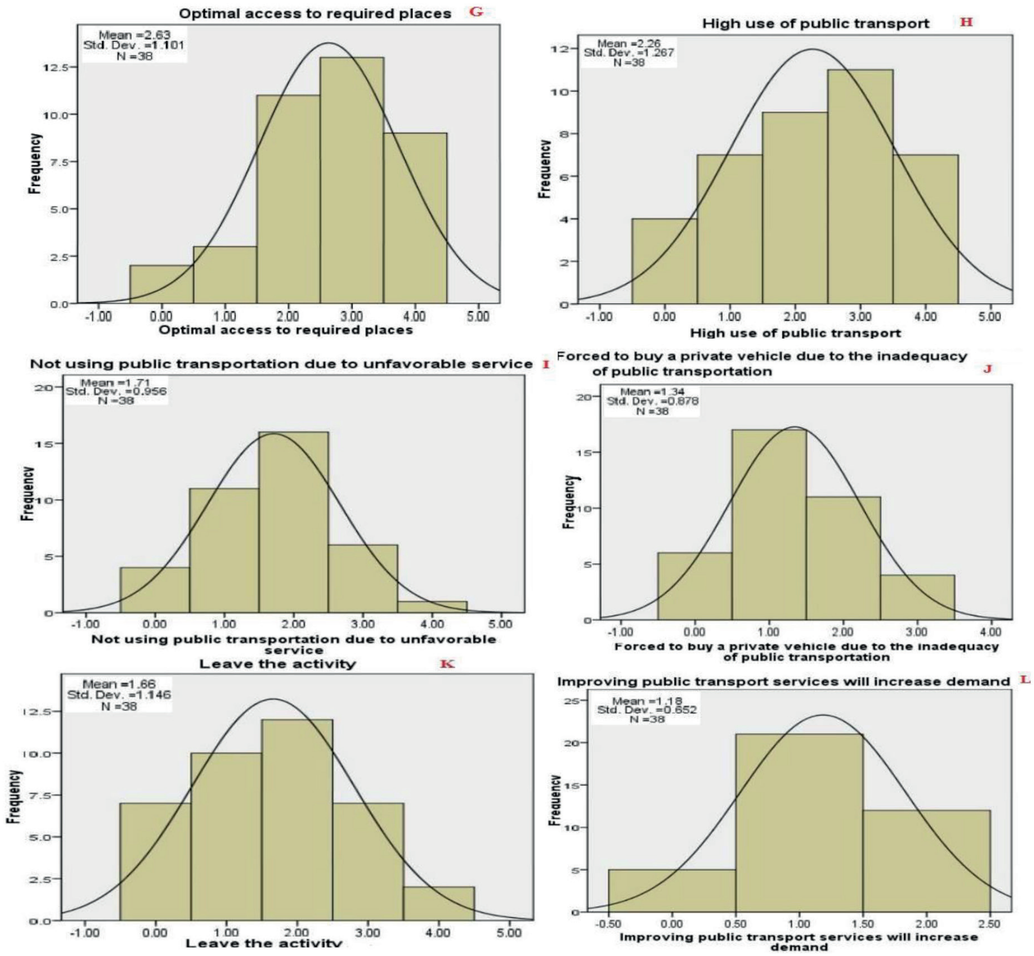

Figure 7 *(Continuation of Figure 6) Frequency diagram related to answer to: G - Question 7; H;-;Question ; I - Question 9; J - Question 10; K - Question 11; L - Question 12.*

Table 2 *Suitable transportation systems for the low-income class in different countries*

Transportation modes	Country
Bus-Dolmus- Metro and Tram- Metrobus	Turkey
Bicycle-Bus-Metro-Taxi	Brazil
Metro (MRT) - City bus - Public bicycles	Taiwan
Metro-Bus-Tram-Taxi	America
Bus - Metro - Docklands Light Rail (DLR) - Water Bus - Local Trains - Public Bikes - Taxi - Tram - Air line Cable Cars	United Kingdom
Bus-Taxi-Minibuses-Metro	Egypt
Metro-Bus-Tram-Taxi-Bicycle	Australia

4 Solution to reduce the transportation costs for towns with affordable residential houses

As mentioned, one of the ways to reduce the transportation costs for the low-income class is to increase the variety of public transportation and improve their services. In Table 2, urban transportation modes, used in countries successful in this field, are presented.

The bus transportation system is one of the most popular and cheapest urban transportation systems, which can be considered the main type of ground transportation. The transportation costs by bus in the mentioned countries are very economical and considered as one of the cheapest modes of transportation (Figure 8-A). The use of modern and standard buses with high comfort facilities in these countries has attracted many passengers to this mode of transportation. The BRT is a bus-based public transportation system designed to improve capacity and reliability over conventional bus systems. In the United States, several medium-

A

B

C

D

E

F

G

H

Figure 8 *A - Bus transportation system; B - Double-decker bus; C – Dolmus; D - Metro and tram; E - Aerial tram; F – Metrobus; G - Docklands Light Railway; H -Airline cable cars*

sized cities have replaced BRT with light rail. In addition, London's iconic double-decker buses are a fast, comfortable and cheap way to travel around the city and create many opportunities to see London sights along the way (Figure 8-B).

Dolmuses are actually buses whose size is smaller than regular buses and their use is faster and more comfortable. 10 to 15 passengers can ride in these dolmuses. The costs considered as a ticket for this vehicle are very low (Figure 8-C).

Metro and tram are one of the best and most economical means of transportation in Turkey. This method of transportation is very fast and efficient and is used to move people in different parts (Figure 8-d). It should be noted that there is an interesting type of tram in New York, which is aerial, which runs along the

East River of Roosevelt Island. This type of tram was opened as the first aerial tram in North America in 1976 (Figure 8-E).

Metrobus is actually the name given to the buses that work in the subway format. Metrobuses are used for fast transportation in the city. Of course, in many of these routes, metrobuses are connected to other public transportation vehicles. With this integration, passengers can easily access different means of transportation and reach their destination easily (Figure 8-F).

Contrary to the thinking of some people who consider using a bicycle as just a hobby or a sport, bicycle is an effective and common mode of public transportation in cities. Using the bicycle sharing method in cities is considered as an important method for commuting inside the city. The citizen bike-sharing program first started in Rio de Janeiro, a city in Brazil, but in less than 10 years it has spread across the country.

Another common mode of transportation in cities is using a taxi. Although commuting by taxi can reduce the travel time, its costs are higher than for other modes of transportation.

The innovative and unmanned Docklands rail system covers London's East and South East London rail system (Figure 6-G). With the use of water buses, one can access the main areas of the England capital very quickly and one can also enjoy the beauty of the river Thames while moving. London's local trains are in close correlation with the subway lines, but the route of these trains is more extended than the underground railway lines and they provide people with the ability to access areas far from the subway.

Airline cable cars is a mode of transportation that has been implemented in the city of London. With the airline cable cars, one can enjoy the beautiful views of the city while moving around the city. Airline cable cars are an easy way to get around the Greenwich Peninsula. The journey with aerial cable cars takes about 10 minutes. Cars with a capacity of 10 people arrive at the station every 30 seconds (Figure 8-H).

4.1 Comparison of suitable transportation systems for the low-income classes in different countries

In general, most of the countries have expanded various modes of public transportation to ensure social justice in transportation and to provide transportation infrastructure for the low-income classes, as well as to reduce traffic pollution and they encourage people to use the public transportation by implementing policies that limit personal motorized transportation and, on the other hand, increase the possibilities of public transportation modes and make it cheaper. The development of a diverse set of public transportation means, with appropriate and cheap facilities, provides the possibility of moving the low-income classes efficiently, while maintaining social justice and this is while neglecting different modes of public transportation, or not improving its facilities and instead of paying too much attention to personal motorized transportation and creating multiple infrastructures for it. In addition to causing various pollutions, including visual, noise and air pollution in the cities, social justice is questioned and the citizenship rights of the low-fashion classes are ignored.

According to the above mentioned modes of transportation, buses, minibuses, subways, trams with suitable facilities, similar to the mentioned examples, can be a suitable option for the transportation of the low-income classes and reduce the transportation costs related to low-income classes, which is usually built on the outskirts of cities and far from city housing and help create a real affordable housing.

5 Conclusions and suggestions

Since the transportation and land use have a close relationship and that it is not possible to create affordable housing without considering transportation costs and the cheapness of land, this research was conducted to investigate the current state of transportation, as well as the transportation costs of the towns' residents with affordable residential houses by preparing and presenting a questionnaire to these residents. In this questionnaire, things like housing costs, the amount of travel to the city center, satisfaction with public transportation services and its diversity, easy access to public transportation and required places, the amount of use of public transportation and the personal vehicle was analyzed, and some of its results are summarized below:

According to the statistics conducted, in the current situation, although the housing prices in towns are lower than in the city center, the costs of transporting the residents of these towns are significant and the public transportation and access to the required places are also unfavorable.

The results of the survey clearly show that the inadequate access to public transportation means and their lack of diversity and the inappropriateness of amenities, public transportation services and, most importantly, the large distance between them, cause the residents of the studied towns to be reluctant to use the public transportation. It should be noted that the results of the survey show that more than 86% of the interviewees believe that with the improvement of public transportation services and conditions, the demand and willingness to use public transportation will increase.

The reluctance to use public transportation due to the problems in the public transportation system of the towns has caused the residents of these towns to use personal transportation or taxis to move to the city center and carry out their activities, which has resulted in a lot of costs. Therefore, creating a coherent set of public transportation modes with facilities and reasonable prices can be a very effective solution to reduce the transportation costs, especially in towns and far from the city center.

By identifying the usual needs of a citizen, the urban layout should be such that in every neighborhood and town, citizens can reach the place they need to meet their needs by traveling a short distance. For example, they can reach schools, clinics, stores, etc. by walking a short distance.

Another way to reduce travel and, as a result, reduce the transportation costs is to improve telecommunication and internet facilities in cities and especially towns; because with telecommunication services, many things can be done offline and virtually and there is no need to move and pay for it.

Grants and funding

This article is extracted from the research project, entitled “Comparative study of urban land models in different countries and the role of governments in providing housing for low-income groups”. The number of this contract is 666/92358, dated 15th November 2021, with the National Land and Housing Organization.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Questionnaire used in this research.

Number	Question	Completely agree	Relatively agree	No idea	Relatively	Against	Completely opposed
1	The costs of housing in the town where you live is lower than in the city center.						
2	You travel to the city center due to daily needs and high employment.						
3	The transportation costs from your place of residence to the places you need are less than in the city center.						
4	You are satisfied with the public transportation of the place of residence to access the city center.						
5	The variety of types of public transportation is suitable in the town where you live.						
6	Access to public transport in your town is very easy.						
7	In the town where you live, it is easy to access all the necessary places, such as supermarkets, hospitals etc. and there is no need to go to the city center.						
8	You use public transportation a lot.						
9	Due to the inadequacy of amenities and the large distance from public transportation you do not use public transportation to get around						
10	Due to the inadequacy and lack of public transportation services and the lack of access to the required places, you have to buy a personal vehicle.						
11	Due to inappropriate transportation services and distance from the city center, forced to give up job or educational, recreational and sports activities.						
12	It is believed that with improvement of the public transportation conditions, there is no need for a private car anymore and the demand is related to public transportation will increase.						

RECKONING LEVEL OF RISK AND SEVERITY (LORS) BASED ON THE GAP ACCEPTANCE AT A THREE-LEGGED UNCONTROLLED INTERSECTION OF A RURAL HIGHWAY

Khushbu Bhatt*, Jiten Shah

Institute of Infrastructure, Technology, Research and Management, Ahmedabad, Gujarat, India

*E-mail of corresponding author: k22112011@gmail.com

Khushbu Bhatt 0000-0002-1251-2121, Jiten Shah 0000-0002-7100-8582

Resume

Traffic safety assessment is an essential part of traffic planning and engineering. At uncontrolled intersections, the severity of crashes has increased manifolds. This is due to the fact of not following the priority rule during the right-turning movements. In conventional methods, past accident records were used to analyze traffic safety. However, the drawbacks of the traditional method to estimate the severity require a lot of accident data for analysis to draw any conclusion and suggest safety measures. The accuracy of the record of accidents and details is highly uncertain. Therefore, surrogate safety measures are being used to analyze the safety. In the present paper, the gap acceptance time (GT) is used to examine the risk and the speed and gap values define the level of risk and severity (LORS). Moreover, using the value of the critical gap, the probability of risk is estimated. Further, the level of risk and severity is computed based on the gap and speed data of vehicles at an uncontrolled intersection. Hence, with the speed and gap data, the level of risk and severity is classified as low risk, high risk and low severe, and high severe. The methodology implemented is validated by using the actual accident data.

