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COMPLEX EVALUATION OF ELECTRIC RAIL TRANSPORT IMPLEMENTATION IN VILNIUS CITY

Summary. The article analyses the current problems of Vilnius city public transportation. The possible solutions (options) and the technical means to improve the attractiveness of public transportation and accessibility are considered. Two main alternatives of means of electric transport (underground and tram) have been singled out for Vilnius city. The suitability of these rail transport means have been substantiated. The nature and density of the work and residence places (areas) of Vilnius city residents have been analysed. The scheme of tram and underground lines projected in Vilnius city are evaluated, which have been composed according to the current and forecasted flows of passengers, the nature of their changes and critical points. The technical economic indicators of the tram routes and underground lines in Vilnius city are analysed: average driving speed, average distance between the stations, the duration of the trip, the capacity of a single means of transport, the costs of line support and the size of investment. The accident rate of urban rail transportation is estimated. Comparative criteria of tram and underground lines are selected. The effectiveness of both rail means of transport in Vilnius city are compared according to three multi-criteria evaluation methods: the sum of ratings, simple additive weighting and geometrical means. The final conclusions and recommendations are provided.

КОМПЛЕКСНАЯ ОЦЕНКА ВНЕДРЕНИЯ ЭЛЕКТРИЧЕСКОГО РЕЛЬСОВОГО ТРАНСПОРТА В ГОРОДЕ ВИЛЬНЮС

Аннотация. В статье анализируются актуальные проблемы общественного транспорта города Вильнюс. Рассматриваются возможные варианты их решения и технический потенциал повышения привлекательности и доступности общественного транспорта. Для Вильнюса выделены две основные альтернативы электрических транспортных средств (метро и трамвай) и обоснована пригодность этих рельсовых транспортных средств. Проанализирована локализация районов, плотность мест проживания и работы жителей города Вильнюса. Оценка схемы проектируемых в Вильнюсе трамвайных путей и линий метрополитена выполнена с учетом текущих и прогнозируемых потоков пассажиров, характера их изменений и критических точек. Анализируются технико-экономические показатели трамвайных маршрутов и линий метрополитена в городе Вильнюс: средняя скорость движения, среднее расстояние между станциями, продолжительность поездки, вместимость одного транспортного средства, расходы на содержание линий и величина инвестиций. Анализируется число инцидентов в городском рельсовом транспорте. Подбираются критерии для сравнения применяемости

трамвайного транспорта и метрополитена. Эффективность обоих средств рельсового транспорта в городе Вильнюс сравнивается тремя методами многокритериальной оценки: методом суммы рейтингов, методом простого аддитивного взвешивания и методом средних геометрических значений. Представлены окончательные выводы и предложения.

1. INTRODUCTION

In recent years Vilnius has been growing fast, and it is increasingly closer interrelated with most of the European Union regions. European Union countries increasingly more actualize our cultural and political heritage which helps to entrench the capital of Lithuania as a historical European city. It should be noted that the essential obstacle for unisonous and sustainable growth of Vilnius is the attractiveness of public transportation [10]. In recent decades the public transportation system in Vilnius city has been developed ineffectively [14]. The communication infrastructure (the street network) during the peak hours (on workday mornings and evenings) is unable to pass the car flows formed [6]. The following problems are attributed to the consequences of especially intensive traffic of urban transportation: air pollution, noise, accidents and car parking problems [11]. The buses and trolleybuses running in the city during the peak hours are overcrowded and very slow due to the transport jams [7]. On the other hand, the very trolleybuses significantly reduce the speed of the entire transport flow in narrow streets of the old town. Therefore, the citizens' trip to work and from it lasts for too long.

Due to insufficiently convenient and effective public transportation and improving economic conditions, part of the residents of Vilnius have started using their own cars to communicate thereby sharpening the difficult problem of traffic jams in the streets. Its importance and price have been presented to the Lithuanian society by the specialists of the Ministry of Transport and Communications of the Republic of Lithuania. According to the calculations of this institution, each year the citizens of Vilnius incur approximately EUR 0.46 bln. loss on the roads due to traffic jams, out of which EUR 0.18 bln. make car fuel consumption, and the remaining EUR 0.28 bln. the loss of time of residents [10].

