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DECISION SUPPORT FOR CHOOSING A SCENARIO FOR ORGANIZING URBAN TRANSPORT SYSTEM WITH SHARE OF ELECTRIC VEHICLES

Summary. This article presents the issue of using decision support tools to select the variant of organization of urban transport system. Two scenarios for the use of electric vehicles were compared, considering not only their emissions and fuel consumption but also the limited accessibility of conventional vehicles to the city. The authors assume that the development of urban traffic organization must go hand in hand with the challenges of planning sustainable urban mobility and reducing harmful exhaust fumes. Furthermore, decision-makers should be equipped with simple decision support tools to generate the best option considering the expectations of transport users. The PTV VISUM tool was used to analyse and visualize two different organization scenarios for a selected city in Poland.

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Keywords: decision support, electric vehicles, urban transport system, travel demand model, pollutant emissions, urban area, limited accessibility of the city, sustainable urban mobility

1. INTRODUCTION

Currently, the ways of shaping transport policy, both on the micro and macro scale; depend on many factors based on a technological, social, environmental, and economic nature. The phenomenon of global warming and the increasing intensity of traffic on roads, especially on the streets of large cities, force the need to care for the natural environment. This applies mainly to city dwellers for whom daily traffic congestion is becoming increasingly common. In such a situation, the search for solutions toward reducing pollution and noise and increasing the safety of life in the city becomes a priority for decision-makers [13, 19, 29, 34]. These authorities are looking for new solutions to be used in the design of traffic organization or to replace the rolling stock with emission-free vehicles. The incentives for the use of electric vehicles are very popular for both individual and public transport [25, 26]. It is also important to use tools that support making the right decisions in the field of traffic organization in the city [1].

As reported by Cartenì et al. [5], the introduction of electric vehicles in cities is one of the best options to meet both the goals of sustainable development and mobility needs. The authors proposed a new approach to e-mobility, replacing the fleet of "old" buses on the Sorrento Peninsula (Italy) with hybrid diesel buses powered by an additional photovoltaic system, to both improve the environment and obtain a return on investment for the private operator managing the transport services. It is estimated that this new type of bus can reduce greenhouse gas emissions by up to 23%, with a 10-year payback period if a private investor is involved. Cartenì, on the other hand, in the article [4], analyzed the benefits of using hybrid electric buses in modified public transport services. In his analysis, the author considered the total carbon footprint and not only the local impacts generated by this vehicle technology. This approach was tested on a new bus line in the medium-sized city of Salerno, Italy.

Planning efficient and ecological transport systems, especially in urban areas, requires the introduction of a transport policy that assumes the future social and economic benefits resulting from the implementation of new environmentally friendly systems of organizational and infrastructural investments [22]. The transport infrastructure in cities is characterized by high density and the possibilities of its expansion are very limited due to existing land development. This was noted by Quak [36], Banister [2], and Rietveld and Bruinsma [37]. Intensive traffic in the city negatively impacts on the natural environment and living conditions. It is mainly associated with exhaust emissions and excessive noise during the day and night, which negatively affects human health. The impact of pollutant emissions from transport on the environment is discussed in several studies, including Jacyna et al. [18], Figliozzi [9], Levy et al. [27], and Pyza et al. [34]. Restrictions on the movement of heavy vehicles are introduced by various types of solutions [41, 46]. The problem of noise that reduces the quality of life in the city is described by Tang et al. [42], Fuks et al. [11], and other authors.

Despite the implementation of advanced solutions in vehicle construction, the high and constantly growing emission of harmful exhaust gas compounds makes it necessary to introduce restrictions on access to selected areas of cities for vehicles with low ecological efficiency. The European Commission is also giving much attention to this problem. The EU documents on transport policy allow for the application of different rates of charges, which depend on the emission class of the vehicle [16].

Many studies show that formulating appropriate recommendations for shaping an environmentally friendly transport system - especially in urban areas - requires a series of complex and time-consuming analyzes [19, 20, 35]. To improve the research process and conduct an appropriate number of various analyzes, it is necessary to have a tool that allows simulations in various boundary conditions and considers the established criteria for assessing the effectiveness of the transport system.

Proper traffic organization in the city consists in reducing the ecological costs of traffic, increasing safety, and improving the quality of life of the inhabitants. Therefore, a systematic approach to solving these problems is necessary. The organization of traffic in the city must consider the specific conditions for the implementation of a wide range of transport services, including individual transport, collective transport, and city supplies, as well as other types of services, such as repairs, services, medical care, etc. For example, Visser et al. [44] and Behrends et al. [3] indicate that significant problems in this respect are variable travel time, vehicle traffic restrictions due to MPW (maximum permitted weight), traffic restrictions for vehicles that do not meet specific exhaust emission standards, etc.

Bearing in mind the increasing popularity and availability of electric vehicles and the current pro-ecological trends, we propose a method of analyzing the impact of the urban traffic structure on the emission of harmful compounds in the context of the city's availability for various types of vehicles, in particular, electrically powered vehicles. The method assumes the use of a transport model built with the use of the PTV VISUM tool. The HBEFA module (that is, The Handbook of Emission Factors for Road Transport) was used to perform environmental analyzes. Individual variants of traffic organization differ in the composition of the fleet for vehicles. Fuel consumption and harmful emissions are criteria to assess the scenarios analyzed. The study used the emissions of passenger cars, trucks, and light commercial vehicles during the morning rush hour and distinguished inbound and outbound traffic, as well as through traffic.

The following issues are discussed in the remaining parts of this article. In the second section, the literature in the research area is reviewed. Particular attention is focused on the methods and tools used to assess transport emissions and determine external transport related to the implementation of electric vehicles and other low-emission vehicles. The next section presents the research problem. A decision support method was described. It enables scenario analyses of the different shares of electric vehicles in the fleet composition and the assessment of harmful exhaust emissions. An important part of this article is a case study based on the macroscopic transport model of the city of Bielsko-Biała (Poland), in which two experiments were carried out with different shares of electric vehicles and restrictions related to the entry into the city for high-emission vehicles. Analyzes were performed considering the value of exhaust emissions and fuel consumption as assessment criteria for the scenarios tested.