Available online: https://doi.org/10.26552/com.C.2023.013

Article info

Received 1 September 2022
Accepted 24 November 2022
Online 14 December 2022

Keywords:

gap acceptance
severity
safety
probability of risk
uncontrolled intersection
conflicting speed

ISSN 1335-4205 (print version)
ISSN 2585-7878 (online version)

1 Introduction

Traffic accidents on the road are one of the major causes of injuries, death, and property loss. Road traffic crashes lead to approximately 1.25 million death of people every year. The statistics show that traffic accidents caused an average of 65123 loss of life and 25540 got injuries as per WHO (World Health Organisation, 2018). Road traffic safety is to be considered first, then to take economic factors into justification. In the case of an accident and prevention, the administrative authority needs to take into account the safety aspect [1]. While designing the road infrastructure the real situation adaptation, based on current trends and development, needs to be considered to respond according to the traffic intensity. The development of the traffic situation is dynamic, difficult to predict, and influenced by several traffic, geometrical and other factors [2]. To improve the functioning of road safety, the context of the overall road traffic safety management system needs to be considered, which contributes to the complex institutional structure involving the authorities that supports the task and process involved to prevent and reduce road traffic accidents [3]. The other major problem identified is to determine the effect of the system on the technical inspection of vehicles to reduce the accident-related studies examined. However, the effect of technical inspection reduced the accident rates in different countries is investigated and summarised [4]. One of the research studies in New Zealand has reduced to no accidents after the application of the vehicle system investigation [5]. The roadside technical inspection analysis examines the possible impact on transport and logistic system, which has not been explored yet. Hence the effectiveness of inspections on the roadside has an impact on road safety, as well [6].

One of the traditional ways to improve road safety is to analyze the crash data and identify the primary factors affecting road accident severity. The accident severity does not happen by chance, as different forms can be forecast and prevented. However, the accident analysis has its limitation regarding the data adequacy and quality from the historical records. Therefore, the analysis of the accident prediction and its severity has drawn the attention of researchers for traffic safety, whereas, accidental events can be analyzed by different techniques and can be avoided [7]. The three common ways to obtain the conflicting data are i) field observation, ii) computer simulation and iii) real driving scenario. In the case of actual driving, the driver's behavior, traffic, and environmental characteristics are taken into consideration. Similar to naturalistic driving, a computer simulator will work on the driving behavior and trajectory of vehicles on the field. Moreover, a computer simulator can be an alternative approach to predicting traffic conflict using machine learning techniques. At present, the availability of a large dataset enables to predict the accidents using machine learning as compared to the traditional statistical approach [8]. In the past two decades, several researchers have worked on the severity prediction of traffic accidents based on past hypothetical data and identified the main factors impacting the severity of accidents. In many countries, a significant reduction in fatal accidents is achieved by adopting a holistic road traffic system. In this approach, all the aspects of the road system, which contribute to traffic accidents are considered. But the decisive here is the recognition that there are limits to human activity, which is the gap acceptance behavior [9-10]. Various studies have shown that the driver's behavior has a major impact on accidents. Even the personality and impulsivity of the driver plays a major contribution to road safety [11-13]. Personality traits directly influence the risky behavior of drivers when external factors do not have a direct impact [14-15].

In the past, various researchers used different surrogate safety measures to assess traffic safety. Gap acceptance (GT), deceleration time (DT), time to collision (TTC), and post-encroachment time (PET) are some commonly used traffic safety surrogate measures [16-17]. On the other hand, PET is one of the most widely used and reliable methods for analyzing traffic safety. The PET is a surrogate safety measure used to identify cases in which two road users pass over a common spatial point or area at a different time [18-19]. PET is the time difference between the first vehicle's exit from the conflict spot and the second vehicle's arrival/entry at the conflict spots. A lower PET value indicates a higher likelihood of collision [18]. One of the research studied the microscopic decision model for the driver's gap acceptance behaviour when waiting at an uncontrolled intersection on a minor road. This model evaluated the risk associated with not accepting the small gaps and the potential benefit of their acceptance [20]. From past studies, it is observed that the gap time is one of the measures of surrogate safety. The estimation of the critical gap enables the prediction of the risk probability and severity. However, there is a lack of research in a similar area and this motivates authors to estimate the level of risk and severity (LORS) and to enhance the safety at unsignallised intersections using the gap time concept. To achieve the objective, the critical gap is estimated using a probabilistic approach and the risk is computed for the vehicle types and right-turning movements [21]. However, there is a lack of research observed for the intersection owing to the unavailability of crash data or past accident records, which are unable to study the severity prediction accurately. Hence, the present paper aims to evaluate the severity and categorize it based on the gap acceptance parameter and conflicting speed of the vehicle. To validate the severity levels, the data of the actual crashes, which have already occurred at uncontrolled T- intersections, is extracted and analyzed.

2 Data collection and processing

Traffic data was collected using videography for six different locations at uncontrolled T-intersections of

Figure 1 *Snapshots of the study locations*

***Table 1** Road inventory details for the study area*

Location	L-1	L-2	L-3	L-4	L-5	L-6
Area	Nadiad (Gujarat)	Anand (Gujarat)	Kalol (Gujarat)	Mehmdavad (Gujarat)	Thandla (Madhya Pradesh)	Peeth (Rajasthan)
State Highway Number	SH-12	SH-83	SH-5	SH-3	SH-39A	SH-91
Characteristics of Major and Minor Road	4-lane divided 2-lane undivided	4-lane divided 2-lane undivided	4-lane divided 2-lane undivided	4-lane undivided 2-lane undivided	2-lane undivided 2-lane undivided	2-lane undivided 2-lane undivided
Width of Major Road (in m)	15	15	17.5	12.5	15	14.5
Width of Minor Road (in m)	10.5	10.5	7.5	6.5	6.6	6.0
Stretch Length (in m)	28	30	50	32	28	26
Width of Conflict Area(m^2)	16 x 20	16.6 x 14	18 x 20	14.5 x 12.5	6.6 x 14.5	5.8 x 14.0
85^{th} Percentile Speed (in kmph)	67	69	75	72	62	57
Peak Hour Volume(PCU/hr)	2024	2146	2750	2725	610	765
Proportion of 2W (%)	62.66	52.03	50.32	58.10	63.75	73.98
Proportion of 3W (%)	16.21	13.99	5.55	12.63	4.64	4.91
Proportion of 4W (%)	17.05	27.88	29.30	22.37	14.63	15.89
Proportion of LCV (%)	2.81	3.96	6.41	1.35	6.53	2.50
Proportion of Bus (%)	0.88	0.62	2.06	1.27	3.64	1.44
Proportion of Truck (%)	0.38	1.50	6.33	4.25	6.78	1.95

rural highways. The videography was done under the fair-weather condition using a high-definition camera. The camera is placed at a vantage point to avoid disturbance in the driving behavior and obtain the actual driving pattern. The location of the camera is selected in such a way that all three movements are covered to extract the other traffic parameters later on. The physical dimension was evaluated from the field and further used for the analysis. The snapshots of the six locations in the study area are shown in Figure 1.

The road inventory details of the study area including the road geometric features, traffic components, and locations are described in Table 1.

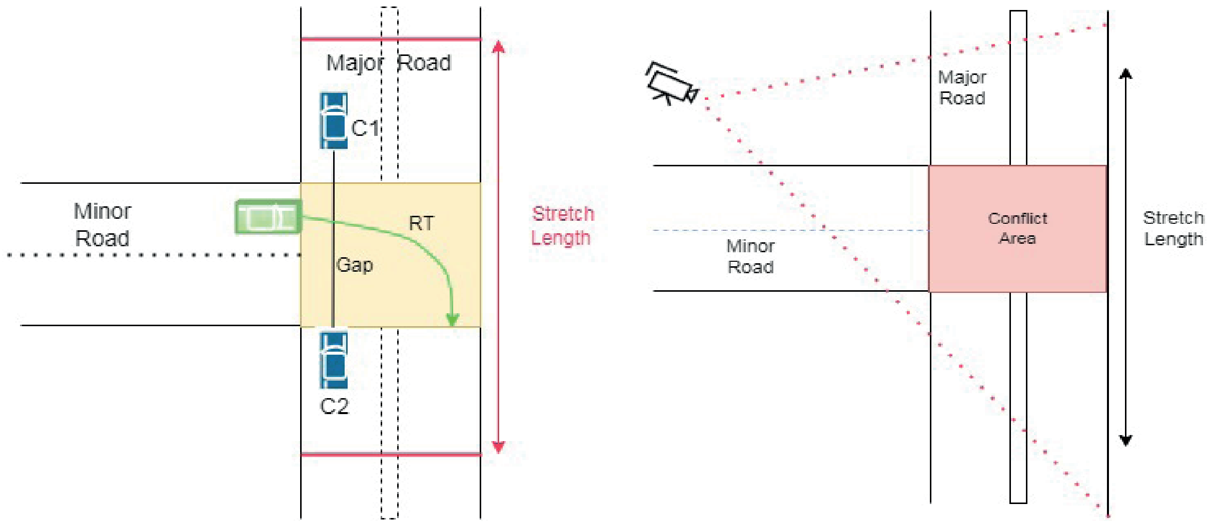
a) Gap data extraction

The gaps were measured in $1/100^{th}$ of a second, which resulted in a total of 2150 (both accepted and rejected) gaps for major and minor right-turning movements. The summary of the traffic proportion at all the intersections and mode-wise share is shown in Table 1. As it is clear that the major proportion is observed for the two-wheelers whereas a small proportion is recorded for heavy vehicles (bus, truck, and LCV). For all the intersections, the two-wheeler proportion varies from 50% to 73%. Further, the gap in acceptance of the right turning movements - from the major and minor approaches is the focus of this study.

The recorded video was played repeatedly to extract the data. The data extraction process was conducted manually and recorded the gap (accepted/rejected), vehicle speed, and classified traffic volume count. In Figure 2(a), C1 and C2 are the leading and following vehicles used to calculate the gap time. The stretch length defined in the figure is for calculating the approach speed of the vehicles. It is estimated using the time taken to cross the stretch length, which is marked on the site during videography and the length of the section is presented in Table 1. The occupancy time of the vehicle is extracted manually by calculating the time taken by the vehicle to cross the conflict area. The gap data is extracted for the major and minor right turn for each location. The gap is estimated as a time headway between the two successive vehicles for major and minor streams. The gap data is used for further analysis and therefore its statistics are described in the next section.

b) Descriptive statistics of accepted gap

The descriptive statistics of the gap accepted are elaborated in Table 2. It shows the minimum, maximum values, mean and standard deviation accepted for each location. From Table 2, it is a piece of clear evidence that the minimum value of the accepted gap shows negligible variation for all the locations, whereas the least standard deviation was observed for location 6 and in contrast, the highest standard deviation was observed for location 1.



(a) *(b)*

Figure 2 *(a) Data extraction methodology and (b) Position of the camera*

Table 2 *Descriptive Statistics for the accepted gap for each location*

	L-1	L-2	L-3	L-4	L-5	L-6
N	269	258	263	135	123	144
Mean	3.08	3.02	3.20	2.08	2.19	1.78
Minimum	1.06	1.09	1.45	1.02	1.03	1.02
Maximum	7.65	8.63	7.72	6.42	6.32	3.63
Variance	1.96	1.64	1.35	0.73	1.16	0.25
Stand Dev	1.40	1.28	1.16	0.86	0.99	0.50

Further, the extracted accepted gaps are used in analyzing and evaluating the critical gap and probability of risk. Figure 3 shows the histogram of the accepted gaps for each location. The different distribution fittings tried to the accepted gap data. The probability distribution functions of gamma, lognormal, Weibull, and General Extreme Value fitted for all the locations are shown in Figure 3. Kolmogorov Smirnov (K-S) test, Anderson- Darling (A-D) test, and chi-square test are used to measure the goodness-of-fit for all the fitted distributions.

The test was performed for different distributions, with a confidence level of 95%, to evaluate each distribution for the accepted gap. Based on the least p-value the best fit of the distribution for each location of the accepted gap is defined.

From Table 3, it is clear that the location-wise distribution is varying as the four distributions- gamma, Weibull, lognormal, and GEV fitted for all the locations. For each location different best fit distribution is obtained considering the least p-value to be the best considering the two-validation test - Anderson darling test and Chi-squared test. The ranking for each location is shown in table 3. However, the most suitable fit is GEV (General Extreme Value) based on the least p-value. Hence, for further analysis, the GEV is considered to estimate the probability of risk (POR). However, it becomes fairly complex to apply the various distributions for the location and vehicle type-wise to obtain more accurate results. The following section deals with the estimation of the critical gap, using the Binary Logit Model (BLM) and the evaluation of POR using the critical gap value [22].

3 Methodology

The present research work focuses on evaluating the level of risk and severity. The methodology for the current research is briefly shown in the form of a flow diagram in Figure 4.

Figure 4 shows the complete methodology of the research work. The data for the study location is collected and extracted manually to estimate the value of the critical gap. Further, the probability of risk is evaluated to understand the correlation between the gap size and risk. Then, the level of risk, severity, and safety are categorized based on different parameters and the approach. Based on the categorization of risk, severity, and safety level, LORS is defined and categorized under three categories. To validate the approach, the actual accident data of speed and the gap are considered, which is explained in the result and discussion section. As a result, the approach of LORS explained in the current research paper is concluded with positive results. However, each step of the chart is explained in detail in the further sections.