Transport specialists suggest overcoming these transportation problems in the city by constructing the tracks of electric rail transport of much greater throughput (capacity): tram rails, underground lines [1, 3] or trains [8]. It is expected that due to smaller rolling resistance these means of transport would produce a great energy saving effect. And the construction of underground would significantly reduce the street flows and would reduce transportation jams during peak hours. Taking into consideration two rail transport systems of the urban as an alternative for the existing one in Vilnius city, the following principles were followed:

1. The new public transport should not increase the pollution of the city and should not produce noise.
2. The tracks of the new means of public transportation should not cross the existing public transportation tracks.
3. The new tracks of the means of transport should be constructed underground or on the trestle-work above the streets.
4. The new tracks of public transportation should not worsen the work of the existing transportation tracks neither during the construction period nor during exploitation.
5. The new tracks of public transportation should interconnect the main urban areas.
6. The new tracks of public transportation should run via the currently undeveloped areas.
7. The main network of the new public transportation tracks should be oriented towards the perspective of Vilnius city development.

The transportation running underground would help to liberate the city from traffic jams, would help to save the citizens' time, would leave more space for public areas, pedestrians and cyclists. An opportunity to dig underground would help to preserve the resources of cultural heritage: the old town, cultural places, buildings, the nature and the cultural layer. Certainly, it is expensive to dig underground, however, the resources of heritage and natural landscape are priceless, and the development should ensure creation rather than destruction.

2. THE STRUCTURE OF TRANSPORTATION OF THE VILNIUS CITY RESIDENTS

The communication is inconvenient due to a significant imbalance of the residential and working areas in the city: approximately 36% of the residents live in the blocks of flats in the western areas of the city. They commute to the central part of the city, where approximately 45% of the work places are concentrated.

Due to the present transportation, structure of the city the priority is given to private cars. The total number of private cars has increased 3.8 times in the period of 1980-2010 and the number of the city population travelling by public transport, walking or cycling is still decreasing (Fig. 2).

This tendency does not imply a well-balanced development of the communication system and has a negative impact on the environment because long distances cause problems for pedestrians and cyclists.
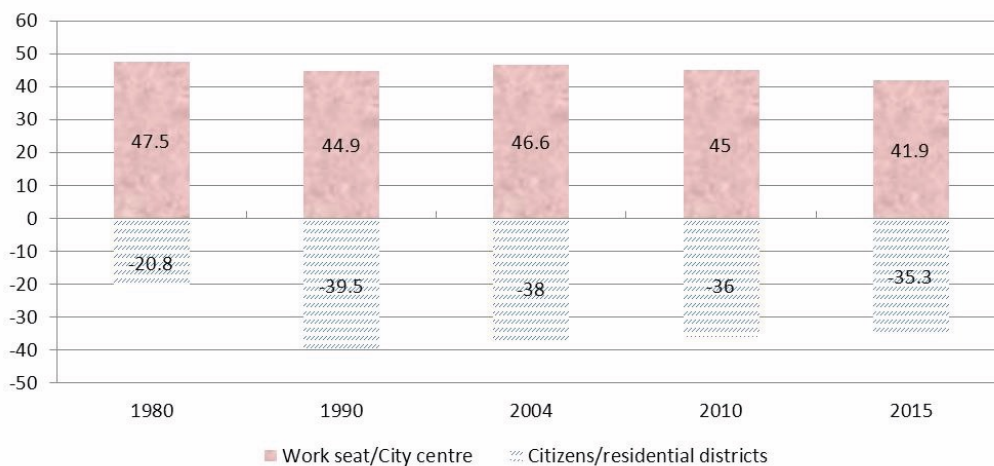

Fig. 1. Percentage of Vilnius population in the main residential and working areas [2]
Рис. 1. Процентное распределение мест проживания и работы жителей города Вильнюс [2]

3. ANALYSIS OF THE PROJECTED RAIL TRANSPORTATION LINES

The length of the tram track sections projected in Vilnius and the duration of their construction have been provided in Table 1.