2. REVIEW OF THE LITERATURE

The study of the impact of transport on the environment is the subject of several scientific studies. This research concerns many problem areas related to:

- identification of negative effects of transport activity on the environment,
- ecological and social aspects of transport system development,
- influence of traffic conditions on environmental conditions,
- transport-related exhaust emissions,
- transport-related emission,

- relations between traffic conditions and quality of life,
- the impact of noise emitted by transport on the quality of life in the city,
- the assessment of safety and health effects of noise regarding costs,
- the impact of mobility management and implementing restrictions on greenhouse gas emissions.

The exemplary publications concerning the issues mentioned above are presented synthetically in Table 1.

Tab. 1

Selected publications related to the issues of the impact of transport on the environment

Research area	Publications
identification of negative effects of transport activity on the environment	Schreyer, C. et al. [6] Jacyna, M. et al. [17] Wasiak, M. et al. [46]
influence of traffic conditions on environmental conditions	Vaitieknas, P. et al. [43] Lu, J. et al. [28] Wang, L. et al. [45] Gundlach, A. et al. [14]
transport-related exhaust emission	Proost, S. [33] Merkisz, J. et al. [30] Chamier-Gliszczyński, N.; Bohdal, T. [7] Kholod et al. [23]
relations between traffic conditions and quality of life	de Palma, A.; Lindsey, R. [8] Levy, J.I. et al. [27] Qingyu, L. et al. [35] Jacyna-Gołda, I. et al. [20]
the impact of noise emitted by transport on the quality of life in the city	Fuks, K. et al. [11] Galilea, P.; de Dios Ortuzar, J. [12] Jakovljevic, B. et al. [21] Filippone, A. [10]
the assessment of safety and health effects of noise regarding costs	Müller-Wenk, R.; Hofstetter, P. [31] HEATCO [15] Korzhenevych, A. et al. [24]
the impact of mobility management and implementing restrictions on greenhouse gas emissions	Shafiei, E. et al. [39] Shi, F. et al. [40] Schubert, T. et al. [38]

The list of scientific papers presented in Table 1 represents only a part of the rich literature of world science, but the analysis of these publications shows that many instruments lead to environmentally friendly changes in transport. Overall evaluations of their effectiveness are also carried out, as well as discussions on the transfer of negative effects of transport between different areas of the transport network (for example, from the city centre) to production and disposal sites of transport equipment and electricity generation sites. Therefore, the issues of shaping an environmentally friendly transport system should be individually considered for each area, given local conditions.

3. THE RESEARCH METHOD

3.1. Notation

To describe the adopted research method, the following basic notation is introduced:

v - variant (scenario) for organizing urban transport system,
V - set of analysed variants (scenarios),
h - period,
k - transport subsystem,
r - mode of transport,
tv - the type of vehicles for transport mode and subsystem,
m - the type of engine,
n - vehicle emission standard,
tp - the type of pollutants from motor vehicles,
(a, b) - transport relation (a – the origin; b – the destination of the traffic flow),
p - path in transport relation (a, b),
(i, j) - section in transport network (i – start node; j – end node of the section),
$X(i, j)$ - matrix of traffic assignment in the transport network.

3.2. General assumptions

The main objective of this research was to develop a transport model that would allow simulation studies to be carried out to shape an environmentally friendly transport system. This model was built using existing specialized software (for example, PTV VISUM) and is a decision support tool in the selection of the optimal scenario for the organization of the urban transport system. The presented form of the model organizes the process of preparing the simulation environment, as well as the scope and manner of simulations performed.

Analysis and evaluation of the functioning of existing or planned systems of various types require a model mapping of the features of the system that are important for research purposes. The scenarios of changes included in set V are the basic elements of the model. They may concern, for example, the construction of new transport connections, changes in the parameters of existing connections, the introduction of new low-emission means of transport, changes in the offer of public transport, access restrictions for specific means of transport, etc.

With this in mind, it was assumed that to assess the impact of electric vehicles in road traffic on the reduction of harmful emissions in the city or to conduct other analyses of pro-ecological changes in the urban transport system, it is necessary to have a transport model for each variant, which must reflect:

- actual fleet composition with their characteristics, as well as their composition included in the v-th scenario - general vehicle structure (for example, passenger cars, light commercial vehicles, truck trailers, and trucks) for each type of traffic, that is, inbound, outbound, and through traffic for the v-th scenario - $FC(v)$;
- the structure of the real transport network, including its technical, economic, and organizational characteristics, as well as links to the origins and destinations of the traffic flow for the v-th scenario - $GE(v)$;
- the volume of transport tasks (that is, transport demand) performed in the urban transport system, given the type of traffic, that is, inbound, outbound and through traffic for the v-th scenario - $QE(v)$;

- organization of traffic in the urban transport system determining the assignment of traffic to the elements of the transport network, considering changes in the v-th scenario - $OE(v)$.

Given the above, the model ($MEST$) of the research problem, that is, the evaluation of the scenarios of the share of electric vehicles in the urban transport system, is described as follows.

$$MEST = \langle FC(v), GE(v), QE(v), OE(v) \colon v \in V \rangle \tag{1}$$

The formal description of the proposed decision model was developed considering the research described in [18].

In the adopted approach, the scenarios represent different proposals for changes that lead to a green and sustainable urban transport system. These changes may be for the different periods of the analysis.

The composition of the fleet can be determined considering the transport subsystem, mode of transport, type of vehicles for the mode and subsystem, type of engine, vehicle emission standard, type of pollutants from motor vehicles, and path in transport relation (a, b). In practice, the fleet composition may differ significantly depending on the section of the transport network under study, especially when considering the internal and external traffic concerning the examined area, that is, inbound, outbound, and through traffic.

For scenario analyses concerning the impact of the share of electric vehicles on the reduction of exhaust emissions, the types of fleet composition presented in Table 2 were introduced. The fleet compositions determined in this way constitute the basis for the development of an appropriate number of demand segments, considering the detailed structure of vehicles.