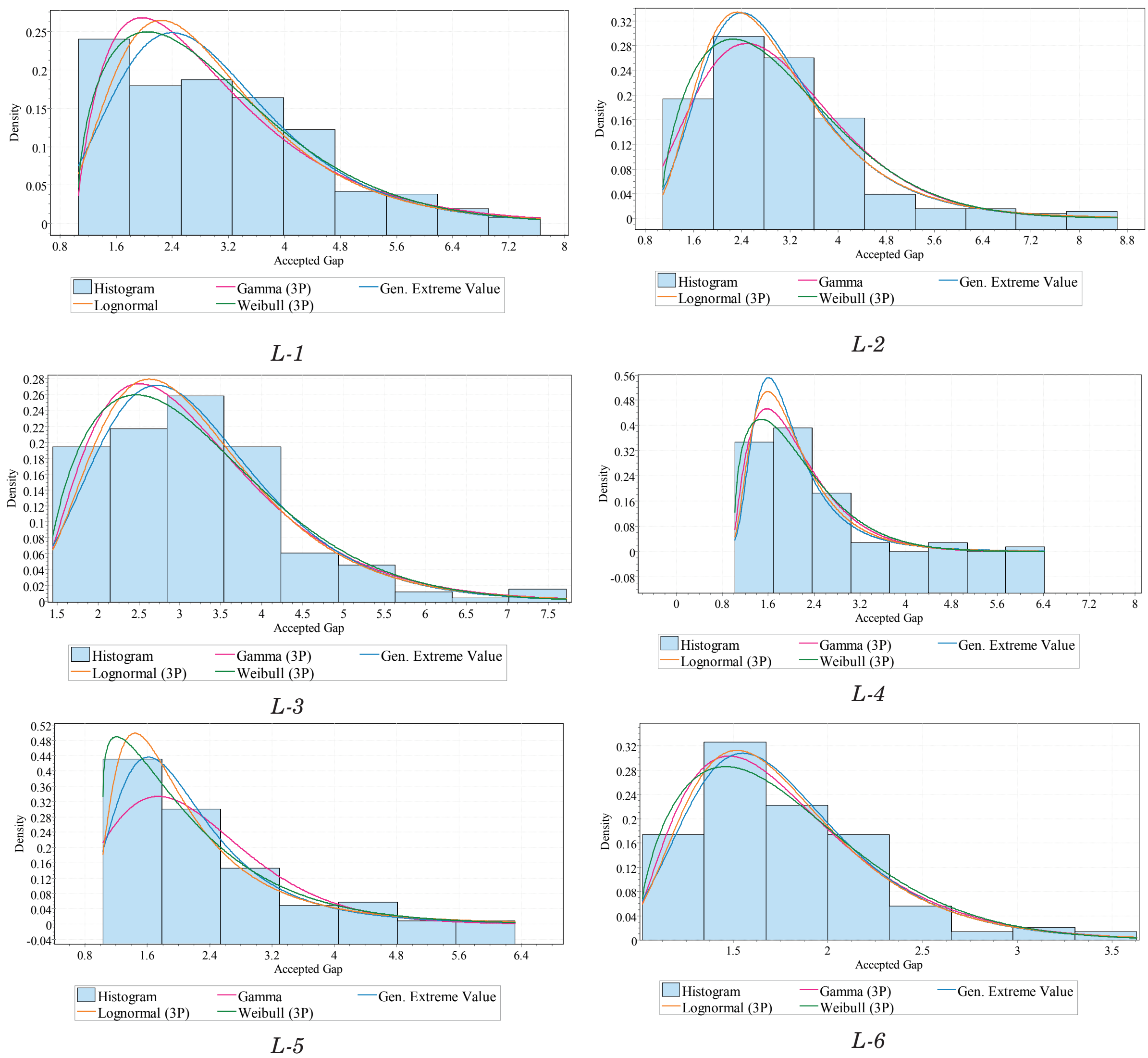


***Figure 3** Distribution fitting for accepted gaps for all locations*

4 Critical gap estimation

The drivers' decision for the gap, i.e. whether to accept or reject an available gap, was modeled as a function of the gap size, waiting time of the offending vehicle, and speed of the conflicting vehicle in the current study, using the binary logit regression. Table 4 displays the model summary. As the critical gap value is estimated using a probabilistic approach, the influence of traffic and geometrical parameters on that value is taken into account [21].

A negative coefficient for the gap size can be found in all of the models developed in this study. It implies that as the gap widens, the likelihood of rejection decreases or the likelihood of acceptance increases. A similar positive sign for the speed of the opposing vehicle can be observed. This demonstrates that as the speed of the opposing vehicle increases, implies the likelihood of rejecting a gap. There are consistent observations for both crossing movements and different vehicle types.

The occupancy time has a negative coefficient. This means that as the occupancy time increases, so does the likelihood of rejection. This demonstrates, as the occupancy time increases, drivers become impatient and force themselves into the traffic flow by accepting and rolling over smaller gaps to navigate through the intersection. There are consistent observations for both the crossing movements and different vehicle types. The current study aims to estimate the critical gap first and then to estimate the severity levels using the probability of risk considering GEV distribution by the gap-acceptance phenomenon in mixed traffic conditions. Table 5, presents the value of the critical gap for the crossing movements and the type of vehicles estimated using a binary logistic regression model.

The observation for the value of the critical gap is that the two-wheelers and three-wheelers are having a lesser value as compared to the car and heavy vehicles due to the area of the vehicle type. Maneuvering the vehicles with a larger area requires more time to take

Table 3 Goodness of fit value for distribution fitting for each location for an accepted gap

Location	Test	Statistic	Lognormal	Weibull	Gamma	GEV
L1	K-S test	p-value	0.074	0.088	0.072	0.074
		Rank	2	4	1	3
	Anderson Darling Test	p-value	1.814	3.626	1.499	1.669
		Rank	3	4	1	2
	Chi-Squared test	p-value	15.519	15.328	13.221	15.771
		Rank	3	2	1	4
L2	K-S test	p-value	0.041	0.074	0.055	0.040
		Rank	2	4	3	1
	Anderson Darling Test	p-value	0.450	3.7267	1.332	0.458
		Rank	1	4	3	2
	Chi-Squared test	p-value	8.897	9.477	6.831	9.964
		Rank	2	3	1	4
L3	K-S test	p-value	0.047	0.076	0.048	0.044
		Rank	2	4	3	1
	Anderson Darling Test	p-value	0.783	2.7978	0.67578	0.646
		Rank	3	4	2	1
	Chi-Squared test	p-value	17.618	9.072	31.427	20.827
		Rank	2	1	4	3
L4	K-S test	p-value	0.093	0.149	0.120	0.045
		Rank	2	4	3	1
	Anderson Darling Test	p-value	1.460	7.719	4.091	0.357
		Rank	2	4	3	1
	Chi-Squared test	p-value	13.351	19.836	26.184	7.975
		Rank	2	3	4	1
L5	K-S test	p-value	0.090	0.142	0.110	0.068
		Rank	2	4	3	1
	Anderson Darling Test	p-value	1.061	4.025	1.681	0.662
		Rank	2	4	3	1
	Chi-Squared test	p-value	19.278	26.328	17.942	16.850
		Rank	3	4	2	1
L6	K-S test	p-value	0.041	0.095	0.056	0.042
		Rank	1	4	3	2
	Anderson Darling Test	p-value	0.307	2.843	0.703	0.262
		Rank	2	4	3	1
	Chi-Squared test	p-value	1.949	7.871	1.8814	6.533
		Rank	2	4	1	3

the right turn as compared to the vehicles with a lesser area [23]. Whereas for the crossing movements, major to minor turning vehicles accept the larger gap compared to the minor to major turning vehicles. Hence, the risk for minor right-turning vehicles is larger, which has been demonstrated in further sections.

5 The risk analysis

The accepted gap or rejected gap is the measurement of the decision of the driver for crossing the intersection. The smaller gap is rejected by the driver whereas the larger gap is accepted [21]. Moreover, a similar concept is applied for both temporal and spatial gaps as only the measurement units are different but the decision of the driver remains the same. When it comes to the matter of the dilemma zone, the spatial gap is in focus, whereas for capacity estimation and delay calculation, the temporal gap plays a crucial role. Hence, a driver accepting a smaller spatial gap sustains more risk as compared to a driver accepting a larger gap. This denotes that the risk (R) is an inverse function of the magnitude of the spatial accepted gap and it can be represented mathematically in the following form:

$$Risk(R) = \frac{1}{Accepted\ gap(s)}. \quad (1)$$

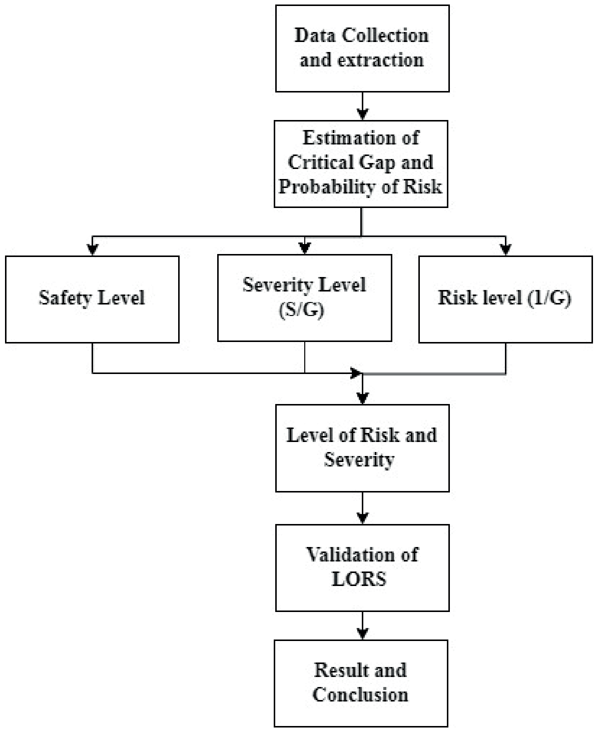


Figure 4 *Research Methodology*

Table 4 *Coefficient of the model and parameters for estimating the critical gap using a binary logit model*

Variables/ Coefficient	Major RT				Minor RT			
	2W	3W	4W	HV	2W	3W	4W	HV
Gap	-0.794	-1.127	-1.02	-0.46	-0.432	-2.19	-1.27	-1.26
Occupancy Time	-0.10	-0.06	-0.02	-0.351	-0.218	-0.074	-0.058	-0.043
Speed	0.017	0.013	0.056	0.051	0.014	0.043	0.064	0.084
Constant	2.649	2.492	0.485	4.078	3.247	3.189	1.66	0.152
Accuracy Prediction	75.7	70.8	63.8	70.0	75.5	74.5	71.4	79.6
Log-likelihood function	533.80	335.89	336.66	139.08	358.50	225.81	231.667	91.65
Cox and Snell R squared	0.274	0.265	0.256	0.176	0.266	0.366	0.246	0.312
Nagelkerke R squared	0.371	0.355	0.341	0.237	0.355	0.488	0.328	0.420

Table 5 *Critical Gap (in sec) value using Binary logit model*

Location/ Vehicle Type	L1	L2	L3	L4	L5	L6
			Major Right-Turn			
2W	2.45	2.92	2.46	2.4	2.39	2.28
3W	2.39	2.43	2.54	2.45	2.44	2.57
4W	3.23	3.57	3.08	2.51	2.93	2.87
HV	4.47	4.18	4.41	3.46	3.55	4.78
			Minor Right Turn			
2W	2.31	2.09	2.45	2.06	2.24	2.29
3W	2.35	2.43	2.53	2.22	2.28	2.36
4W	3.27	3.19	3.55	3.33	3.23	3.39
HV	3.55	3.42	3.92	3.44	3.53	3.55

The above equation shows that the greater the value of the accepted gap, the lower the risk, and vice-versa. According to the researcher, the Probability of Critical Crossing Conflicts (PCCC) is an indicator of operational risk for unsignallised intersections [24]. It is derived using the EVT (Extreme Value Theory) modeling for the

Table 6 Probability of Risk based on critical gap values (X_1< Risk <X_2)

Location	L1	L2	L3	L4	L5	L6
			Major Right-Turn			
2W	72.76	48.44	75.30	38.19	34.91	17.65
3W	75.75	79.92	73.71	25.85	47.61	18.82
4W	59.33	61.52	75.21	45.15	26.41	11.06
HV	65.14	73.78	47.32	25.98	16.71	12.50
			Minor Right Turn			
2W	65.04	88.75	76.90	80.01	27.65	31.59
3W	84.02	79.31	77.28	73.18	37.99	33.95
4W	73.21	73.73	55.70	59.42	45.48	25.28
HV	92.29	88.13	67.41	81.73	31.19	18.47

post-encroachment time (PET) data. The current study derives risk probability from a similar concept and is used to estimate level-of-risk and severity (LORS).

Although several researchers have demonstrated that the gap acceptance behavior enables the suggestion of safety measures, there is a lack of research on the probability of risk (POR). Recently, the researchers explained how the EVT can be used to estimate the number of conflicts in a specific section [25-26]. To estimate the POR, the best-fit distribution must be estimated and according to analysis, the GEV distribution is found to be the best-fitted distribution model. Hence, the GEV is used to estimate POR in the present study.

Assume X1, X2, X3,…Xm as independent random variables (in the present case, the value of risk) with a similar probability distribution, where Yn = max (X1, X2, X3,…., Xm). When n→∞, the Yn will converge to a GEV distribution [27], as shown in Equation (2).

$$f(x) = \frac{1}{\sigma}\exp\Big(-(1+kz)^{-\frac{1}{k}}(1+kz)^{-1\frac{1}{k}}\Big) \quad k \neq 0, \quad (2)$$

where, z=(x-µ)/σ, µ is the location parameter, σ is the scale parameter and k is the shape parameter.