As it can be seen from the data of Tab. 1, the construction of a single tram line in Vilnius city would last from 6 to 12 months.

3 underground lines have been projected for the initial stage in Vilnius city (see Fig. 3).
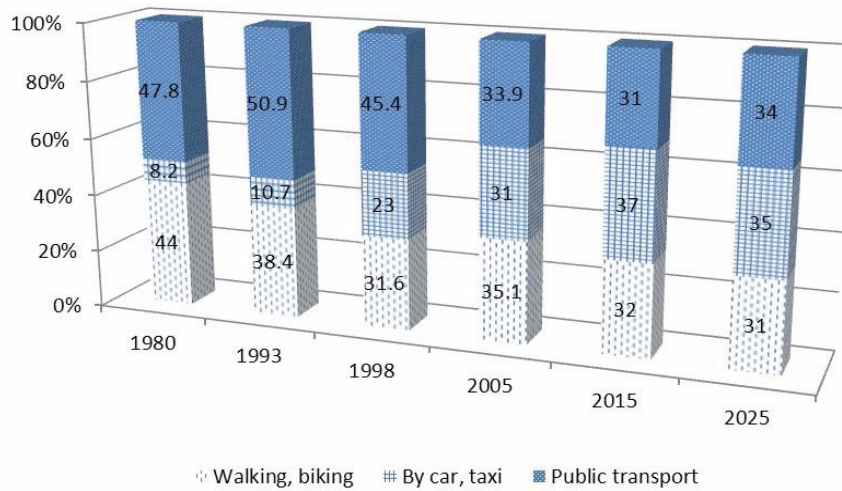
Fig. 2. Percentage of passengers' transportation within the city of Vilnius in 1980-2025 [2]
Рис. 2. Процентное распределение объёма перевозок пассажиров в Вильнюсе с 1980 по 2025 [2]

- **Line Nr. 1 "Viršuliškes - Katedros aikštė"**

The biggest passenger flows are concentrated in the intersection of Justiniškės and Laisvės streets. It is suggested to start the construction of Vilnius underground from this line, by installing and starting to exploit the track from Viršuliškės up to Mindaugas Bridge. The perspective development of this line is feasible both to the westward direction (to Pilaitė), and eastward (to the direction of Žirmūnai).

16,000 of passengers should be transported on the projected underground line No. 1 during the peak hours, i. e. between 7 and 9. Once a train is selected, the capacity of which is 600 passengers per trip, approximately 30 trips would be necessary for transportation of this number of passengers, therefore, four underground trains would run on this section every four minutes. Where the exploitation speed is approximately 42 km/h, it would take 7 minutes to overcome a 5 km section and the train would stop at the manoeuvre section for one minute, hence, in total it would take 8 minutes for it. Once the passenger flow is reduced to 3000-4000 per hour, the number of trains can be reduced to two, and the interval between the trips could be increased to 8 minutes.

Table 1

The length of the tram track sections and the indicative duration of their construction