Tab. 2

Fleet composition

Name of the fleet composition	Designation of the type of the fleet composition	Group of vehicles
Urban	U1 U2 U3	passenger car light commercial vehicle mix (trucks, truck trailers, articulated trucks)
Average	A1 A2 A3	passenger car light commercial vehicle mix (trucks, truck trailers, articulated trucks)
Motorway	M1 M2 M3	passenger car light commercial vehicle mix (trucks, truck trailers, articulated trucks)
Electric	E1 E2 E3	passenger car light commercial vehicle mix (trucks, truck trailers, articulated trucks)

Another important issue is the emission factors for individual modes of transport. They can be determined using standard values derived from exhaust emission standards; however, a much better approach is to use the results of detailed tests of real road emissions. Such studies show that the amount of pollutant emissions is also related to the length of the routes. This means that actual emission factors should be considered following the distribution of route lengths for homogeneous groups of transport relations.

In the pro-environmental model of traffic organization, due to the scope of this conducted research, we introduced restrictions on access to the city. These restrictions may apply to vehicle types (for example, heavy goods vehicles), vehicles with certain engine types, or vehicles that do not meet the required emission standards.

In addition, the model considers all standard constraints imposed on the traffic flow, that is, constraints related to the balance of the stream in the nodes of the transport network, the additivity of traffic and its non-negative nature, as well as the constraints that guarantee the fulfilment of a specific transport task.

3.3. The ecological indicator of transport in the city

Exhaust fumes are an effect of the significant negative impact of transport on the environment. The emission of harmful substances depends on the type of vehicle and its engine, including compliance with the emission standard, speed, and distance travelled. Accordingly, emissions of tp-th type of pollutant for k-th transport system in the h-th period are calculated according to the following formula:

$$E_k^{tp,h} = 3600 \cdot 10^{-6} \cdot \sum_r \sum_{(i,j)} \sum_{(a,b)} \sum_p \sum_{tv} x_{k,(i,j)}^{r,tv,(a,b),p,h} \cdot$$
$$\cdot \sum_m \sum_n \frac{u_k^{r,tv,(a,b),m,n,h}}{100\%} \cdot \frac{l_{(i,j)}^r \cdot e_{k,(i,j)}^{r,tv,m,n,tp}}{v_{k,(i,j)}^{r,tv,h}(X(i,j))} \cdot \psi_k^{r,tv,(a,b),p,m,n,tp} \quad \text{[kg]} \tag{2}$$

where:

$x_{k,(i,j)}^{r,tv,(a,b),p,h}$ - traffic flow consisting of a certain type of vehicle moving in section (i,j) for path p in relation (a,b); [veh],

$u_k^{r,tv,(a,b),m,n,h}$ - share of vehicles of a certain type; [%],

$l_{(i,j)}^r$ - length of the section (i,j) in transport network for a certain transport mode; [km],

$e_{k,(i,j)}^{r,tv,m,n,tp}$ - emission of the pollutant from a certain type of vehicle moving in the section (i,j); [mg/s/veh],

$v_{k,(i,j)}^{r,tv,h}(X(i,j))$- velocity in section (i,j) for vehicles of a certain type under traffic assignment consistent with the matrix $X(i,j)$ in h-th period; [km/h],

$\psi_k^{r,tv,(a,b),p,m,n,tp}$- an indicator of the distance effect on the emission of the pollutant by certain types of vehicle for path p in relation (a,b); [–].

Among vehicle pollutants caused by the flows in urban areas, the most harmful are carbon monoxide (CO), nitrogen oxides (NO_x), hydrocarbons (HC), particulate matter (PM), and carbon dioxide (CO_2). They have disastrous effects on the environment, ecology, and human health. Carbon (C) is one of the most influential factors that accelerate global warming. The level of emissions of these substances depends largely on the speed of the vehicles.

The impact of the urban transport system on the environment, given the share of electric vehicles, was estimated based on the air pollutant emission index $E_k^{tp,h}$. However, from the approach of the assumptions of sustainable mobility, a comprehensive assessment of the influence of the urban transport system related to external costs should also include the effects [24]:

- noise emission,
- accidents,
- congestion,
- water and soil pollution.

3.4. The scheme of the method

A specific approach is required to support the decision on the choice of scenario to organize the urban transport system with the share of electric vehicles to reduce exhaust emissions. The general scheme of the method is shown in Figure 1. It assumes the implementation of the transport model. However, to perform this type of analysis, an appropriate level of detail of the model is necessary.