The POR is defined as an area under the probability density function of GEV distribution between the thresholds of the gap representing serious conflicts. The POR can be computed using the following Equation (3).

$$Probality\ of\ risk\,(POR) = \int_{LL}^{UL} f(x)\ dx\,, \quad (3)$$

where f(x) is the probability density function of the GEV distribution, LL and UL represent the Lower and Upper limits of risk, representing critical conflicts, respectively.

Whether the driver chooses to accept or reject a gap within the dilemma zone, will rely on the characteristics of the approaching vehicle (vehicle type and speed), traffic volume, and the traffic control signs at the intersection. Additionally, gender, age, and driving behaviors contribute to the dynamic nature of accepted gaps. Drivers might prefer a wider space over a narrower one. However, given the variety of gaps that are accessible, a driver can be conflicted about whether to accept or reject a particular gap [28]. Therefore, considering these dynamics in gap-acceptance phenomena, it becomes imperative to arrive at a single gap value, potentially representing the population. Recently, a study reported that spatial critical gaps could characterize the risk of crossing conflicts [29]. Based on the critical gap value, the risk of crossing conflict was characterized as serious and non-serious conflicts. Therefore, the critical gap value was used in the present study to evaluate the POR of the un-signalized T-intersections.

Considering the critical gap as a threshold to define the serious conflict, the equation to estimate the POR can be rewritten as:

$$Probality\ of\ risk\,(POR) = \int_{\min imum\ risk}^{risk\ at\ critical\ gap} f(x)\ dx\,. \quad (4)$$

Table 6, shows the probability of risk for the crossing movements and different vehicle types for each location. It can be observed that minor to major right-turning vehicles have a higher probability of risk due to smaller gap-accepting behavior. Moreover, when the vehicles are compared, the heavy vehicles (92%) have the higher risky behaviour, related to the other vehicle types (65 %). The location-wise risky behavior comparison shows that L-6 (11% -33%) is safer as compared to the other locations (25% -92 %). Therefore, it can be determined that the probability of risk of vehicles for the crossing movements is depended on the driver's gap acceptance behavior.

The severity index is a value that indicates the hazardousness of the accidents at road sections, although it can be classified as minor/major injury or fatal depending on the harm to the vehicle and the passenger. In general, the severity index is defined as the ratio of the actual injuries that occurred to the total number of accidents. However, due to the unavailability of the accident data, an alternative approach is used in this paper to estimate the severity level using the gap acceptance behavior of the driver and the speed of the vehicle [17], the severity level is classified using the ratio of the speed to the gap of an individual vehicle; the particular value for the different vehicles is determined

Table 7 *Speed to Gap Ratio Value*

Location / Vehicle Type	L1	L2	L3	L4	L5	L6
2W	21.60	35.20	23.10	31.05	34.26	20.34
3W	19.17	25.32	19.62	22.82	26.21	21.27
4W	24.65	17.60	21.43	27.06	30.72	18.86
HV	13.12	9.68	10.92	21.58	23.97	18.32

Figure 5 *Average Silhouette value for three clusters in a two-step clustering technique*

Table 8 *Speed-to-gap ratio classification using various clustering techniques*

Clustering Technique	Cluster 1	Cluster 2
K-Mean Clustering	5.38	11.72
Two-step Clustering	5.65	11.85
Hierarchical Clustering	5.62	11.92

for each location.

Table 7, shows values of the speed-to-gap ratio for different vehicle classes and locations. The speed-to-gap ratio is used to classify the threshold for the level of risk and severity.

6 Severity analysis

Clustering is the process of arranging a set of objects belonging to the same group. In the present study, the severity of each gap is computed and clustered using different techniques. The three-clustering methods were used, namely - two-step clustering, k-mean clustering, and hierarchical clustering.

In Figure 5, the average silhouette for two clusters for the two-step clustering is shown, where two-clustering is having fair results for the quality of the cluster. Due to the following results, the clustering is done under two categories, as for one and three clustering the quality of the model has decreased to poor. Hence, the two clusters are developed using the three different clustering techniques.

Table 8 shows the results of the clustering by three different methods. It can be observed from the table itself that the variation of the values does not vary much. For classifying it into clusters the lower value is considered. As the value is considered for the safety purpose the lower value if considered, will be safe for the higher value as well.

Table 9, presents the risk calculated based on the reciprocal of the accepted gap and to normalize the value, a critical gap value is used. The speed-to-gap ratio is classified based on the clustering techniques. The combination of both the gap-to-critical gap ratio and the speed-to-gap ratio is utilized to identify the level of risk and severity respectively. The HRHS, i.e. High-Risk High Severity is defined as the value of risk less than 1 and the speed-to-gap ratio greater than 11.72. The other term, i.e. HRLS - High-Risk Low Severity is where the value of risk is less than or equal to 1 and the speed-to gap ratio is between 5.38 to 11.72; lastly, the LRLS - Low-Risk Low Severity is where the value of the risk is greater than 1 and the speed to gap ratio is less than 5.38. This concept is developed based on the practical considerations that if the gap and critical gap ratio were less than 1, the driver's behaviour is riskier. On the other hand, if the ratio is greater than 1 means that drivers perceive less risky behavior. Hence, the complete analysis is done based on the concept of the high and low risk and severity, which is further correlated with safety for ease of understanding and validating the approach.

The level of safety is categorized as safe, which means that it does not have any probability of conflict.

Table 9 *Classification of risk, severity, and safety based on speed and gap parameter*

G/CG	Level of Risk	S/G	Level of Severity	Classification of Crash	Level of Safety
<1	High Risk (HR)	>11.72	High Severe (HS)	Demise	Fatal (HRHS)
<=1	High Risk (HR)	<5.38	Low Severe (LS)	Major Injury	Highly unsafe(HRLS)
>1	Low Risk (LR)	<5.38	Low Severe (LS)	Minor Injury	Unsafe (LRLS)

*G/CG: Gap to Critical gap and S/G: Speed to Gap Ratio

Car-Truck (Fatal) *LCV- Car (Highly Unsafe)*

Car- Bus(Fatal) *LCV- Car (Highly Unsafe)*

Figure 6 *Few snapshots of the actual accidents that occurred at an uncontrolled three-legged intersection*

Unsafe shows that the probability of conflict is greater, but the injury to the passenger or driver is negligible or had a minor injury, whereas highly unsafe means major injury to the passenger or a driver and severe destruction to the vehicle/s. A fatal or disastrous accident means that there is a demise of one or more people due to the conflict and vehicles are damaged entirely. All the categories shown in Table 9, for the safety or level of risk and severity (LORS), are defined above.

7 Result and discussion

The number of crashes at the uncontrolled intersection is increasing, but the record of the actual accidents is not readily available with the details. Hence, this study has moved forward a step, to observe the severity level of actual accidents that have already occurred at an uncontrolled intersection. Moreover, this evaluation of accidents also enables for the validation of the above level of risk and safety, based on the speed and gap data. Therefore, to validate the severity and risk levels, the accidents are evaluated using an open-source video (YouTube videos). Table 10, denotes the validation of the severity and risk levels using the data (speed and gap) of actual accidents that occur at a similar type of intersection for the different vehicle types. Capturing the actual accidents is a quite tough task, but still, some data was available, which is used to validate the approach.

A few images of the crashes are shown in Figure 6. The videos are played repeatedly to obtain the value of the gap and the speed is calculated by the time taken to cross a particular stretch and distance is extracted from the video. Hence, the speed of the vehicle is calculated and used for further analysis to estimate the speed-to-gap ratio. The level of safety of the accident is observed under three categories- unsafe, highly unsafe, and fatal. However, the predicted LORS is based on the speed and gap value, whereas the observed LORS (level of safety) is estimated based on the actual accident scenario from the open-source video. Further, the observed and predicted LORS is compared and the detailed analysis is discussed in Table 10.

Table 10, shows the crashes that occurred by the vehicle type, gap time, speed of the conflicting vehicle, critical gap (estimated using BLRM), predicted LORS, and observed LORS of the accidents. The prediction

***Table 10** Actual accident data validation with the predicted severity level*

Vehicle Type	Gap (s)	Speed (kmph)	Critical Gap (s) (Calculated using BLRM)	Risk = G/CG	Speed / Gap	Predicted LORS (from S/G and AG/CG)	Observed LORS (from video)
M2W	3.98	25.25	1.63	2.44	6.34	LRLS	LRLS
M2W	3.4	22.48	1.78	1.91	6.61	LRLS	HRLS
M2W	1.76	34.85	2.97	0.59	19.80	HRHS	HRHS
M2W	2.53	35.45	3.08	0.82	14.01	HRHS	HRHS
M2W	2.49	28.62	2.81	0.89	11.49	HRHS	HRHS
M2W	2.11	22.15	3.41	0.62	10.50	HRHS	HRHS
M2W	1.69	32.46	3.31	0.51	19.21	HRHS	LRLS
M2W	2.23	25.62	4.13	0.54	11.49	HRHS	HRHS
M2W	3.39	28.15	2.87	1.18	8.30	LRLS	HRHS
M2W	1.63	32.48	3.81	0.43	19.93	HRHS	HRHS
M3W	2.56	24.62	3.02	0.85	9.62	HRHS	LRLS
Car	2.13	39.45	2.56	0.83	18.52	HRHS	HRHS
Car	2.63	33.26	3.04	0.87	12.65	HRHS	HRLS
Car	1.84	45.89	3.54	0.52	24.94	HRHS	HRHS
Car	3.97	30.25	2.83	1.40	7.62	LRLS	LRLS
Car	2.42	45.23	4.28	0.57	18.69	HRHS	LRLS
HV	3.45	32.68	2.6	1.33	9.47	LRLS	HRLS
HV	2.81	45.18	3.68	0.76	16.08	HRHS	HRHS
HV	2.27	35.84	3.33	0.68	15.79	HRHS	HRLS
HV	2.44	42.15	3.67	0.66	17.27	HRHS	HRLS
HV	3.7	32.45	3.68	1.01	8.77	LRLS	LRLS
HV	3.11	28.46	2.76	1.13	9.15	LRLS	LRLS
HV	3.5	25.15	2.16	1.62	7.19	LRLS	LRLS
HV	2.36	36.87	3.35	0.70	15.62	HRHS	LRLS
HV	3.32	35.48	3.44	0.97	10.69	HRHS	LRLS
HV	3.09	25.86	4.15	0.74	8.37	HRHS	HRLS
HV	2.54	32.15	4.59	0.55	12.66	HRHS	LRLS
HV	2.05	32.54	4.04	0.51	15.87	HRHS	HRLS

Note: HRHS- High-Risk High Severity (fatal), HRLS- High-Risk Low Severity (highly unsafe), LRLS- Low-Risk Low Severity(Unsafe)

accuracy of the approach is evaluated based on the observed and the predicted LORS. If the observed and predicted value were the same for a particular accident the crash prediction accuracy is considered 100% whereas, if either risk or severity is predicted accurately then it is considered to be 50% accurate. Moreover, if the predicted and observed value does not match, then it is considered to be 0. Therefore, the average accuracy prediction for the observed and the predicted level of severity comes to 66.07%. This approach can further be modified to enhance prediction accuracy by acquiring more crash details and records. Last but not the least, the observations and the predictions done in the present study are the initial approach to increase safety. The uniqueness of this research is that the actual accidents are used to validate the results. The accuracy percentage of the approach gives fair results and that can be modified by getting more data.

Hence, it can be presumed that the risk and severity level estimated enables in the reduction of the severity of accidents. The prediction of the level of risk and severity (LORS) is evaluated based on the speed and gap acceptance behavior of the driver for different vehicle types at right-turning movements.

From Figure 7, the LORS can be classified as HRHS, HRLS, and LRLS depending on the accepted gap and speed parameter. In the graph, the X- axis denotes the G/CG - gap to the critical gap ratio, which defines the level of risk. If the ratio is less than 1, it is less risky and a ratio greater than 1 perceives higher risk. Moreover, the Y-axis denotes the level of severity based on the speed-to-gap ratio, values greater than 5.38 and lesser than 11.72 define low severity and a ratio greater than 11.72 defines high severity. Hence, the combination of the risk and severity levels enables the delineation of the LORS. Based on the LORS, remedial measures can be suggested

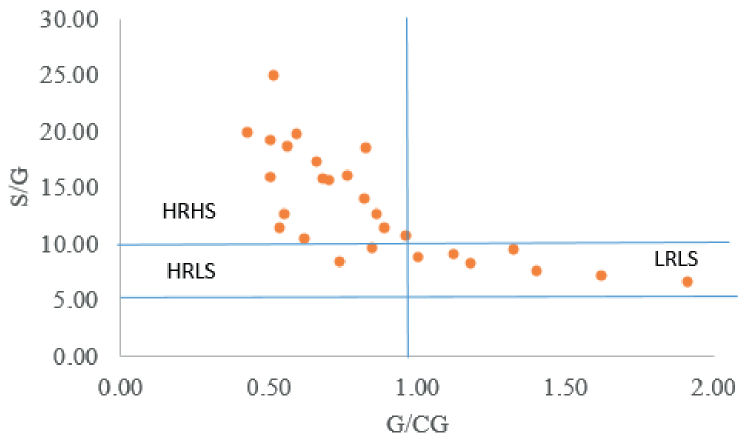


Figure 7 *Level of Risk and Severity based on Speed and Gap Value*

Table 11 *Remedial measures based on LORS*

G/CG (Risk)	S/G (Severity)	LORS	Remedial Measures
<1	>11.72	HRHS	ADAS (Advanced Driver Assitance System)
<=1	<5.38	HRLS	Road Markings
>1	<5.38	LRLS	Stop Signal

to reduce the severity of crashes at uncontrolled three-legged intersections. As per LORS, a few measures that can be suggested are presented in Table 11.

