Aplinkos tyrimai, inžinerija ir vadyba, 2010. Nr. 3(53), P. 36-42 *ISSN 1392-1649*
Environmental Research, Engineering and Management, 2010. No.3(53), P. 36-42

Improvement Possibilities of City Transportation System by Using PINAVIA Interchange

Aušrius Juozapavičius[1], Stanislovas Buteliauskas[1] and Rimvydas Krasauskas[2]
[1]*Department of Engineering Management, The General Jonas Žemaitis Military Academy of Lithuania*
[2]*Department of Mathematics and Informatics, Vilnius University, Lithuania*

(received in August, 2010, accepted in September, 2010)

The article analyzes transportation system problems of a common city by taking an example of Vilnius city and reveals drawbacks of street infrastructure and traffic organization which are responsible for traffic congestion and its consequences in many cities including Vilnius. A new high capacity Pinavia road interchange is presented. Mathematical model of the new interchange is described enabling transport specialists to optimize and adapt it to a given location. Unique features of the new Pinavia interchange are used to develop an improvement strategy of a city transportation system.

Keywords: *transport congestion, road interchange, Pinavia, clothoid, congestion minimization strategy.*

1. Introduction

According to the data of the Statistical Office of the European Commission, traffic congestion in many cities costs the European economy around 100 billion euros each year, or 1% of EUs GDP (Green Paper 2007). Similar problem persists in major cities of Lithuania – Kaunas, Klaipėda, Šiauliai, and especially Vilnius, where similar calculations estimate the losses of traffic participants due to traffic congestion and accidents to be more than a third of a billion euros each year.

Known solutions to these problems require large financial resources of the government or municipality, and most of them give no direct financial return, therefore the implementation of the solutions if usually slow and/or partial. A strategy for the reconstruction of a city infrastructure is presented in this article, where unique features of a new road interchange make it possible without any changes to the road infrastructure in the center part of the city to solve the traffic congestion problems by attracting investors from the private sector.

2. Analysis of Vilnius city situation

2.1. Principles of formation of residential areas

These are the main features of the Vilnius city structure: centermost part with narrow streets surrounding blocks of residential and administrative buildings of architectural significance; middle part of the city with broader streets and larger blocks of industrial and administrative purpose buildings; and surrounding asymmetrically formed residential and industrial micro-districts.

Fig. 1 depicts the asymmetric distribution of the residents with respect to the work places in Vilnius. Concentration of work places in the centermost part of the city forms pulsating passenger flows: in the morning they move towards the center (and transit to the other side), and the reverse in the evening. Access between the micro-districts is complicated due to a lack of main roads with intersections of sufficient capacity.

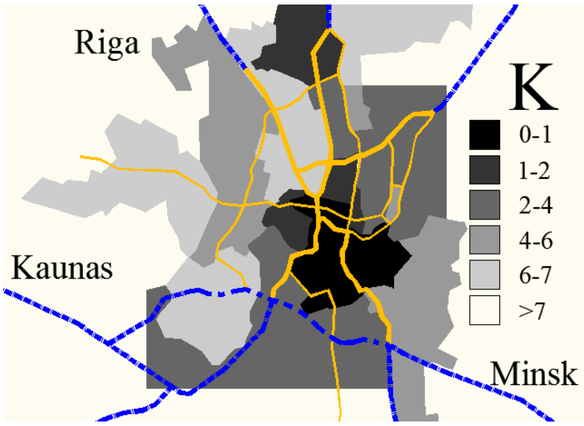

Fig. 1. *Distribution of ratio K of the number of residents to the number of work places in Vilnius micro-districts (Based on census data of Vilnius municipality, Department of Statistics of Lithuania 2001)*

2.2. Dynamics of the traffic intensity in Vilnius city

During the six years of 2003 to 2008 the number of passenger cars registered in Vilnius has increased by 40%, whereas the number of buses used for public transport fell by 6% (Department of Statistics of Lithuania 2009). Moreover, data on traffic intensity growth indicate a faster increase in the traffic intensity (56% rise from year 2003 to 2008) compared to the rise of the car numbers (Transport and Road Research Institute 2008). One of the causes was a rapid expansion of private house districts in outer Vilnius.

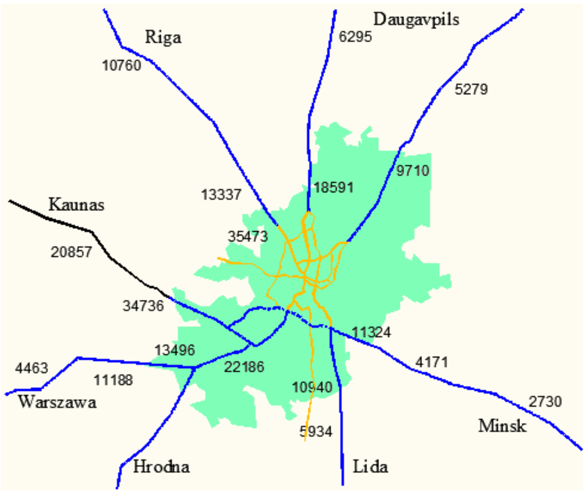

Fig. 2. *Traffic intensity (the number of vehicles per 24 hours) on main Vilnius roads (Transport and Road Research Institute 2008)*

All major intercity roads go through the center of Vilnius, where they are marginally broader and mostly intersect each other at the same level. Therefore, flows of transit traffic join the inner traffic of the city and significantly increase the overall intensity (Fig.2) leading to congestion. The effectiveness of the public transport is affected directly, because the routes of the public transport use the same streets and have no dedicated lanes in the center part of the city.