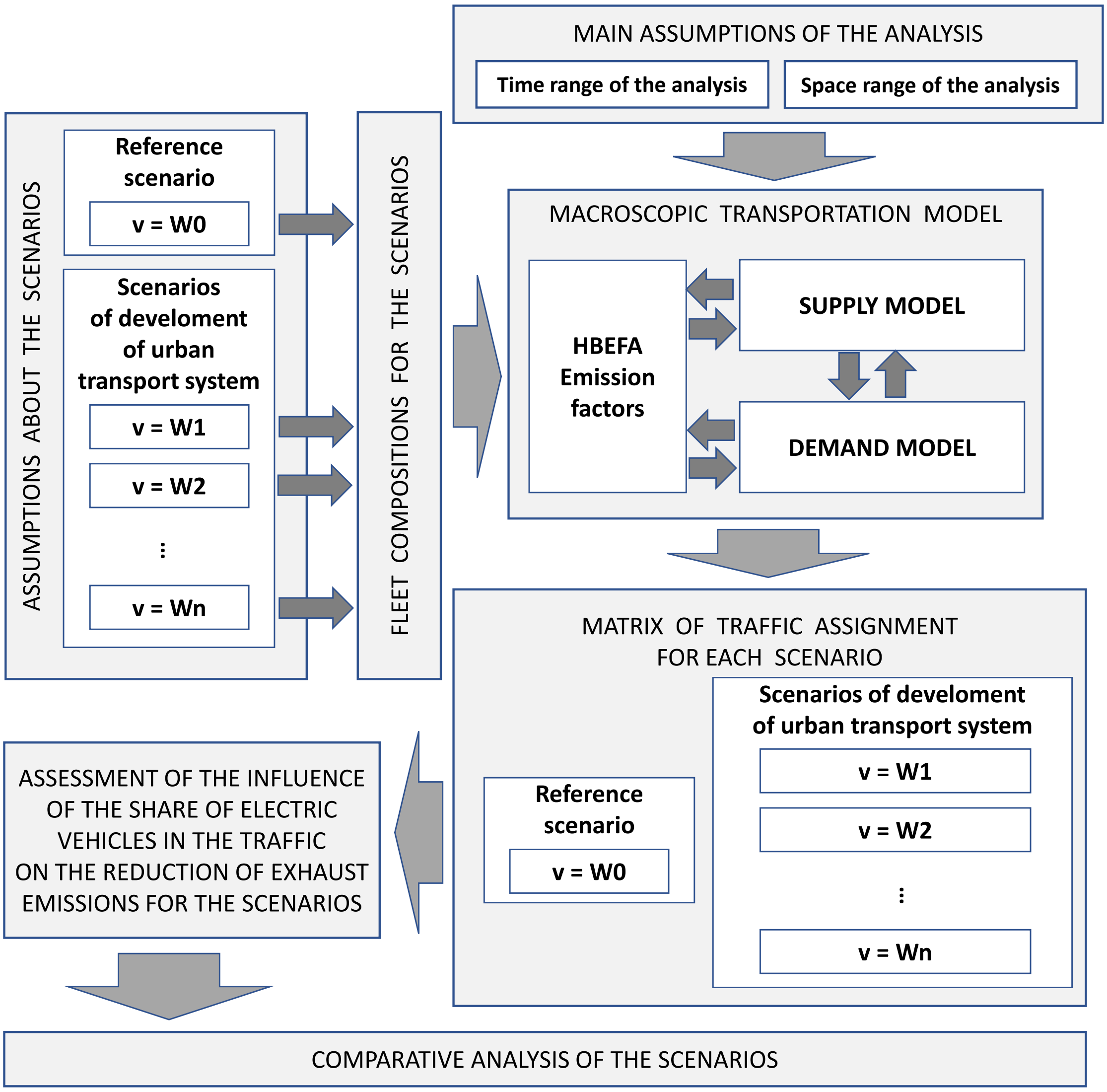


Fig. 1. General method framework

In addition to the assumptions about the fleet composition related to the different scenarios, it is necessary to define the temporal and spatial scope of the study. The period of analysis depends on the directions of the transport policy. It can cover both the 24-hour and a selected shorter period, for example, the traffic rush hour. Moreover, analysis can be performed for the existing state and forecast horizons. The spatial scope depends on the adopted restrictions on the share of high-emission vehicles in the entire city or its separate areas, for example, areas located in central parts of the city.

The simulations made with the use of the macroscopic transport model are the main part of the analysis. The developed method assumes the implementation of the PTV VISUM software, which includes a special emission calculation procedure based on HBEFA (The Handbook of Emission Factors for Road Transport), that is, a publicly available database of emission factors for road transport, developed at the request of several European countries (including Germany, Switzerland, Austria, Sweden, Norway, and France). It contains emission factor values (hot, cold start, evaporation) for all regulated and important non-regulated air pollutants, as well as fuel consumption and CO_2 emissions for different vehicle types. It determines both the desired emissions and the optional excess emissions during a cold start, given different traffic situations, traffic volume, and fleet composition [32].

The use of the HBEFA procedure in the VISUM software enables the determination of the dispersion of harmful substances emissions on sections of the transport network divided into appropriate categories. During the environmental traffic impact assessment process, the fuel consumption for the entire network (expressed in quantity/g) for a specific demand segment is converted into unit consumption (expressed in l/100 km) separately for diesel and petrol. First, the amount of fuel is divided by its density, and then it is related to the mileage for a specific demand segment. To assess fuel consumption for the entire vehicle fleet, including electric vehicles, the results are also presented in [MJ]. The result of the analysis carried out with the VISUM software is the assessment of the emission of harmful substances and fuel consumption for various scenarios.

In the method developed, it was assumed that the assessment of the impact of the share of electric vehicles in traffic on the reduction of harmful substances is based on the matrix of traffic assignment for individual scenarios. The last stage of the analysis consists in comparing the results obtained for the individual scenarios of the development of the urban transport system, that is, W1-Wn, with the results for the reference scenario W0.

The following measures divided into two main groups were used for the assessment:

- Group 1—measures related to the total emission of selected harmful substances, including:
  - carbon dioxide (CO_2) reported total [g],
  - carbon monoxide (CO) total [g],
  - hydrocarbons (HC) total [g],
  - nitrogen oxides (NOx) total [g],
  - particulate matter (PM) 10 μm total [g].
- Group 2—measures related to fuel and energy consumption, including:
  - fuel consumption diesel total [g],
  - fuel consumption gasoline total [g],
  - fuel consumption electric total [MJ],
  - fuel consumption total [g],
  - fuel consumption total [MJ].

The measure values are obtained for the whole city in the analyzed period (the morning rush hour).

4. CASE STUDY

4.1. Research area

The macroscopic transport model built for the city of Bielsko-Biała was used to assess the impact of introducing electric vehicles into circulation for the reduction of exhaust gas emissions. Bielsko-Biała is located in the southern part of Poland in the Silesian Voivodeship near the border of the Czech Republic and Slovakia. Its area is approximately 124.5 km^2. The location of Bielsko-Biała against the background of the Śląskie Voivodeship is shown in Figure 2. The city of Bielsko-Biała is the seat of the Bielsko poviat authorities, as well as the main city of the Bielsko agglomeration and central to the Bielsko Industrial District. It also constitutes a significant centre of the southern sub-region of the Silesian Voivodeship, which is one of the four areas of the development policy of the voivodeship.