Table 11, deliberated the safety measures that can be implemented in the existing intersection to reduce the severity of accidents based on LORS. As the LORS is identified on the gap acceptance parameter and speed of a vehicle, the safety measures are suggested on similar parameters. Moreover, this study can further be extended for different types of intersections with varying geometrical and traffic characteristics.

8 Conclusion

Traffic movements at an uncontrolled three-legged intersection are highly complex. The high speed at the intersection is one of the attributes of conflicts at the right-turning movements. This complex right-turning manoeuvre increases the risk of collision and creates a threat to safety for both offending and conflicting vehicle types. Various measures are available to analyze traffic safety, out of which the gap time is used in the present paper. This study calculates the gap size and estimates the critical gap and probability of risk, which is further used to evaluate the level of risk and severity.

The classified level of risk and severity, obtained from the actual accident data that occurred at similar types of intersections are validated. The ratio of speed to the gap is used to classify the level of severity, which gave two thresholds of 5.38 and 11.72 after using the clustering technique. Additionally, the ratio of the gap to the critical gap was used to classify the driver's risky behavior in the section. If the ratio was less than 1; it denotes the risky behavior of the driver. Moreover, if the ratio is greater than or equal to 1; the driver perceives less risky behavior. Hence, the LORS is categorized as HRHS, HRLS, and LRLS. The actual conflicts at the three-legged uncontrolled intersections are acquired by the open-source video. The data for speed and gap are extracted and the LORS is estimated based on the data, i.e. the predicted LORS. The level of safety is observed, which is further correlated with the LORS (observed LORS). In comparison, the accuracy percentage for the approach was found to be 66.07%. Based on the severity of crashes observed, suitable remedial measures can be implemented to reduce the severity of accidents at unsignallised intersections on rural highways. The value of the gap and the speed of a vehicle can be used to categorize the level of risk and severity (LORS). This analysis can be further extended for estimating the level of risk and severity for each vehicle type and different road sections.

Grants and funding

The authors received no financial support for the research, authorship and/or publication of this article.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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PARATRANSIT SAFETY AS A KEY RESOURCE FOR SUSTAINABLE MOBILITY IN DEVELOPING COUNTRIES

Md Tawkir Ahmed[1,*], Md Sifat Bin Siraj[2], Tiziana Campisi[3]

[1]College of Transportation Engineering, Tongji University, Shanghai, China
[2]School of Transportation and Logistics, Southwest Jiaotong University, Sichuan, China
[3]Faculty of Engineering and Architecture, University of Enna Kore, Enna, Italy

*E-mail of corresponding author: tawkir_ahmed@tongji.edu.cn

Md Tawkir Ahmed 0000-0002-5338-0882, Md Sifat Bin Siraj 0000-0002-7734-6590
Tiziana Campisi 0000-0003-4251-4838

Resume

A vital mode of transportation for short term mobility is paratransit. There are several studies on paratransit safety in developed nations but the developing nations like Bangladesh pay less attention to the issue. Therefore, the primary objective of this study is to evaluate the safety of paratransit using the perceptions of riders and drivers. Negative binomial model (NBM) was used to calibrate the safety of paratransit using 451 responses in Chittagong city. The study's findings highlight the significance of perceptions of travel safety in enhancing accessibility during the routine travel. Vehicle speed limits (km/h), which reduce the chance of accidents and having an institutional driver's license are among the variables that have emerged for the betterment of safety. Therefore, identifying factors that can makes these transportation systems safer will allow service managers and controllers to optimize passenger and driver safety.

Article info

Received 30 April 2022
Accepted 4 December 2022
Online 25 January 2023

Keywords:

paratransit
safety and security
negative binomial model
sustainable mobility

Available online: https://doi.org/10.26552/com.C.2023.018

ISSN 1335-4205 (print version)
ISSN 2585-7878 (online version)

1 Introduction

Paratransit is one of the emerging transportation modes among today's urban transportation systems. It is also known as informal or semi-formal public transportation. Paratransit encompasses a variety of modes including car sharing, bike sharing and micro transit. Which have developed largely in conjunction with new technologies (smartphones, GPS, electronic payments etc.) and includes on call services that are useful for low-demand areas, especially after the recent pandemic [1].

People who live in the rapidly increasing metropolitan world want efficient transportation. Travel demand has risen dramatically in developing countries, considerably outstripping available transportation options. As a result, in emerging countries, local public transit fails to match the demand for public mobility [2]. Poor service quality, low output, poor maintenance strategy and overcrowding have all been identified as contributing factors to public transportation failing to fulfill the demand [2-3]. Therefore, people have begun to embrace various paratransit modes (both motorized and non-motorized) that allows more time efficient transport to their intended location [2]. Based on paratransit's purpose, many experts have recommended incorporating it as a feeder for the public transit systems to improve the performance of urban transportation networks.

Several studies in the literature show that some segments of the population such as the elderly still have psycho-social problems that hinder the use of these means [2].

A study conducted by [3] developed a fail-safe methodology to help transport service operators identify and correct errors before they generate significant security problems.

Moreover, the recent pandemic has profoundly changed the frequency of travel and modal choices. In order to minimize the use of vehicle, it is useful to spread public transport and para-transit services. It is necessary to include modern vehicles and simple booking systems within everyone's reach. An excellent service is also connected to the training of drivers who must carry out the transport safely and punctually. To date, most paratransit drivers are not well trained and, in some cases, lack adequate knowledge of traffic rules and passenger safety.

Paratransit is responsible for more than half of all the public transportation demand [4-8]. Many cities in emerging countries are experiencing this phenomenon. Rapid growth in metropolitan population and per capita income, along with insufficient existing transportation infrastructure, has boosted paratransit use as a low-cost and convenient means of public transportation. Paratransit is a low-cost means of transportation that gives passengers the impression of driving their own vehicle [5]. Paratransit options play a vital role in developing countries' urban transportation sectors by offering transportation services to a large number of people [6]. It offers considerable benefits to both drivers and riders based on accessibility, flexibility of movement, easy and unhindered lane movement, and inexpensive operation and maintenance costs [2].

Paratransit is a very important mode of transportation in developing countries because it is very accessible and cheap [7]. Most of the passengers are familiar with paratransit especially in developing countries [8-9]. However, most of the paratransit drivers are not well trained even they have no adequate knowledge about traffic rules and passengers' safety. As a result, there were frequent accidents and reckless driving on the roads [10]. Using the Binomial Logistic Regression model technique, Joewon et al. [10] conducted a study to represent the safety and security issues in paratransit operation based on user perception in a developing country. They analyzed the data considering two distinct models with and without experience of accidents to predict and explain users' future choices.

Joewono and Kubota [11] examined the mode choice behavior of four selected paratransit (becak, ojek, bajaj and angkot) drivers in terms of several policy interventions. A stated preference (SP) survey was carried out to conduct this study from two important point of views i.e., social and environmental aspects.

Several criticalities characterize the paratransit systems in general. Some of these challenges can lead to significant service failures that could endanger passengers, increase insurance costs and decrease productivity, as well as damage the reputation of the public transport system. Current technologies make it possible to control this transport service through sensors and software. Those things can reduce the errors committed that could compromise the safety of the paratransit service [9-12].

Most transit systems in rural or small urban areas do not implement these modern technologies due to huge costs [8-12]. It is therefore necessary to hope that in the coming years, inexpensive but effective error prevention techniques that are easy to understand and implement, will be implemented.

Chittagong, like the rest of Bangladesh, is a heavily populated city where road users and travelers rely heavily on paratransit modes such as tempos, auto rickshaws and other similar vehicles to get around [12]. The widespread adoption of paratransit options in Bangladesh indicates people's trust and eagerness. The most casual kind of transportation is paratransit, which ranges from rickshaws (human-powered) to small minibuses with 25 seats. While safety mismanagement of paratransit is common in developed countries. This mismanagement has been happening in most of the growing cities including Chittagong for a long time. These problems cannot be solved in a short period of time. Hence, there is a need for long term planning to mitigate this problem.

The purpose of this study is to assess the attitudes of passengers and drivers regarding the safety concern of paratransit. Therefore, the current study concentrated on an initial literature search utilizing Google Scholar and university library databases that were focused on academic literature. Next, a survey was conducted based on passenger and driver perceptions about the safety of paratransit within Chittagong city. Furthermore, the safety of the paratransit system in Chittagong city was calibrated using the Negative binomial model (NBM).

2 Literature review

Several studies were found on paratransit safety subject matter [12-15]. A study based on the perception about safety and security of the road users and drivers of paratransit as well as that of non-users and civil servants in the city of Bandung, Indonesia. Factor analysis was carried out based on a questionnaire survey to find out significant factors. The results showed that the most fundamental attributes for improving the existing condition in developing countries are the passenger and driver awareness about the paratransit safety and security. Authors have also proposed three basic agendas for improving the paratransit safety namely technology, management, and institution [16].

The behavior of paratransit operators was evaluated using structural equation modeling in the region of Phnom Penh, Cambodia. The interviewed transport drivers expressed a desire to offer feeder service to the bus, regardless of the potential financial consequences. Moreover, the study was an attempt to evaluate driver perception about newly introduced public bus and their motive for operating as feeder service.

A face to face interview survey was carried out to enumerate the existing operational characteristics based on safety perceptions between paratransit operation and fare for motorized paratransit modes in Phnom Penh, Cambodia. Phun and Yai [17] showed that the fare of several paratransit was affected by distinct factors including trip attributes and working environment of drivers.

Priye and Manoj [18] studied passenger safety perceptions of three-wheeled electric rickshaws as a paratransit mode using 388 participants in Patna, India. This research shows that the residing people of Patna in general were not pleased with the present condition and design of the vehicle based on the overall safety perceptions about the electric rickshaws.

To explore paratransit service, a study was conducted based on the public's reaction regarding the service quality, vehicle safety condition, driver performance, and cost of travels. They used binomial logistic regression model to find out significant factors regarding paratransit service. Additionally, they proposed some policy regarding paratransit system based on public requirements [19].

The sustainability criterion for establishing a new mode of transport "Locally Adapted, Modified and Advanced Transport (LAMAT)" is complex and diverse. Four basic factors should be concerned for establishing paratransit system as a sustainable transport i.e. improvements the service quality, integration with mass transit systems, promotion of electric paratransit modes and government support in Asian developing countries [20].

Based on the users' perceptions and the degree of acceptance of paratransit services, Phun, Kato and Yai [21] conducted a study exploring the characteristics and perceptions of two distinct paratransit modes (Motodop and Remork, N.B. Motodop is a motorcycle taxi while Remork consists of a two-wheeled carriage pulled by a motorcycle) in Phnom Penh. A questionnaire survey was conducted with 479 Motodop and 263 Remork users. They found that Remork users have a considerably lower probability of driving accidents than Motodop users do.

A study was conducted by Pramanik and Rahman [22], to evaluate the current situation and the operational features of battery-operated three-wheelers, or "E-rickshaws," in Rangpur, Bangladesh. They found that e-rickshaws are an effective mode of transportation because they offer last-mile connections (end of an individual trip made by public transport). However, it is very challenging to maintain the tariff structure because most drivers are not registered as paratransit drivers. Another study showed that transportation system should be included basis operation and strategic things namely technical specifications, age, equipment and safety rules [23].

They found that drivers are generally captive to Ojek and Bajaj (Motorcycle & Taxy manufacturing company) according to model estimation results and

Table 1 *Paratransit issue focused on previous literature*

References	Statistical Model	Developed (1)/ Developing (2) Country	Topic
Joewono and Kubota (2005) [10]	Binomial Logistic Regression.	2	Paratransit Safety and Security
Joewono and Kubota (2006) [11]	Factor Analysis	2	Paratransit Safety
Joewono and Kubota (2007) [19]	Binomial Logistic Regression Model	2	Paratransit Operation
Tangphaisankun, Nakamura and Okamura (2009) [31]	Structural Equation Model (SEM).	2	Paratransit Safety
Tubis and Werbinska (2014) [32]	Normal statistical analysis	2	Paratransit Safety
Phun and Yai (2015) [17]	Box-Cox Regression model	2	Paratransit Safety
Rahman et al. (2016) [33]	Structural Equation Modeling (SEM)	2	Paratransit Operation
Phun and Yai (2016) [16]	Structural Equation Modeling (SEM)	2	Paratransit Safety
Phun, Kato and Yai (2016) [20]	Normal statistical analysis	2	Paratransit Operation and Safety
Chowdhury, Uddin, Datta and Taraz (2018) [3]	Multinomial Logistic Regression (MLR)	2	Paratransit Operation and Safety
Chowdhury (2018) [34]	Multinomial and an Ordered Logit model.	2	Paratransit Safety
Pramanik and Rahman (2019) [35]	Normal statistical analysis	2	Paratransit Safety
Priye and Manoj (2020) [18]	Exploratory Factor Analysis (EFA) and Principal Component Analysis (PCA)	2	Paratransit Safety
Sharma, Pandit and Bose (2020) [28]	Structural Equation Modelling (SEM)-RIDIT technique.	2	Paratransit Operation and Safety
Wright (2021) [26]	Normal statistical analysis	2	Paratransit Safety
Priye (2021) [36]	Grey Relation Analysis	2	Paratransit Safety

subsidies for the low-emission vehicles have an impact on drivers' mode choice, especially paratransit [24].