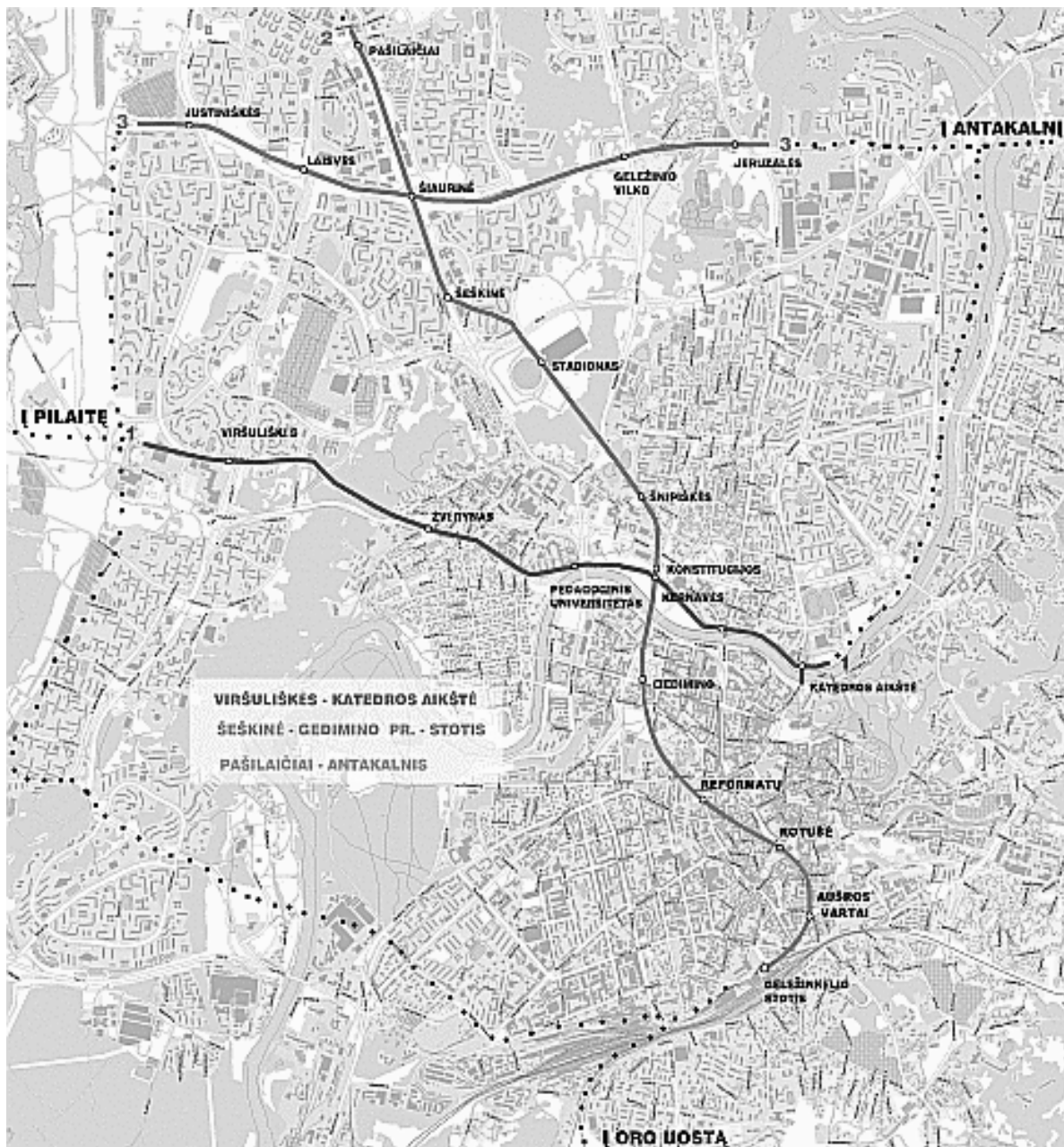| Section	Length of section	Average duration of construction
	km	days
Santariškės - Ateities St.	2.14	299.85
Ateities St. - Ozo St.	2.82	395.12
Ozo St. - Žalgirio St.	1.31	183.55
Žalgirio St. - Konstitucijos Ave.	1.07	149.92
Konstitucijos Ave. - Islandijos St.	1.23	172.34
Islandijos St. - Station	1.85	259.21
In total:	**10.42**	-

Fig. 3. Designed lines of Vilnius city underground
Рис. 3. Проектируемые линии метрополитена города Вильнюс

- **Line Nr. 2 "Šeškinė - Geležinkelio stotis"**

The first stage of construction of line No. 2 would be the construction of the section from the perspective intersection between Šiaurinės St. and Gediminas Ave. This line would intersect with line No. 3 and with line No. 1 at the Kernavė Bridge. As long as the archaeological research of the second stage of this line Gedimino Ave.-Railway Station section would last at the places of perspective underground stations and the construction site of the railway station transportation hub, the section Šeškinė-Gediminas Ave. of line 2 would be sufficiently loaded. Once this line is extended up to the railway station, it would become the main trunk-line of the underground system. The track of

this line will be extensively discussed, considered and talked about. In this regard, archaeologists and monument preservers should say a word.