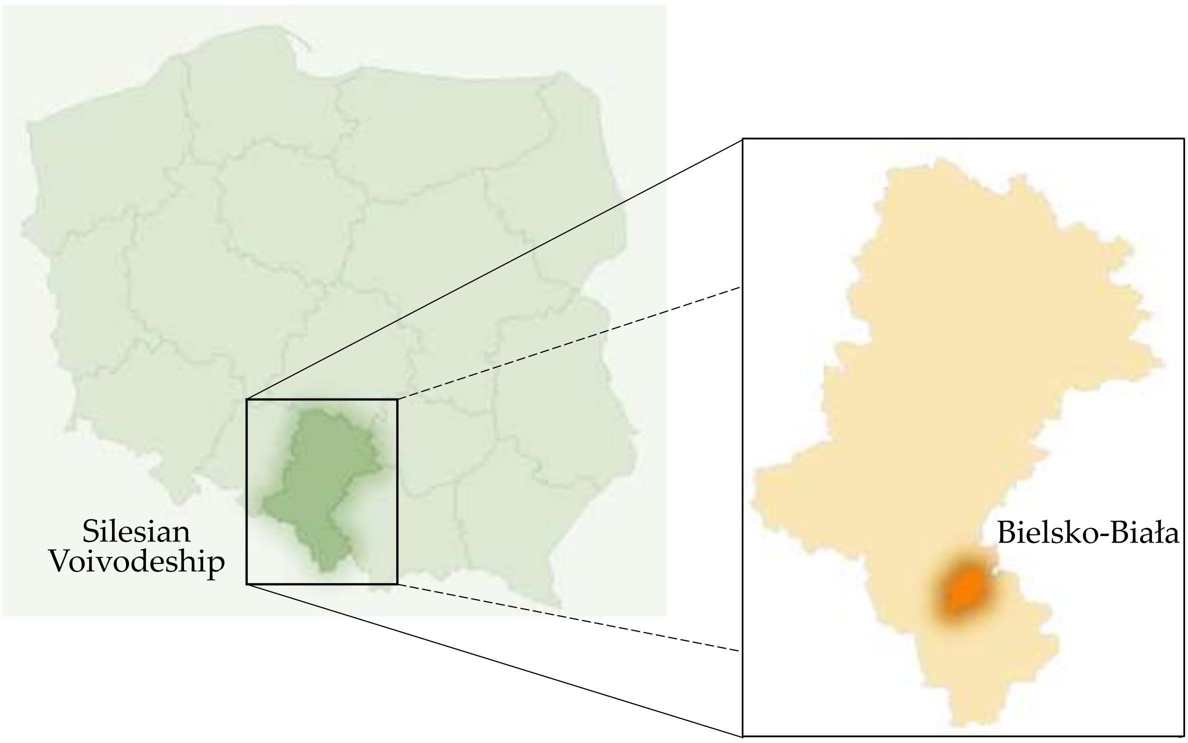


Fig. 2. Location of the city of Bielsko-Biała

Bielsko-Biała is one of the economically well-developed cities in Poland. It serves as the main administrative, industrial, commercial and service, academic, cultural, and tourist centre of the Silesian border area. From year to year, the city is also becoming an increasingly important centre of modern technologies, where dynamic development is visible, especially in the IT industry. Due to the proximity of the Upper Silesian conurbation and Kraków, as well as the Czech Ostrava and Slovak Žilina, Bielsko-Biała is an important centre of cross-border development.

The dynamic development of the city is also favoured by its location at the crossroads of international and national transport corridors, which makes it an important road and rail junction not only in the Śląskie Voivodeship but also nationwide. Due to the convenient location of the city in the network of national and provincial roads and the existing system of these roads, supplemented with county and municipal roads, the city is characterized by a high level of accessibility from other municipalities of the province and the country. They ensure the connectivity of the city area and its accessibility. Geographic and demographic indicators of road density are, respectively, 4.38 [km/km^2] and 31.41 [km/10,000 residents]. There are 1,237 intersections on the road in the city, including 51 (that is, 4.1%) intersections with traffic lights. The average length of the section between the intersections is approximately 479 m.

The population of Bielsko-Biała in December 2020 amounted to 169,756 people and has shown a downward trend since 2010. Variability values in this respect are shown in Figure 3. The largest share of the population, ranging from 64 to 56%, is of working age. Since 2010, this share has been decreasing annually by about 2%. On the other hand, a systematically growing number of people of post-working age can be observed, which in 2020 amounted to 44,000 and constituted over 26% of the city's population. With the share of people of pre-working age at a similar level (the change in this regard has not exceeded 1% since 2010), it means that the society of the city of Bielsko-Biała is ageing. However, since 2017, smaller changes can be noticed in this regard (below 3%).

Fig. 3. Demographic indicators in the city of Bielsko-Biała: a) variability in the number of inhabitants, b) annual dynamics of changes in the number of inhabitants

The number of vehicles registered in the city of Bielsko-Biała is constantly increasing. This applies to both cars and trucks, as well as motorbikes. Figure 4a shows the motorization rate values for each of these groups of vehicles. Age is also an important aspect related to the composition of the vehicle fleet in the urban transport system. Figure 4b shows the structure of passenger cars older than 8 years in the city of Bielsko-Biała in the years 2015-2020.

In 2015, a comprehensive travel survey of the city and its immediate surroundings was conducted. The results indicated that the mobility of active transport people, that is, those who made at least one trip a day, was approximately 2.2 trips/day. However, given the entire population of the city, it turned out that the mobility of an average inhabitant of Bielsko-Biała was equal to 1.59 trips/day. The highest average number of trips made by active transport residents of the city of Bielsko-Biała was related to optional purposes, such as social meetings, sports, recreation, or official matters. A significant number of trips were also made for work-related purposes. Trips related to school (education) were less important. The data collected were used to build a macroscopic transport model, which is a simulation tool that supports scenario analysis.

a) b)