As the paratransit system of transport plays a significant role in the urban area in the developing country, Victory and Ali [25] conducted a study using a Multinomial Logit Model (MNL) to forecast the paratransit utility. They considered three quantitative variables i.e. trip length (km), travel cost (rupees), and travel time (minutes) as well as four qualitative variables i.e. reliability, comfort, road condition, and convenience for this study. The results revealed that the travel costs, reliability, convenience, and comfort have mostly influenced the utility of the mode.

Wright et al. [26] studied on the types of modes in the public transport system in five Caribbean countries i.e. Jamaica, St. Lucia, Barbados, Guyana, Trinidad, and Tobago. They found that in these areas, paratransit modalities are more widely used and more reliable than public buses. They added that the peoples are still dissatisfied with the kind of service they deliver. From their suggestions, Governments must prioritize public transportation and invest in an efficient, well-planned infrastructure that can coexist with the emerging paratransit system [26].

Pramanik and Rahman [22] conducted a survey to determine the most important elements affecting paratransit passenger satisfaction in Sylhet, Bangladesh. They used a Multinomial and an Ordered Logit model to analyze passenger satisfaction and found that the female passengers were unsatisfied with current paratransit systems. They added that existing modes' fitness and cleanliness were judged to be influential attributes. They concluded that the fare structure makes this method of transportation popular, but operational flaws like congestion make the future of existing options uncertain [27].

Sharma, Pandit and Bose [28] used Structural Equation Model (SEM) to complete the analysis and found that paratransit can be implemented as a feeder system for mass transits and other public transits. They recommended some parameters, which need to be improved to make paratransit more efficient, namely safety, security policy, ease of accessibility, connection policy, paratransit comfort, and convenient service improvement policy [28].

Table 1 summarizes several prior studies in developing countries for paratransit safety, security and operation. Based on previous literature review, safety for paratransit in developing countries is difficult to come by, especially in Bangladesh condition [27-30]. The authors discovered that no research has been done on paratransit safety in Chittagong city using Negative binomial model (NBM) (Table 1). Hence, this study is an attempt to explore the contributing factors for paratransit safety.

The third, fourth, and fifth sections will be discussed about study area and methodology, model development, and model validation respectively. The sixth section will be presented the analysis results using NBM. Finally, the last section of the paper will be discussed about the conclusion and recommendation of the study.

3 Study area and methodology

Chittagong is Bangladesh's most important seaport and the second-largest metropolis. It is located in South-East Bangladesh, on the north bank of the Karnaphuli River, on the Bay of Bengal's shore. The Bay of Bengal is on the west, Cox's Bazaar is on the south, Chittagong hill tracts are on the east and the Feni River is on the north side of Chittagong city (Figure 1). Its population is estimated to be 4.5 million and people live in an area of 184 square kilometers [29].

The city of Chittagong was selected as it has some critical issues related to public and shared transport

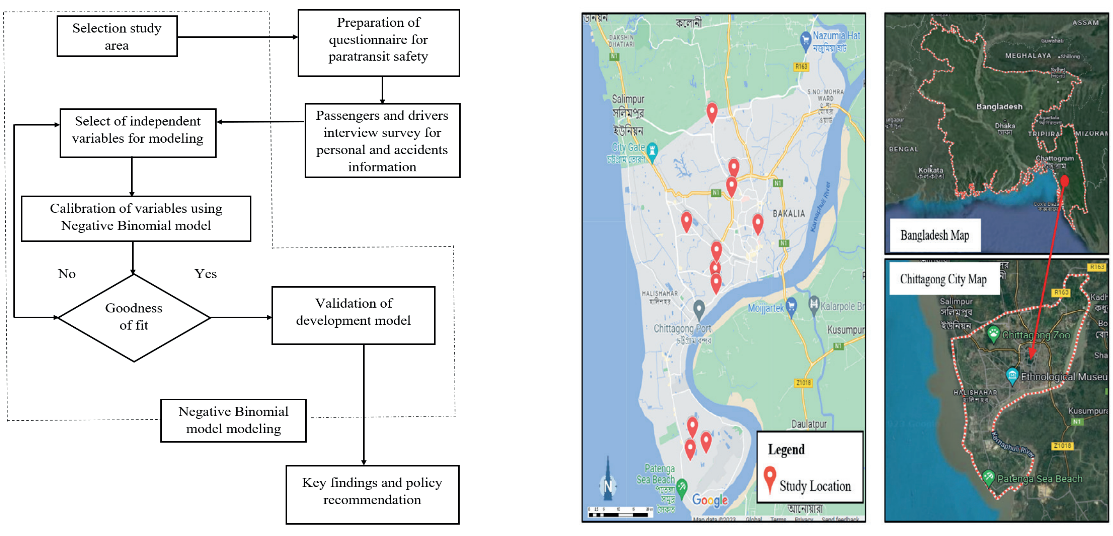

Figure 1 *(a) Methodology flow chart, (b) Study area with survey location*

services. Some literature studies confirm that public transport services need a significant improvement in terms of quality and safety. A study was conducted [25] based on passengers experience of the existing service quality of paratransit. The results show that about 86% of the investigated population uses public transport due to its low cost. From this study it emerges that the behavior of the driver and the level of personal safety inside the bus have been assessed as very poor. While they found some factors have satisfactory service value namely speed of bus, availability information on buses, transport costs, lighting, and travel time.

Likewise, the present work aims to investigate the paratransit services in the Chittagong city. In particular the present research focused on an initial literature search centered on academic literature using Google Scholar and university library databases. Next, a questionnaire survey was conducted on passenger and driver perceptions of safety for paratransit used in the industrial city of Chittagong, Bangladesh. The Negative binomial model (NBM) was used to calibrate the safety for paratransit in Chittagong city (Figure 1).

3.1 Survey implementation and distribution

A questionnaire survey was conducted under the rigorous observation. The survey was carried out in eleven locations of Chittagong city which are prominent paratransit hubs. From the 10th of June 2021 to the 25th of August 2021, 277 driver and 174 passenger (total=451) were interviewed in the chosen locations (Figure 1) on weekdays and weekends. However, the sample size is sufficient for the study area [1-10].

Sample size for infinite population

$$S = \frac{z^2 \times p \times (1-p)}{M^2}.$$

$$S = \frac{(1.96)^2 \times 0.5 \times (1-0.5)}{(0.05)^2}, \; S = 384.16. \tag{1}$$

Here:
S = Sample size for infinite population,
Z = Z- score (for 95% confidence level = 1.96),
P = Population proportion (assumed to be 50% = 0.5),
M = Margin of error (5% = 0.05).

$$\text{Adjusted sample Size} = \frac{(s)}{1+\left[\frac{(s-1)}{(population)}\right]} = \frac{(s)}{1+\left[\frac{(384.16-1)}{(4500000)}\right]} = 384.12 \approx 385 \tag{2}$$

Respondents were chosen at random from the survey sites. The survey includes several parameters including Gender, Age, Accident type, Interview person, Vehicle type, Passengers occupation, Education, Monthly income (BDT), Drivers driving experience (year), Speed of Vehicle (kmph), Reason of accidents, Vehicle involve with crush, Frequency of stopping per hour, Institutional driving training license, Driving on road in a day (hours), Drivers sleep in a day (hours), Time of accident and Road Condition.

3.2 Applied method

Negative binomial model (NBM) was used to calibrate the safety perception of paratransit users. Since NBM can handle over dispersed count outcome variables and is popularly used for safety related studies [1, 13, 25]. Hence, the NBM was used to determine the safety condition of paratransit in Chittagong city (Tempo, Laguna, Easy Bike, mini-Bus, and CNG) (Figure 2). Mainly, probability and loglikelihood distribution function was used to calibrate the model. Details of the NMB was discussed in section 4.

4 Model development

The i-th observation of the dependent variable has the following probability in the Negative binomial (NB) model distribution function yi [25-30].

$$p(yi) = \frac{\Gamma(yi+r)}{yi!\Gamma(r)}\left[\frac{\mu i}{\mu i + r}\right] yi \left[\frac{r}{\mu i + r}\right] r. \tag{3}$$

For the vector of observed independent variables, *xi*, the conditional mean of *iy* is given by:

$$E\left(\frac{yi}{xi}\right) = \mu i = e^{x/\beta}. \tag{4}$$

Figure 2 *Pictorial view of paratransit in Chittagong city (source: author elaboration)*

The disadvantage of the Poisson distribution in terms of equality of mean and variance is the reason for the investigators' preference for the NB distribution. The following is the connection between the mean and variance of the NB distribution:

$$V(Y) = \mu + \frac{1}{r}\mu^2 . \tag{5}$$

Since the variance of the NB distribution is always bigger than the mean, it fits data with more volatility. The dispersion parameter is $a = \frac{1}{r}$. The use of Poisson distribution helps to produce better results for accident data with modest dispersion, however, if there was excess dispersion in the data, the variance of the data will be bigger than the mean, in which case the NB distribution is preferable.

In addition to the regression parameters, the dispersion parameter should be computed in the NB regression model. Since r must be positive, $r = \ln r$ is approximated instead and it can take any value. The following equation yields the log-likelihood of the NB model:

$$L = \sum_{j=1}^{n}\left[\sum_{j=0}^{yi-1}\ln(e^{r*}+j) - \ln yi! + yi\ln(\mu i) - \right. \\ \left. -(e^{r*}+yi)\ln(\mu i + e^{r*})\right] + ne^{r*}\ln(e^{r*}) \tag{6}$$

As in the Poisson model, the Newton-Raphson iteration process is used to estimate β and r [30].

5 Model validation: loglikelihood ratio test

Loglikelihood is a measure of how well all of the independent variables affect the outcome or dependent variable. This can be assessed by comparing the fit of null model and given model. Likelihood of the null model is the likelihood of the observation if the independent variables had no effect on the outcome. Likelihood of the given model is the likelihood of obtaining the observations with all the independent variables incorporated in the model. The difference of these two is a goodness of fit index LL, χ^2 statistics with k degree of freedom [1, 8]. The equation can be written as follows.

LL = –2 (log likelihood of null model -
log likelihood of given model). (7)

***Table 2** The response's descriptive statistics of demographic and trip characteristics*

Attributes	Category	N (%)	Codes
Gender	Male	394 (72.83)	2
	Female	57 (27.17)	1
Age	12-30	251 (55.65)	1
	31-40	131 (29.06)	2
	41-50	60 (13.30)	3
	>50	9 (2.00)	4
Interview person	Driver	277 (61.42)	1
	Passenger	174 (38.58)	2
Vehicle type	Tempo	290 (64.30)	1
	Laguna	102 (22.62)	2
	Easy Bike	59 (13.08)	3
Passengers occupation	Service holder	87 (50.00)	1
	Student	50 (28.74)	2
	Business	15 (8.62)	3
	Housewife	10 (5.75)	5
	Others	12 (6.90)	4
Education	Primary	158 (35.03)	2
	Secondary	168 (37.25)	1
	Higher Secondary	25 (5.54)	5
	Graduate	51 (11.31)	3
	Post Graduate	12 (2.66)	6
	Illiterate	37 (8.20)	4
Monthly income (BDT)	0-8000	170 (37.69)	1
	8000-20000	83 (18.40)	2
	>20000	198 (43.90)	3

$$\text{Chi-square, } x^2 = \sum \frac{(Oi - Ei)^2}{Ei} \tag{8}$$

Here, X^2= chi square, Oi = observed value, Ei = expected value.

$$\text{Pseud } R^2 = 1 - \frac{\ln(\text{likehood of filled model})}{\ln(\text{likehood of null model})} \tag{9}$$

6 Model results

Table 2 shows the analyzed variables and their statistical evaluations obtained by entering the specific coding. The proportion of male and female passengers was imbalanced, with 72.83 % male and 27.17% female. Majority of the passenger age was 12-30 years (55.65%). Most of the interviewed person was driver (61.42%). In terms of vehicle type, tempo (64.30%) was the dominant one because the mode is available on all roads in Chittagong city. In terms of passengers occupation, 50% was service holder, 28.74% was student. Because they used paratransit as their most used mode for travel. The majority of the survey people had primary (35.03%) and secondary education (37.25%). The highest monthly income group was more than 20 thousand (43.90%). In the fourth column of Table 2, the codes are used as substitutes of the attributes categories as required by the STATA software (Table 3).

Table 3 displays the respondent's descriptive statistics on paratransit safety related characteristics. Most of the accident observed by passengers and drivers were possible injury (52.99%) and property damage only (15.96%). While 2.44% passenger and drivers were death due to paratransit accident. In terms of drivers driving experience, 51.62% of the drivers had 6-15 years driving experience. The dominant speed limit of the paratransit vehicle was 30-40 km/h (74.37%).