- **Line Nr. 3 "Justiniškės - Antakalnis"**

This line No. 3 will run from the West to the East and will connect the perspective Western bypass with Saulėtekis complex (student campus) in Antakalnis. Once line No. 3 is constructed, there would be an opportunity for various ring options of the lines to be constructed. In addition to this, it would be possible to develop the transportation system of underground. One of them is to construct a line via Lazdynai, *Litexpo* complex, down the streets of Gerosios Vilties and Panerių up to the railway station, where it would be connected to line No. 2.

4. THE PRICE AND THE RENT OF THE LAND USED FOR THE CONSTRUCTION OF THE LINES

Comparing the underground and the tram systems, one of the selected criteria was the price of land. The argument for the inclusion of the price of land into the losses of society is that, by constructing an underground track instead of the tram, the residents will be able to further use the part of land on which the tram track is running.

The price of land was calculated according to the mass evaluation models of land parcels approved by the Republic of Lithuania in 2012. The value of land is calculated as follows:

$$Z_V = K_{land} \cdot p \cdot l \qquad (1)$$

where: Z_V – value of land, Eur/m^2; K_{land} – average price of land in the track planned, Eur/m^2; p – the width of the tram track, m; l the length of the tram line, m.

To calculate the rent of land R, the value of land and the average VILIBOR interest rate for one year is used by using mass evaluation, which is calculated according to the data of the Bank of Lithuania of 2007-2012. To calculate the rent the following formula was used:

$$R = \frac{Z_V \cdot A_{VILIBOR}}{100}; \qquad (2)$$

where: $A_{VILIBOR}$ – average VILIBOR interest rate of 2007 to 2012.

The losses of the society due to the use of land for the construction of the tramlines in Vilnius are presented in Table 2.

Table 2

The losses of the society due to the use of land for the construction of the tram line in Vilnius

Parameter	Indicator
The width of the tram track, m	6.9
The length of the tram track, m	10,420
Total area of territory, m^2	71,898
Average price of land, Eur/ m^2	230.56
Price of land, million Eur	**16.6**

As it can be seen from Table 2, for the construction of tramlines approximately 72,000 m^2 of city land would be needed that would cost approximately EUR 16.6 million. The losses of the land rent due to the tram construction in Vilnius would account for EUR 260.1 thousand per year, where the interest rate is 1.57%.

5. THE COSTS OF THE CONSTRUCTION OF URBAN RAIL TRANSPORTATION LINES

To construct tram and underground lines huge investments are needed so that cities, before deciding which means of transport to choose, would have to carry out detailed calculations of the

necessary capital investments [4, 9, 12, 13]. The total price of the investment into Vilnius tram network is evaluated by analogue, i. e. according to the data of the tram project of the city of Orleans. The total price of one kilometer accounted for EUR 16.8 mln. By evaluating the conditions of Lithuania, the average price per kilometre may be smaller by 20%.

Taking into consideration the data of construction companies, the installation of underground lines in Vilnius city would cost 30% more than the installation of the planned tram lines. In this case, the average price per kilometer for the underground track would cost EUR 19.6 mln. Therefore, the presumption may be that to construct the underground of Vilnius it may cost not less than EUR 35 mln./km or 2.3 times more than the construction of the tram track kilometer.

Table 3

The possible price for the construction of 10.4 km rail transport line in Vilnius

Price	Tram	Underground
Total price of investment, million Eur	157.0	364.0
Average 1 km price, million Eur/km	15.1	35.0

As it can be seen from Tab. 3, the installation of underground lines is twice more expensive than the installation of the tramlines.