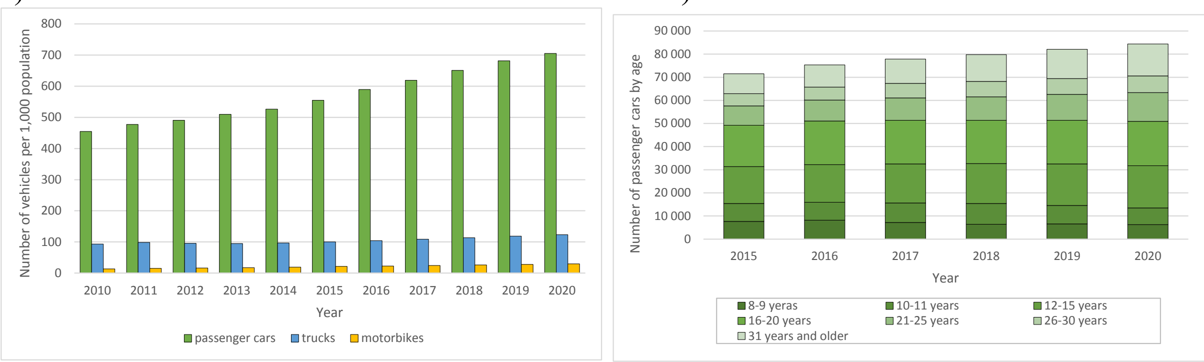


Fig. 4. Motorization indicators in the city of Bielsko-Biała: a) variability in the motorization rate, b) variability in the structure of passenger cars older than 8 years

The proposed method assumes the need to distinguish between inbound, outbound, and through traffic. The average volume of car traffic in the morning rush hour is:

- for inbound traffic: 14,403 [E/h], that is, 47.79%,
- for outbound traffic (the city is the origin of the trip): 5,698 [E/h], that is, 18.91%,
- for outbound traffic (the city is the destination of the trip): 8,159 [E/h], that is, 27.07%,
- for through traffic: 1,880 [E/h], that is, 6.24%.

To build scenarios for the development of the urban transport system, sections were defined for trucks, truck trailers, and articulated trucks in through traffic.

4.2. Assumptions concerning the scenarios

The analysis covers two scenarios for introducing restrictions on the accessibility of the city for high-emission vehicles:

- Scenario W1: The entry of high-emission vehicles from outside the city is not allowed,
- Scenario W2: The entry of all high-emission vehicles is not allowed.

In both scenarios, through traffic is allowed.

To assess the impact of the share of electric vehicles in traffic on the reduction of harmful emissions in the city, we built a transport model using the PTV VISUM software with an appropriate level of detail due to the type structure of vehicles for the selected area of analysis. This made it possible to conduct scenario analyses considering at least:

- types of traffic, that is, inbound, outbound, and through traffic;
- types of fleet composition (as specified in Table 3).

The share of particular types of vehicles in each of the types adopted in the fleet composition is presented in Table 3. It shows only the types of vehicles that constitute a significant share in the composition of the fleet (more than 5%).

Considering the composition of the fleet, we define the vehicle structures in the transport model for both the reference scenario W0 and the scenarios W1 and W2, which are presented in Table 4.

Tab. 3

Emission concepts in the fleet composition under study

Designation of the type of fleet composition	Emission concept and its share in the fleet composition (notation consistent with HBEFA used in PTV VISUM)		
U1	PC petrol Euro-2 (7.83%);	PC petrol Euro-4 (16.21%);	PC diesel Euro-2 (10.07%);
	PC diesel Euro-3 (17.99%);	PC diesel Euro-4 (13.73%);	PC diesel Euro-4 (DPF) (12.42%);
U2	LCV diesel M+N1-I Euro-3 (6.23%);	LCV diesel M+N1-I Euro-4 (8.93%);	LCV diesel N1-II Euro-3 (8.42%);
	LCV diesel N1-II Euro-4 (12.08%);	LCV diesel N1-III Euro-2 (5.43%);	LCV diesel N1-III Euro-3 (17.01%);
	LCV diesel N1-III Euro-4 (24.40%);		
U3	Rigid Truck 7, 5-12 t diesel Euro-III (7.92%);	Rigid Truck >14-20 t diesel Euro-III (7.57%);	Rigid Truck >20-26 t diesel Euro-III (13.02%);
	Rigid Truck >20-26 t diesel Euro-V (6.37%);		
A1	PC petrol Euro-2 (7.83%);	PC petrol Euro-4 (16.21%);	PC diesel Euro-2 (10.07%);
	PC diesel Euro-3 (17.99%);	PC diesel Euro-4 (13.73%);	PC diesel Euro-4 (DPF) (12.42%);
A2	LCV diesel M+N1-I Euro-3 (6.23%);	LCV diesel M+N1-I Euro-4 (8.93%);	LCV diesel N1-II Euro-3 (8.42%);
	LCV diesel N1-II Euro-4 (12.08%);	LCV diesel N1-III Euro-2 (5.43%);	LCV diesel N1-III Euro-3 (17.01%);
	LCV diesel N1-III Euro-4 (24.40%);		
A3	Rigid Truck >20-26 t diesel Euro-III (5.41%);	TT/AT >34-40 t diesel Euro-III (12.93%);	TT/AT >34-40 t diesel Euro-V (20.78%);
M1	PC petrol Euro-2 (7.83%);	PC petrol Euro-4 (16.23%);	PC diesel Euro-2 (10.07%);
	PC diesel Euro-3 (17.99%);	PC diesel Euro-4 (13.73%);	PC diesel Euro-4 (DPF) (12.41%);
M2	LCV diesel M+N1-I Euro-3 (6.23%);	LCV diesel M+N1-I Euro-4 (8.93%);	LCV diesel N1-II Euro-3 (8.42%);
	LCV diesel N1-II Euro-4 (12.08%);	LCV diesel N1-III Euro-2 (5.43%);	LCV diesel N1-III Euro-3 (17.01%);
	LCV diesel N1-III Euro-4 (24.41%);		
M3	TT/AT >34-40 t diesel Euro-III (19.11%);	TT/AT >34-40 t diesel Euro-V EGR (5.42%);	TT/AT >34-40 t diesel Euro-V SCR (30.73%);

Designation of the type of fleet composition	Emission concept and its share in the fleet composition (notation consistent with HBEFA used in PTV VISUM)		
E1	PC BEV electric (100%);		
E2	LCV BEV M+N1-I electric (33.33%);	LCV BEV N1-II electric (33.33%);	LCV BEV N1-III electric (33.34%);
E3	TT/AT BEV electric (25.00%);	Rigid Truck BEV ≤7.5 t electric (25.00%);	Rigid Truck BEV >7.5-12 t electric (25.00%);
	Rigid Truck BEV >12 t electric (25.00%);		