According to the drivers and passengers perception, the major reason for accident was mechanical fault (24.39%), environmental effect (18.63%) and driven faster (16.63%). In terms of vehicle involved with crash, the dominant mode was bus (58.54%). Most of the paratransit drivers had tendency to stop vehicle frequently (59.21%) for picking passengers. 68.59% drivers had institutional training or they had knowledge about paratransit driving (Table 3). 64.62% drivers drove 3-8 hours (64.62%) in a day. Most of the drivers slept more than 8 hours (89.17%) in a day. Most of the accident occurred at night (72.06%) and the road condition was good (79.38%) in terms of passengers and drivers perception.

After processing the survey data, Negative binomial Model was applied to obtained the results shown in Table 4. The second column is the coefficient and the third column is the p value of variables.

For NBM, the type of accident (possible injury, property damage only, non-disabling injury, fatal, disabling, death) is considered as a dependent variable, while the other aspects are considered as independent variables.

The model used 17 independent variables including gender, age, respondent, vehicle type, occupation of passengers, education, monthly income (BDT), drivers' driving experience (year), vehicle speed (km/hour), vehicle involved with crush, crash frequency per hour, having institutional driving license, driving on road in a day (hours), drivers' sleep in a day (hours), accident time and road condition. The analysis shows that the P value (Probability) of Vehicle type (0.004), Reason of accidents (0.000) and Speed of vehicle (km/h) (0.003) are positively and statistically significant with the Type of accident. Which indicates, when the types/ number of vehicles, the reason for accidents and the speed of vehicles on the road increase, then the types of accidents increase. Furthermore, among the type of vehicle Tempo has large accident probability and Easy Bike has small accident probability. While having an institutional driver's license (0.042) is negatively and statistically significantly correlated with accident types. This indicates, when drivers with institutional driving license increase, then the types of accidents decrease. Log likelihood of Negative binomial model is (-709.239). Wald chi^2 Value is Significant (0.001) and the value is (38.30). Pseudo R^2 value for accident type in paratransit is found (0.73), which indicates a good model.

In the third column of Table 4 (p-value ranking) is shown that the reason of accidents, vehicle speed (km/h), vehicle type, institutional driving license are strongly related to the type of accident. Moreover, there is no relationship with other variables (e.g., frequency of stopping per hour, time of accident, vehicles involved with crushing and road condition, etc.) according to P value.

7 Conclusion

The present research is a first step of investigation the safety of paratransit in the Chittagong city using the perception of passengers and drivers. Negative binomial model was used to evaluate the survey data. The results obtained underlined the importance of the perception of travel safety in determining the perceived accessibility of this mode of transport in daily travel.

Furthermore, both the type of vehicle and the reason for the accident but also the speed of the vehicle and the driving license are factors which contributes to the safety of paratransit. Moreover, it has emerged that some factors such as vehicle speed (km/h), the reason for the accident and the possession of a driving license are strongly correlated with the different types of accident. It is necessary to train deivers and maintain designated speed limit to minimize most of the paratransit accident. Additionally travel safety knowledge among drives and passengers should be increased by governmental and

__Table 3__ The response's descriptive statistics on paratransit safety related characteristics

Attributes	Category	N (%)	Codes
Accident type	Possible injury	239 (52.99)	1
	Property damage only	72 (15.96)	2
	Non incapacitating injury	58 (12.86)	3
	Fatality	48 (10.64)	4
	Incapacitating	23 (5.10)	5
	Death	11 (2.44)	6
Drivers driving experience (year)	1-5	130 (46.93)	1
	6-15	143 (51.62)	2
	>15	4 (1.44)	3
Speed of vehicle (km/hr)	20-30	20 (7.22)	1
	30-40	206 (74.37)	2
	>40	51 (18.41)	3
Reason of accidents	Talking with passenger	42 (9.31)	3
	Talking on phone	16 (3.55)	2
	Mental condition (anger, sleepy, etc.)	17 (3.77)	4
	Non-expert driver	54 (11.97)	6
	Driven faster	75 (16.63)	7
	Sound Effect	44 (9.76)	5
	Mechanical fault	110 (24.39)	9
	Environmental effect (smoke, fog, rain, etc.)	84 (18.63)	8
	Others	9 (2.00)	1
Vehicle involved in a crush	Bus	264 (58.54)	6
	Bike	97 (21.51)	5
	Truck	35 (7.76)	4
	Car	30 (6.65)	3
	Pedestrian	20 (4.43)	2
	Others	5 (1.11)	1
Frequency of stopping per hour	1-4	103 (37.18)	1
	5-7	164 (59.21)	2
	>7	10 (3.61)	3
Have institutional driving training license	Yes	190 (68.59)	2
	No	87 (31.41)	1
Driving on road in a day (hours)	3-8	179 (64.62)	1
	8-15	98 (35.38)	2
Drivers sleep in a day (hours)	5-8	30 (10.83)	1
	>8	247 (89.17)	2
Time of accident	Day	126 (27.94)	1
	Night	325 (72.06)	2
Road condition	Good	358 (79.38)	1
	Bad	93 (20.62)	2

nongovernmental initiatives.

The aim of the study is to investigate the current safety condition of paratransit. The results also lay the foundations for mitigating the critical issues related to safety and placing greater attention on those aspects of transport safety on which the greatest attention by transport companies, but also at the level of government authorities.

Therefore, a long-term planning and optimization approach to paratransit safety should be implemented

Table 4 *Negative binomial model for safety for paratransit*

	Coefficient	P value	P-value ranking
Constant (Accident Type)	0.833	0.010	(out of ranking)
Gender	0.098	0.417	9
Age	0.045	0.325	8
Interview person	0.234	0.214	6
Vehicle type	0.041	0.004	3
Passengers occupation	0.049	0.144	5
Education	0.017	0.561	10
Monthly income (BDT)	-0.057	0.288	7
Driving experience (year)	-0.037	0.637	13
Speed of vehicle (km/h)	0.226	0.003	2
Reason of accidents	0.000	0.000	1
Vehicle involved in a crush	-0.011	0.692	15
Frequency of stopping per hour	-0.019	0.795	17
Have institutional driving training license	-0.166	0.042	4
Driving on road in a day (h)	-0.047	0.592	11
Drivers sleep in a day (h)	-0.063	0.625	12
Time of accident	-0.031	0.737	16
Road condition	-0.036	0.674	14
		Model Fit Results	
Log likelihood	-709.239		
Wald chi^2 (Prob > chi^2)	38.30 (0.001)		
Pseudo R^2	0.73		

in the build, including continuous quality improvement based on contextual needs. The research also found that although there is a large literature describing paratransit services in general, some aspects remain unexplored to date. In particular, addressing issues such as data management and privacy for shared mobility is still under-researched. Therefore, the more research that can address these gaps, the better strategies and policy actions can be used to integrate and improve service for all users.

The study has some limitations such as the paratransit safety assessment survey was conducted within Chittagong city. However it would be better if the entire Chittagong division could be considered. Only the Negative binomial model (NBM) was used for the evaluation of paratransit safety, hence it will be better to use some random parameter models for further study. Overall, the internal effect of the model was not explored in the study, which could be useful for further evaluation. The relation between drivers and passengers perception can be explored in future study. Furthermore, future study should be carried out among different countries considering different factors.

Grants and funding

The authors received no financial support for the research, authorship and/or publication of this article.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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UNIVERSITY OF ŽILINA
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Univerzitná 8215/1,
010 26 Žilina,
Slovakia

Ing. Janka Macurová
tel.: +421 41 513 5143
e-mail: janka.macurova@uniza.sk

ELECTROMAGNETIC FIELD EXPOSURE IN THE PUBLIC SPACE OF THE SLOVAKIAN CITY

Michal Trnka[1,*], Patrik Gálik[2], Eva Kráľová[1], Rastislav Važan[3]

[1]Institute of Medical Physics, Biophysics, Informatics and Telemedicine, Faculty of Medicine, Comenius University in Bratislava, Bratislava, Slovakia
[2]Department of Psychiatry, Faculty of Medicine, Comenius University in Bratislava, Bratislava, Slovakia
[3]Institute of Physiology, Faculty of Medicine, Comenius University in Bratislava, Bratislava, Slovakia

*E-mail of corresponding author: michal.trnka@fmed.uniba.sk

Michal Trnka 0000-0003-4599-1971, Eva Kráľová 0000-0002-7256-9648

Resume

The main objective of our research was to map the exposure to electromagnetic smog in the frequented space of shopping centres in the city of Bratislava and to compare our results to the actual hygienic limits. The measurements of the low- and high-frequency electromagnetic fields were performed at different places in shopping centres. Our results did not exceed the Slovak current limits in any of the measurements. However, almost all of them markedly exceed new permitted limits according to EUROPAEM. Based on our results, stricter limits in many European countries and increasing evidence on possible harmfulness of long-term exposures to artificial electromagnetic fields, preventive carefulness can be recommended - to support the research in this field, to prepare professional public education and possibly to prepare the stricter Slovak exposure limits.

Article info

Received 26 July 2022
Accepted 4 December 2022
Online 21 December 2022

Keywords:

electromagnetic fields
exposition limits
health risks
public health

Available online: https://doi.org/10.26552/com.C.2023.014

ISSN 1335-4205 (print version)
ISSN 2585-7878 (online version)

1 Introduction

Exposure of humans to electromagnetic fields (EMF), low-frequency (LF) within the frequency range from 1 Hz to 100 kHz, high-frequency (HF) within the frequency range from 100 kHz to 300 GHz is not a new phenomenon. However, during the twentieth century, environmental exposure to man-made electromagnetic fields has been steadily increasing. Technical technological innovations constantly provide new sources, especially high-frequency electromagnetic fields, even directly in homes and public spaces (transport, Wi-Fi network, wireless energy meters, wireless games etc.). In connection with this, there are also growing concerns today about the possible negative effects of such high and continuous long-term exposure to artificial electromagnetic fields [1].

In an effort to protect the public health, many countries have tightened their health and safety limits in this area and the Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR), established by the European Commission, has also addressed the issue of protection strategies [2]. Research in this area has brought new safety warnings and indications concerning, in particular, the nonthermal effects of electromagnetic smog.

It is also worth noting, for example, that the International Agency for Research on Cancer (IARC), a part of the World Health Organization (WHO), has included electromagnetic fields in Group 2B among possible human carcinogens [3] and the WHO has organized in 2004 an international workshop on Electrical Hypersensitivity, where this has been defined and recognized as a real problem [4-5].

There are many different guidelines and recommendations in the world that also set health and safety limits for human exposure to electromagnetic radiation, namely, the electromagnetic fields. However, many of them are now outdated and expired (dated back to the beginnings of research in this area). In many European countries, including Slovakia, the recommendations developed by the International Commission for Nonionizing Radiation Protection, abbreviated ICNIRP [6], are currently valid. In Slovakia, these recommendations were applied in practice in 2007 [7]. However, new recommendations, with significantly lower exposure limits, should also be mentioned, e.g. those published by the European Academy of Environmental Medicine - EUROPAEM [8] or BioInitiative [9]. These new recommendations are based on several researches in recent years and correspond to the effort for the so-called “Preventive measure”, as the effects of long-term exposure to electromagnetic radiation from artificial sources are now difficult to estimate more accurately and several studies point to its potential harmfulness.

The purpose of our research was to map the exposure to various types of artificial electromagnetic fields in the public areas of the major shopping centers in Bratislava and to compare the values to the current health and safety limits according to ICNIRP and EUROPAEM.

2 Materials and methods

2.1 Study design

Exposure measurements to electromagnetic fields were made in three selected large shopping centres located in three different districts of Bratislava. We marked them in the text with e letters A, B and C, to maintain anonymity. The measurements in the shopping centers were made at a height of 1.5 meters in the middle of the shopping route. The measurement locations in the shopping centers (SC) were distributed symmetrically on each floor along the shopping routes. Total number of measurement locations n = 90 (SC-A: n = 40, SC-B: n = 30, SC-C: n = 20). The different numbers of measurement locations are related to different lengths of shopping routes of individual SCs. The average values were then calculated for each SC.

2.2 Procedure

All the measurements were performed during the working days in the afternoon between 2:00-5:00 PM. Exposure to the both low-frequency (LF) within the frequency range from 20 Hz to 50 kHz and the high-frequency (HF) within the frequency range from 50 MHz to 3,500 MHz electromagnetic fields was measured in all shopping centres locations.

However, in the case of well-shielded electric circuits, the electric component of low-permeability is almost zero and there exists practically only a magnetic component. The three orthogonal strength components (X, Y and Z) of the magnetic field were measured at each location, from which the final value of magnetic induction (μT) was subsequently calculated. The HF electromagnetic fields were characterized by a power density ($W.m^{-2}$) that best expresses the exposure to these fields.

2.3 Measurement equipment

Three devices were used for the measurements. An “EXTECH EMF450” multi-field EMF meter (Extech Brand, Nashua, NH) was used to measure exposure to LF and HF electromagnetic fields. The device measurement range in the mode of measurement of magnetic induction is 0.02 - 200 μT and in the mode of measurement the electric field intensity is 50 - 2000 $V.m^{-1}$ in the frequency range of 50/60 Hz. The device measures the power density for frequencies 50 - 3,500 MHz in the range 0.02 $\mu W.m^{-2}$ - 554.6 $mW.m^{-2}$.

A “PF5 Pocket Power Frequency Meter” (EMFields Solutions, Sutton, United Kingdom) was used to measure exposure to LF electromagnetic fields. The device measures in the frequency range 20 Hz - 50 kHz. It can be used in the magnetic induction measurement mode in a measuring range of 0.02 - 2 μT or the electric field measurement intensity mode in a measuring range of 5 - 200 $V.m^{-1}$.