Traffic intensity distribution during the day indicates the morning and evening peaks when the congestion becomes a problem (Fig.3). A mere 15% increase in the overall traffic intensity could lead to a day-long congestion, and considering the growth rate of the number of cars (8% a year), one could predict this critical situation to come in a year or two (however, the consequences of the economic crisis should also be taken into account).

2.3. Transport traffic structure

Vehicles were counted during the morning peak hour in several main streets of Vilnius center. The largest part – 70% of the traffic is constituted by passenger cars, which carry only 12% of all passengers. Buses and trolley-buses constitute only 13% of the traffic and carry 75% of passengers. The remaining 17% is micro-buses carrying 13% of passengers. On the average, there are 1.5 passengers in a passenger car, 7 passengers in a micro-bus and around 50 passengers in a bus. Fast buses, quite popular 20 years ago, are no longer present due to traffic congestion.

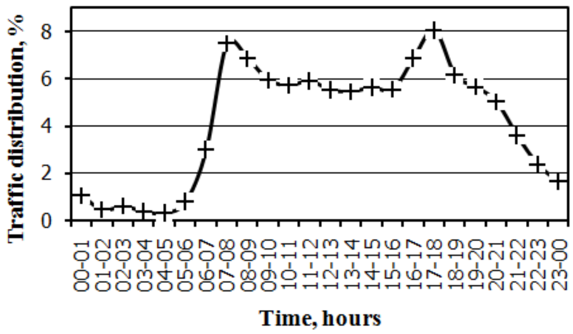

Fig. 3. *Distribution of traffic intensity in the western part of Vilnius during the day (Vilniaus Planas GOC 2004)*

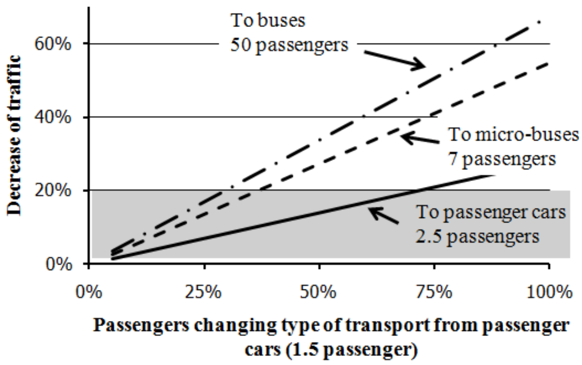

Fig. 4. *Traffic intensity dependence on traffic structure*

The traffic congestion is caused mostly by passenger cars. As shown in Fig.4, one needs 75% of all passenger cars to carry 2.5 passengers on the average instead of the current 1.5 in order to decrease the overall traffic intensity by 20%. However, the same effect can be achieved by making passengers of 35% of passenger cars to switch to micro-buses, or only 30% of passenger cars to switch to buses. According to Fig.3, this change of traffic structure would be sufficient to eliminate current congestion in Vilnius city.

2.4. Vilnius street infrastructure and traffic organization

All major Vilnius streets do not meet the requirements of their category – they all have single-level regulated intersections and pedestrian crossings.

Theoretical capacity of symmetrically regulated one level intersection is twice smaller compared to the intersecting roads. Such intersections form pulsating traffic – the road after the intersection is not fully used, while the road before the intersection is congested. The pulsating traffic prevents the possibility of decreasing the number of lanes after the intersection. Despite the essential drawbacks of single-level regulated intersections, one of these is planned in the western Vilnius bypass.

Most of the public transport routes cross the river dividing Vilnius into two (Susisiekimo Paslaugos 2010). However, all bridges have larger capacity compared to the road intersections beside them.

A part of Vilnius streets have dedicated lanes for public transport. However, there are no such lanes in the zone of the largest traffic congestion.

Vilnius has a newly developed coordinated traffic control system. Such systems work effectively only when the capacity of regulated intersections is larger than traffic intensity. They do not work during the peak hours, and they are best suited for one-directional traffic control.

3. Main causes of traffic congestion

These are the main causes of Vilnius traffic congestion:

Transit traffic crosses the center part of Vilnius: the city needs bypass roads, because all major intercity roads currently go through the city.

The ratio of the number of passenger cars to the number of public transport vehicles is too large: the public transportation system is not attractive enough – the public transport is too slow, there are no parking lots at the end points of public transport routes, no access limitations for private transport in the center part of the city.