Tab. 4

The fleet compositions in the transport model adopted for the reference scenario W0 and the scenarios W1 and W2

Type of Traffic	Scenario W0	Scenario W1	Scenario W2
Inbound traffic	U1, U2, U3	U1, U2, U3	E1, E2, E3
Outbound traffic (the city is the origin of the trip)	U1, U2, U3	U1, U2, U3	E1, E2, E3
Outbound traffic (the city is the destination of the trip)	A1, A2, A3	E1, E2, E3	E1, E2, E3
Through traffic	M1, M2, M3	M1, M2, M3	M1, M2, M3

From the designation of the type of fleet composition (urban, average, motorway, and electric), three types of vehicle groups were distinguished, that is, passenger car, light commercial vehicle, and mix (trucks, truck trailers, articulated trucks). For each type, the emission concept and its share in the fleet composition were presented. In the group of passenger cars, diesel vehicles that meet the EURO III emission standard are of the largest share. This does not apply to the vehicles in the electric fleet composition. In the group of light commercial vehicles, diesel N1-III vehicles with the EURO IV emission standard have the largest share. In turn, in the group of mixed cars, diesel (> 34-40 tonnes) that meets the Euro-V emission standard has the highest share.

4.3. Results of the analyses

The results of the scenario analysis of the reduction of exhaust emissions by introducing electric vehicles are presented in Table 5.

The degree of reduction in harmful substances in each of the scenarios of the development of the urban transport system about the reference scenario is presented in Figure 5. Considering the environmental criterion, the W2 scenario is much more favourable.

According to the information presented in Figure 5, there is a noticeable reduction in harmful substances for the development of the urban transport system between the two scenarios analysed. For each of the measures (total CO_2 reported [g], total CO [g], HC total [g], NOx total [g], and PM (10 µm) total [g]), the solutions used in the W2 scenario are more favourable. The highest emission reductions occurred for CO total [g] and HC total [g] (more than 80%).

Tab. 5

The values of the measures to assess the impact of the share of electric vehicles in traffic on the reduction of exhaust emissions for the reference scenario W0 and the scenarios W1 and W2

Measure of Assessment	Scenario W0	Scenario W1	Scenario W2
Group 1			
CO_2 reported total [g]	42,343,255.82	30,980,307.60	12,793,777.41
CO total [g]	184,107.10	157,676.72	28,837.32
HC total [g]	29,186.26	26,295.47	3,917.20
NOx total [g]	194,904.37	140,482.04	54,408.70
PM (10 μm) total [g]	7991.16	5968.66	2092.81
Group 2			
Fuel consumption diesel total [g]	9,504,016.51	6,868,988.59	2,628,879.40
Fuel consumption gasoline total [g]	5,076,530.12	3,798,898.96	1,782,903.60
Fuel consumption electric total [MJ]	21.96	51,183.13	128,239.83
Fuel consumption total [g]	14,580,702.09	10,668,006.20	4,411,871.06
Fuel consumption total [MJ]	616,895.76	502,408.14	314,809.19

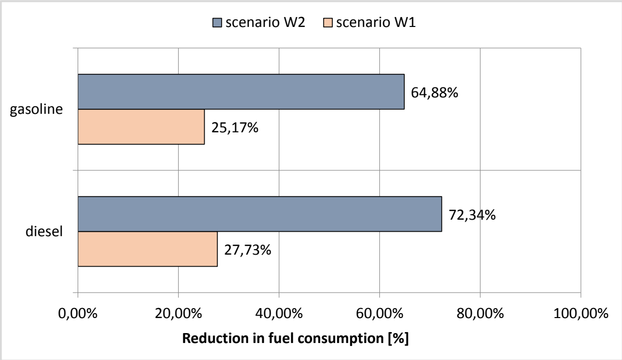
a) b)

Fig. 5. Reduction in harmful substances for the urban transport system development scenarios: a) for scenario W1, b) for scenario W2

The fuel consumption for the scenarios examined for the urban transport system regarding the reference scenario is shown in Figure 6. The results of the analysis confirm the positive impact of the changes introduced in traffic organization for the W2 scenario. Figure 6a shows that the reduction in fuel consumption for diesel and gasoline vehicles in scenario W2 exceeds 64%. On the other hand, Figure 6b shows that the solution presented for the W2 scenario will increase the consumption of electric fuel by more than 584,000%.

The analyses also include indicators of total fuel consumption, expressed in [g] and in [MJ], which also considers electricity consumption. Figure 7 shows the increase in total fuel consumption for the urban transport system development scenarios W1 and W2 and the reference scenario W0, expressed in [kg] and [MJ].

a) b)



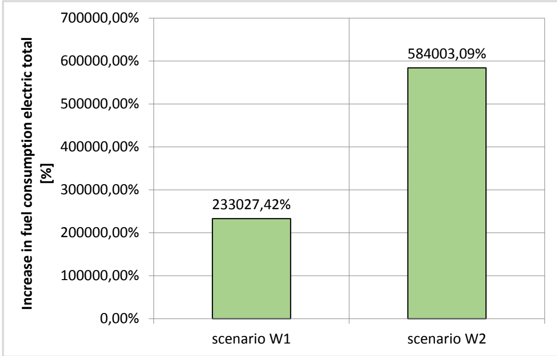


Fig. 6. Change in fuel consumption for the urban transport system development scenarios: a) reduction for diesel and gasoline, b) increase for electric total

The results presented in Figure 7 also confirm the positive environmental impact of both the solutions used in scenario W1 and scenario W2. Fuel consumption values expressed in [kg] apply only to vehicles with diesel and gasoline engines, while the values expressed in [MJ] include electricity used in vehicles. Both scenarios are favourable in economic and environmental terms. Fuel consumption values are more than 26% lower than the reference scenario for high-emission fuels and by more than 18% for all types of fuels. It is also worth noting that scenario W2 is more favourable (regarding scenario W0) than scenario W1 by more than 42% for vehicles powered by high-emission fuels and more than 30% for all vehicles. This is a reduction of all the characteristics examined (that is, total fuel consumption in [kg] and [MJ]) by more than 2.5 times for the W2 scenario compared to the W1 scenario.