The “HF-Analyzer Gigahertz, HF35C” (Gigahertz Solutions, Furth, Germany) was used to measure exposure to HF electromagnetic fields. The device measures the power density for frequencies 800 - 2,700 MHz in the measurement range 0.1 - 2,000 $\mu W.m^{-2}$. To measure very high exposures, an electronic element attenuator DG20 is attached that reduces the sensitivity of the measuring device by a factor of 100 (= 20 dB). The device then measures in the range of 10 - 200,000 $\mu W.m^{-2}$. This device measures in two modes. The RMS (Root Mean Square) mode represents the quadratic average of all the pulses, often called the effective value and in the PEAK mode, which senses the peak (maximum) values of the pulse signal.

All the broadband EMF meters were self-calibrated before measurement.

2.4 Statistical analyses

We present the data as the mean ± SD and (range). The differences in the categorical variables between the three groups were analyzed using Kruskal-Wallis Test with the Post-Hoc Mann Whitney U test. All the tests were carried out at a significance level of $\alpha = 0.05$. (In Kruskal-Wallis Test p-value of < 0.05 was considered statistically significant). The IBM SPSS Statistics 25 statistical program was used for the statistical processing of measured data.

Table 1 *Exposure to electromagnetic fields in shopping centres. LF = low frequency; HF = high frequency.*

Place of measurement (number of measurements)	LF electromagnetic field magnetic induction [μT]			HF electromagnetic field power density [μW.m^{-2}] RMS mode			HF electromagnetic field power density [μW.m^{-2}] PEAK mode		
	mean	max	min	mean	max	min	mean	max	min
Shopping centre A (40)	0.09	0.25†	0.01	79	450†	10	305†	750†	70
Shopping centre B (30)	0.18†	0.43†	0.05	265†	725†	20	1 904†	10 950†	20
Shopping centre C (20)	0.11†	0.29†	0.02	180†	1 100†	7	1 115†	3 500†	70
Limit ICNIRP		100 ^			10 000 000 ¦			- ‡	
Limit EUROPAEM		0.1			100			100	

† *The resulting value means exceeded limits of EUROPAEM.*

^ *The resulting value of the magnetic induction is in this case calculated according to the formula 5/f (kHz) (that is, for 50 Hz the resulting value of the magnetic induction is 100 μT).*

¦ *The resulting value of the power density is, in this case, calculated according to the formula f (MHz)/200 (i.e. for example for 2,000 MHz the final value of the power density is 10,000,000 μW.m^{-2}).*

‡ *ICNIRP does not specify the PEAK limit.*

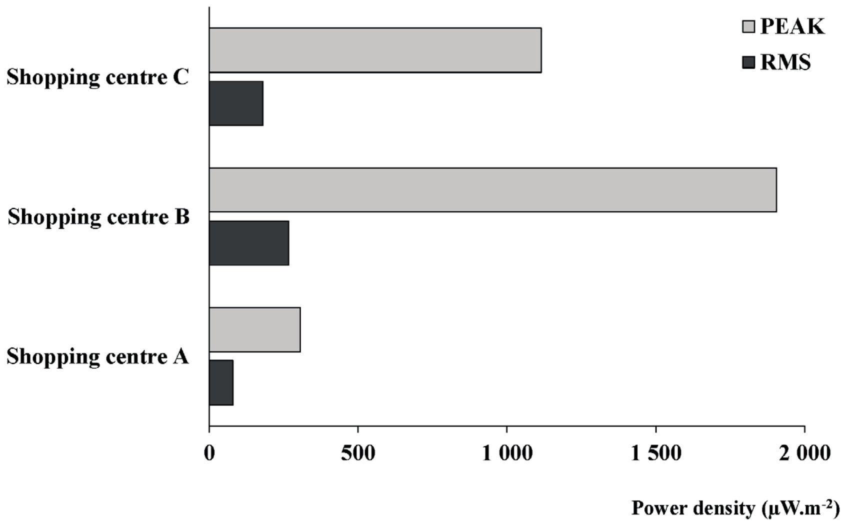

Figure 1 *Mean values of exposure to electromagnetic fields in shopping centres displayed in different modes*

3 Results

The results of the statistical processing of the measured data (mean, maximal and minimal values) are presented in table 1 and graphically. Table 1 contains data on the exposure to LF and HF electromagnetic fields in the large shopping centres in Bratislava and Figure 1 shows differences in measured LF electromagnetic fields exposures in different modes.

In the shopping center A (40) the magnetic induction was 0.094 ± 0.010 μT, the power density in the RMS mode 78.75 ± 13.41 μW.m^{-2} and the power density in the PEAK mode 304.78 ± 24.07 μW.m^{-2}. In shopping centre B (30) the magnetic induction was 0.184 ± 0.019 μT, the power density in the RMS mode 265.40 ± 28.89 μW.m^{-2} and the power density in the PEAK mode 1904.49 ± 565.01 μW.m^{-2}. In Shopping centre C (20) the magnetic induction was 0.111 ± 0.018 μT, the power density in the RMS mode 179.75 ± 65.92 μW.m^{-2} and the power density in the PEAK mode 1114.80 ± 238.51 μW.m^{-2}.

We compared individual parameters in all the shopping centers and found significant differences in the measured values between individual shopping centers. In the measurement of the electromagnetic field LF - magnetic induction, the Kruskal-Wallis H test indicated that there is a significant difference in the dependent variable between the different groups, $\chi^2(2) = 16.88$, $p < .001$. The Post-Hoc Mann Whitney U test, using an alpha of 0.05, indicated that the mean ranks of the following pairs are significantly different (SC-A vs. SC-B and SC-B vs. SC-C). In measurement of the power density of the electromagnetic field HF - RMS mode, the Kruskal-Wallis H test indicated that there is a significant difference in the dependent variable between the different groups, $\chi^2(2) = 28.23$, $p < .001$. The Post-Hoc Mann Whitney U test, using an alpha of 0.05, indicated that the mean ranks of the following pairs are significantly different (SC-A vs. SC-B and SC-B vs. SC-C). In measurement of the power density of the electromagnetic field power density - PEAK mode, the Kruskal-Wallis H test indicated that there is a significant difference in the dependent variable between the different groups, $\chi^2(2) = 30.45$, $p < .001$. The Post-Hoc Mann Whitney U test, using an alpha of 0.05, indicated that the mean ranks of the following pairs are significantly different (SC-A vs. SC-B and SC-A vs. SC-C). Upon closer examination of the technical documentation of individual installations in shopping centers, we discovered that each shopping center has different parameters of unified access points (signal strength, performance etc.).

In all the measurements of LF and HF fields in shopping centers, older limits according to ICNIRP and still valid in Slovakia were not exceeded even once. The new limits, according to EUROPAEM, were exceeded only slightly in the LF electromagnetic fields. The average values of exposure to the electromagnetic fields of LF in shopping centers, in one case only slightly exceeded and in one case reached the value of 0.1 µT of the EUROPAEM limit. However, the average values of exposure to HF electromagnetic fields exceeded the EUROPAEM limit (100 $\mu W.m^{-2}$) in the Peak mode several times, in all three shopping centres. In two centers, this limit was significantly exceeded in the normal RMS measurement mode, as well and the maximum value was even at the level of 1100 $\mu W.m^{-2}$.

Values exceeding the stricter EUROPAEM limits are marked in the tables in bold.

(Note: the electric component of LF electromagnetic fields in the shopping centres was assumed to be almost zero in all places - therefore we do not list it in Table 1 and we only present the magnetic component of the LF electromagnetic fields).

4 Discussion

According to the effects, electromagnetic radiation can be divided into two groups: ionizing and non-ionizing. Ionizing radiation has enough energy to ionize, that is, to release an electron from an atom or molecule, or to break a chemical bond. The population is not exposed to stronger sources of ionizing radiation, but today is surrounded by various sources of artificial nonionizing radiation, e.g. electromagnetic smog (electric systems, radio and television transmitters, networks of mobile operators, WIFI etc.). The effects of non-ionizing radiation can be divided into thermal and non-thermal.

Although the thermal effect leading to tissue overheating has been known for a long time, currently, thanks to new methodological possibilities, nonthermal effects and their mechanisms are the subject of research. One of these mechanisms is, for example, the ability of the electromagnetic field to activate voltage-gated calcium channels. The increased intracellular calcium concentration activates the calcium signaling pathway, thereby stimulating nitric oxide synthesis. Nitric oxide then reacts with superoxide, forming an extremely reactive peroxynitrite. Its decomposition produces free radicals responsible for oxidative stress and carcinogenesis [10-11]. Another possible mechanism is a direct effect on cellular organelles and microtubules of the cytoskeleton, which could be damaged by the mechanism of the so-called resonant absorption [12] or even by the direct effect on DNA, which behaves as the so-called fractal antenna [13].

Despite the fact that the nonthermal mechanisms of electromagnetic radiation have not yet been sufficiently investigated, there is a growing evidence and indications that truly long-term and continuous exposure to relatively weak artificial electromagnetic fields can contribute to development of various health problems and serious diseases. The impact of the electromagnetic field is mentioned in particular in connection with neurological diseases, such as Alzheimer's and Parkinson's disease [14-16] or brain tumors [17]. A contribution to the development of certain forms of autism cannot be excluded. In this context, leukemia is also mentioned in the literature [18-19].

The IARC (International Agency for Research on Cancer) has classified HF electromagnetic fields as possible human carcinogen [20]. Exposure to a high-frequency electromagnetic field can also cause a variety of neurobehavioral changes in susceptible individuals, particularly fatigue, mood swings, headaches, sleep disorders and concentration [21].

Research in this area is very complicated, since electromagnetic radiation is a factor, whose consequences appear to manifest itself in humans only after a very long time. In addition, other simultaneous factors (genetics, the presence of other diseases, lifestyle, level of stress, exposure of the body to toxic substances etc.) are acting.

The findings obtained in experiments on cells and animals can suggest a lot, but their direct transfer to humans is problematic. Therefore, it is likely that the definitive confirmation or rejection of the negative effects of electromagnetic smog on humans will not be possible for a longer period of time. It is currently reasonable to take the position of the so-called precautionary measures - to support research in this area, to sensitively inform the public about possible risks, about levels of electromagnetic smog exposure at different locations and about possible measures to reduce the level of exposure.

Our research provides information on the levels of population exposure to electromagnetic smog, respectively, artificial electromagnetic fields in frequently visited public spaces of the Bratislava city. We compared the results of our measurements to the limits of the most important European recommendations for exposure to electromagnetic fields, ICNIRP and EUROPAEM. The European Union and the Slovak Republic [22] have also taken over the ICNIRP limits that are still the official limits in Slovakia. These limits do not take into account extreme pulse fluctuations (peaks) and are based only on influence of the contact currents induced in the body and the thermal effects of HF electromagnetic fields [6]. Recent EUROPAEM recommendations already take into account the nonthermal effects of HF electromagnetic fields and their recommended limits already take into account the magnitude of the intensity and power density measured in the Peak pulse mode. The Peak measurement mode, unlike the conventional RMS mode, also records extreme pulse fluctuations, thus providing a more accurate picture of the “activity” of the electromagnetic field.

5 Conclusions

Although the values of HF and LF electromagnetic fields measured in the shopping centers in Bratislava city did not exceed the limits currently valid in the Slovak Republic (corresponding to the ICNIRP limits), this should not be a reason for complete satisfaction, as they significantly exceeded the limits of the new recommendations according to EUROPAEM. In several countries are stricter limits in this area and the growing evidence of possible harmful effects of long-term exposure to the artificial electromagnetic fields would reqiured to formulate preventive measures. Therefore it should be considered to strengthen limits for this area in the Slovak Republic. Moreover, the neighboring countries gradually adjust these limits. At the same time, it would be appropriate to support research and raise public awareness of this issue.

Acknowledgement

This research was funded by a grant from the Cultural and Educational Grant Agency of the Ministry of Education, Science, Research and Sport of the Slovak Republic KEGA 023UK-4/2021.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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VEDECKÉ LISTY ŽILINSKEJ UNIVERZITY
SCIENTIFIC LETTERS OF THE UNIVERSITY OF ZILINA

VOLUME 25 Number 1

January 2023

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Published quarterly by University of Žilina in EDIS - Publishing House of the University of Žilina.

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Komunikácie - vedecké listy Žilinskej univerzity v Žiline
Communications - Scientific Letters of the University of Žilina
University of Žilina
Univerzitná 8215/1
010 26 Žilina
Slovakia

E-mail: komunikacie@uniza.sk
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ISSN (print version): 1335-4205
ISSN (online version): 2585-7878

Registered No. (print version): EV 3672/09
Registered No. (online version): EV 3/22/EPP
Publisher, owner and distribution:
University of Žilina, Univerzitná 8215/1,
010 26 Žilina, Slovakia

Company identification number IČO: 00 397 563
Frequency of publishing: four times a year
Circulation: 150 printed copies per issue
Print edition price: free of charge

Publishing has been approved by:
Ministry of Culture, Slovak Republic

15th International Scientific Conference on Sustainable, Modern and Safe Transport

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CONTACT

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Univerzitna 8215/1, 010 26 Zilina, Slovakia
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