6. ECONOMIC EXPRESSION OF THE SPEED DIFFERENCES OF THE URBAN RAIL TRANSPORTATION

Having analysed the data of the distance between the tram stations and the average speed by using statistic methods (Fig. 2 and Fig. 3), it turned out that there is a direct correlation between the analysed variables. The average speed of a tram is approximately 18 km/h, where the distance between the stations is 400-500 m, and this speed will reach 30 km/h, where the distance between the stations is 700-900 m. The distance between the tram stations is much smaller than that between underground stations, therefore, the average speed of trams is smaller.

For calculation, the average length of the residents' trip in kilometers was taken into consideration. An economic expression of the speed differences of the tram and underground was produced, which has to be added to the price of the tram as annual loss. To evaluate the economic expression of the tram and underground speed difference, the following formula was used:

$$E_{speed} = (P \cdot L_{trip} \cdot (V_{underground} - V_{tram}) \cdot DU_{average} \cdot 365)/(V_{underground} \cdot V_{tram}); \qquad (3)$$

where: P – potential demand; L_{trip} – average length of the trip; $V_{underground}$, V_{tram} – average speed of underground or tram; $DU_{aver.}$ – average hourly salary.

It was calculated that due to the difference in speed when exploiting the underground in Vilnius EUR 5.9 mln. would be saved per year.

The data of the public transportation of 24 European cities was processed when calculating the average speed of trams and underground transportation. The dependence of average speed of underground on average distance between the stations has been provided in Fig. 4, and that of tram in Fig. 5.

Having processed the statistical data presented in Fig. 4 and 5, it was calculated that average statistical communication speed in the city when travelling on underground train is 36.2 km/h, and on tram – only 22.4 km/h. Therefore, the duration of the tram trip would be longer by approximately 40%.
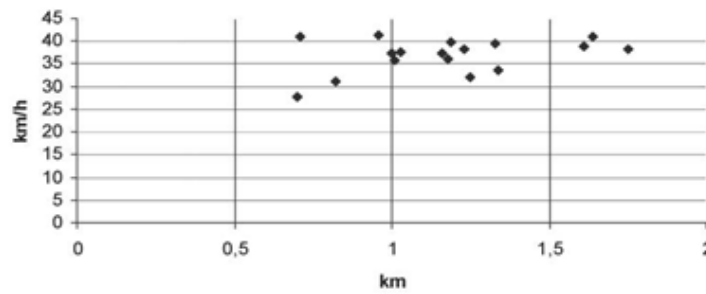
Fig. 4. The dependence of average speed of underground trains on average distance between the stations
Рис. 4. Зависимость средней скорости движения поездов метрополитена от среднего расстояния между
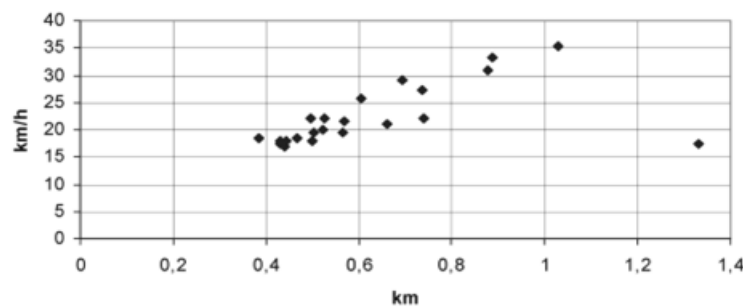   станциями

Fig. 5. The dependence of average speed of trams on the average distance between the stops
Рис. 5. Зависимость средней скорости движения трамваев от среднего расстояния между остановками

7. THE EXPLOITATION AND DEPRECIATION COSTS OF TRANSPORT LINES

The exploitation costs show how much of funds are needed to ensure the functioning of the transportation system. The exploitation costs are made of the price of labour force (wages of employees, the size of which is determined by qualification, responsibility, the complexity of work, etc., training of employees, treatment, turnover of employees, etc.), training, costs of resources (need for electric power, etc.), depreciation and other costs related to the exploitation of the system. Depreciation is attributed to the exploitation costs. Depreciation is calculated according to the direct principle from the start of using the equipment or the buildings.