5. DISCUSSION

Improving the quality of life in cities is one of the greatest challenges facing society today. An important aspect of this problem is the effort to minimize the environmental pollution resulting from the development of civilization that leads to increasing human interference in the ecosystem. Various studies have been conducted to identify sources of pollution, among which transport plays an important role. Scientific research conducted to find solutions aimed at reducing the negative impact of transport on the environment focuses on the development of electromobility.

This article presents the results of a research carried out using the example of a large city in Poland (Bielsko-Biała). The results are the values of the measures to assess the impact of changes in the accessibility of the area and the related traffic organization for users of electric cars and conventionally powered vehicles, presented in three groups. Analyses were performed for two scenarios that were compared with the scenario for the existing state. The research results indicate that, regardless of the scenario considered and the area for which the analyses were performed, the highest values of assessment measures of Group 1 were for CO_2 reported total [g], and the lowest for PM (10 μm) total [g] and HC total [g]. In turn, the measures of Group 2 were related to the generic structure of the traffic and should not be compared in this way.

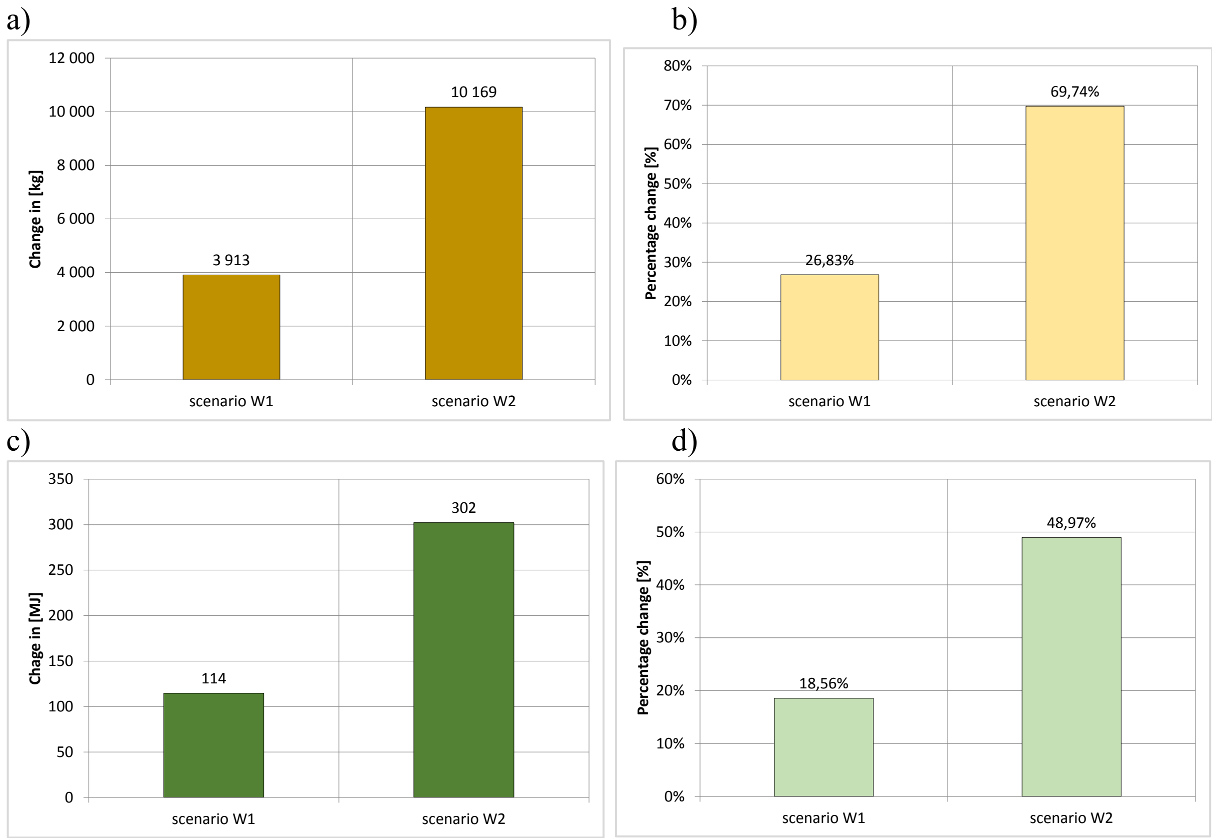


Fig. 7. Reduction in total fuel consumption for the urban transport system development scenarios: a) and b) expressed in [kg] and [%], c) and d) expressed in [MJ] and [%]

From the results obtained for the entire city, it should be noted that for each of the scenarios analysed, there was a decrease in the values of all evaluation metrics, except for total electrical fuel consumption [MJ]. This is particularly evident in Figure 5, which illustrates the reduction in pollutants for the scenarios studied relative to the reference scenario W0. The characteristic with the least reduction (positive impact) is HC total [g] for scenario W1. However, the highest profit was observed using the solution developed for the W2 scenario regarding HC [g] at the level of more than 86%. Similar conclusions can be drawn for fuel consumption. The reduction in fuel consumption expressed in [kg] and [%] for the W2 scenario is more than 69%, and for consumption expressed in [MJ], more than 48% given the existing state.

6. CONCLUSIONS

The introduction of electric vehicles in cities is one of the priorities of decision-makers. The method presented in this paper can be applied in cities and areas of different sizes to parameterize the composition of the desired municipal transport fleet and traffic organization.

The accessibility scenarios of the city of Bielsko-Biała for vehicles with different fleet compositions for inbound, outbound, and through traffic were analysed. The greatest reduction in pollutant emissions can be achieved by introducing restrictions for all users of individual transport in the city.

Two scenarios (W1, W2) were developed restricting entry into the city for high-emission vehicles. The results were compared with the reference scenario W0. It was observed that for both scenarios W1 and W2, the reduction of harmful substance emissions was obtained. However, the W2 scenario, in which all high-emission vehicles were prohibited from entering the city, is more advantageous regarding both emissions of harmful substances and fuel consumption.

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