Average exploitation costs of underground systems (with depreciation) are approximately less than half for the exploitation costs of the tram systems (with depreciation). The evaluation of the underground and tram system exploitation costs used in the US is submitted in Table 4.

Table 4

The evaluation of underground and tram systems exploitation costs

System	Exploitation price (EUR/pass. km)
12 light tram systems in the US	0.21
22 automatic underground systems in the US	0.12
The relation of exploitation costs	1.75

As it can be seen from Tab. 4, the relation between the underground and tram exploitation costs is 1:1.75.

7.1. Accident rate of the rail transport in the city

Ensuring complete safety is one of the priorities of public transportation. High level of accident rate is a city problem producing moral, financial and other losses. Accidents cause halt of public and other means of transport, traffic congestion is produced, moral and financial losses are incurred, trust in public transportation is reduced.

According to the data of other countries, trips on the so called heavy rail are safer than those on light rail [5]. The data of the deaths on heavy and light rail of the US Bureau of Transportation Statistics have been provided in Table 5.

Table 5

Comparison of death rate on light (tram) and heavy (underground) railway systems in 1995-2012

Means of transport Type of transport	Death/100 mln. pass. Km			
	1995-2000	2001-2006	2007-2012	Average
Light rail	32.68	21.82	25.32	26.61
Heavy rail	8.44	5.14	3.46	5,68
Relation	3.87	4.2	7.3	4.7

Data of Tab. 5 suggest that the level of death rate on light railway (tram) systems is more than 4 times bigger than that on the heavy railway system. The number of injuries in 1995-2012 per hundred million of passenger kilometers is submitted in Tab. 6.

Table 6

The differences in number of injuries on light (tram) and heavy (underground) railway system

Means of transport	Injury/100 mln. pass. Km			
	1995-2000	2001-2006	2007-2012	Average
Light rail	1521.6	1057.2	471.8	1016.9
Heavy rail	59.4	60	48.6	56
Relation (times)	25.6	17.6	9.7	18.2

From the data submitted in Tab. 8 one can see that the number of injuries in the tram system during the reference period was 18 times bigger than the number of injuries in the underground system.

8. THE COMPARATIVE EVALUATION OF THE INSTALLATION OF THE UNDERGROUND AND TRAM SYSTEMS IN VILNIUS CITY

8.1. Multi-criteria evaluation methods

With most of the methods, a different normalization or data transformation of the initial data (indicator values) are used. The basis of the quantitative methods are made of the matrix of the indicators characterizing the compared objects, statistical data or expert evaluation (R = [$i;j$], i=1,..., m and j=1,..., n; here: m – number of indicators, n – number of compared objects (alternatives). Each method has its own advantages and specificity.

Three multi-criteria evaluation methods are applied in this analysis:
1) the sum of ratings method;
2) the simple additive weighting method;
3) the geometrical means method.

8.1.1. The sum of ratings of all the indicators

The sum of ratings of all the indicators V_j for each j-th object, which is determined according to the following formula:

$$V_j = \sum_{i=1}^{m} m_{ij};$$

(4)

where: $m_{ij} - i$-th place of indicator j-th object. A prerequisite for the application of the method is prior indication of the character of the maximizing and minimizing indicators.

On the other hand, for instance, to reconstruct the minimizing indicators into maximizing ones according to this formula:

$$r_{ij} = \frac{\min r_{ij}}{r_{ij}}$$

(5)

where: $r_{ij} - i^{th}$ indicator value for j^{th} object, where the smallest indicator value will obtain the greatest value equal to one.

The calculations show that this method is the simplest one and it is expedient to apply it only for initial approximate evaluation.

8.1.2. Additive weighting method

The sum of all the normalized values of the additive weighting (SAW) is calculated S_j for each jth object. It is calculated according to the equation:

$$S_j = \sum_{i=1}^{m} \omega_i r_{ij};$$

(6)

where: $\omega_i - i$-th indicator importance coefficient; $r_{ij} - i^{th}$ indicator normalized value for j^{th} object.

The normalization of the initial data in this case is completed according to the following equation:

$$r_{ij} = \frac{r_{ij}'}{\sum_{i=1}^{n} r_{ij}};$$

(7)

where: $r_{ij}' - i^{th}$ indicator value for j^{th} object.

The greatest value of S_j is when it is the biggest.

8.1.3. The method of geometrical means

The geometrical means Π_j (method GM) of all the normalized values of the indicators is indicated according to this equation:

$$\Pi_j = \sqrt[m]{\prod_{i=1}^{m} \omega_i r_{ij}'}.$$

(8)

The sequence of object priorities indicated according to the formula (8) does not depend on the weighting of the indicators ω_i, therefore, this size may be not included into the formula.

8.2. Calculation of the effectiveness criteria of the use of urban rail transport

For initial evaluation of urban rail transport the following evaluation criteria are used:
(1) the price of constructing urban rail transport lines, in EUR;

(2) average speed of urban rail transport, km/h;
(3) deaths caused by urban rail transport accident rate, 100 mln. pass. km;
(4) injuries caused by urban rail transport accident rate, 100 mln. pass. km;
(5) exploitation costs of urban rail transport, EUR/pass. km.

Parameter importance coefficients r_y accepted are the following:
(1) the price of construction of urban rail transport lines – 0.5;
(2) average speed of urban rail transport – 0.2;
(3) deaths caused by urban rail transport accident rate – 0.1;
(4) injuries caused by urban rail transport accident rate – 0.1;
(5) exploitation costs of urban rail transport – 0.1.

The types of urban rail transport are marked with the following alternatives: tram – T; underground – M.

Urban rail transport evaluation criteria are marked with the following indicators R_j: the price of line construction – R_1; average speed – R_2; accident rate (deaths) – R_3; accident rate (injuries) – R_4; exploitation costs – R_5. The best (achievable) urban rail transport indicators are $R_j=1.0$.

The values of underground and tram evaluation criteria and importance coefficient values are provided in Tab. 7.

Table 7

The values of urban rail transport criteria and importance coefficients

Parameter	Alternative		Importance coefficient r_y
	T	M	
R_1	1.0	0.43	0.50
`R_2	0.62	1.0	0.20
R_3	0.21	1.0	0.10
R_4	0.06	1.0	0.10
R_5	0.57	1.0	0.10

Having completed calculations with the existing data, the results received are summarized in Tab. 8.

Table 8

By using various methods, consolidated evaluation results of urban rail transport were produced

Alternatives	Name of evaluation method						Seat average	Seat
	SV		GM		SAW			
	Seat	Value	Seat	Value	Seat	Value		
M	1	6	1	0.13	1	0.51	1	**1**
T	2	9	2	0.05	2	0.48	2	**2**

As it can be seen from the data of Tab. 8, underground has all the best ratings when taking into consideration all three multi-criteria evaluation methods.

9. CONCLUSIONS

1. The research has established that currently the average communication speed in Vilnius city during peak hours is only 15 km/h.
2. Having completed a statistical analysis of the data of 24 European cities, it has been established that average speed of underground is 36.2 km/h, and that of trams is 22.4 km/h. Hence, average speed of communication by tram is smaller by approximately 40% than by underground. By exploiting underground in Vilnius one could save EUR 5.9 mln. per year due to the speed difference.

3. The investments for the construction of underground line in Vilnius city would be 2.3 times bigger than those for the construction of an analogue tramline. On the other hand, investments for underground system, having evaluated underground and tram construction social losses, are only by 28% bigger than the costs of installation of analogue tram line.

4. From global practice, one can see that the accident rate of heavy rail systems (underground) is 18 times smaller than that of light rail systems (trams).

5. Having completed a complex evaluation of the urban rail transport by applying three evaluation methods (according to 5 criteria), it was unambiguously established that the installation of the underground system in Vilnius city would be more advantageous.

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