Concentration of working places in the city center is too large.

Main roads leading to the city center have the same capacity throughout all their length.

Capacity of intersections of main city roads and major intercity roads do not correspond to the category of these roads.

Two-way traffic in the city center, where the street density is high: the coordinated traffic control system is not fully utilized.

Most of these causes are common in many European cities due to their similar historical growth patterns.

4. Possible means for decreasing traffic congestion

One of the best known means for decreasing traffic congestion is building city bypass roads. They are fully functional only when they completely surround the city, and when they have no single-level intersections. A major drawback of this solution is the need of large investments. For this reason, only half of the bypass is being currently planned in Vilnius (Master plan of Vilnius development 2007).

Another effective solution is to increase the role of public transport by imposing limitations for passenger cars entering the city center. However, this solution should be applied in parallel with an increase in public transport quality and building of parking lots at the terminal points of the public transport routes.

A third effective solution – implementation of alternative transportation spaces (such as subway), however it also needs large concentration of passengers, preferably at the end points of the routes, not mentioning the implementation costs.

The most effective solution – renovation of single-level intersections to multi-level junctions is often limited by a lack of finances and insufficiently large areas of land.

Organization of one-way traffic in the center part of Vilnius is complicated due to a highly irregular distribution of streets.

Every single one of these means does not give the final solution to the traffic congestion problem, and their integrated implementation requires large resources.

5. Strategy for the improvement of a city transportation system

In order to essentially refine the transportation system and eliminate transport congestion in a given city a new strategy for the improvement of the transportation system is presented, where the key element is a new type of road junction – Pinavia. The strategy is based upon the improvement of major roads around the city, decentralization of working places, and creates conditions for utilization of new effective transportation spaces.

5.1. New type road interchange - Pinavia

Pinavia interchange of four roads (Fig.5) is a two-level intersection with high capacity and no intersecting traffic flows. Due to a unique placement (braiding) of roadways the traffic flows pass each other via four small overpasses (or tunnels) (Buteliauskas 2008). Traffic goes in a circular motion, and no lanes need to be changed while passing the junction. Radii of all curves in the junction can be set equal or larger than the smallest radius of the curves of the intersecting roads, thus the driving speed in the junction can be equal to the speed on the intersecting roads. A large (several hectares) continuous plot of land in the center of the junction is easily accessible without crossing other traffic flows (Fig.6).

Fig. 5. Two-level Pinavia interchange of four roads

Due to an easy access and good strategic position of the territory in the center of the junction it is possible to use it as a large attraction point for passengers by building hotels, sales outlets, centers of logistics, etc.

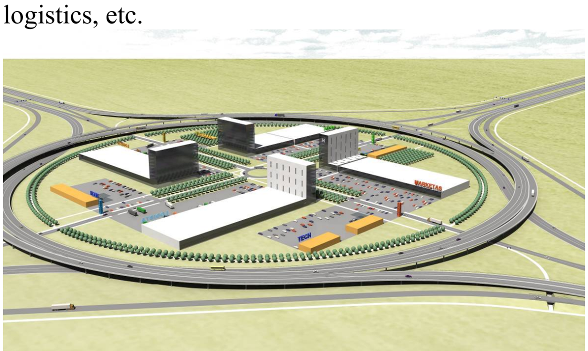

Fig. 6. Pinavia interchange (urbanization)

5.2. The strategy of a new transportation system

A scheme of the new Vilnius city transportation system strategy (suitable for many cities) is presented in Fig. 7. Necessary elements of the system are the circular city bypass and Pinavia interchanges at its crossing points with the major intercity roads. The category of the previously major roads is diminished in the inner part of this circle. Also, some traffic limitations (such as ecological fees) may be imposed for driving towards the city center. Apart from the aforementioned urbanization, parking lots for passenger cars and terminal points of intercity bus routes are established in the center part of Pinavia interchanges. Due to a large concentration of passengers it also becomes purposeful to organize terminals of city micro-bus, bus and even subway routes inside the Pinavia interchange.

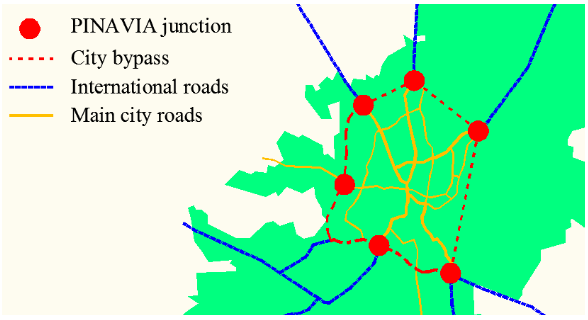

Fig. 7. Strategy of Vilnius city transportation system

The strategy complies with all requirements for decreasing the traffic congestion:

Transit flows are directed around the city.

Passengers obtain favorable conditions for changing means of transportation from a passenger car to a public transport.

Traffic limitations give priorities to the public transport and thus its speed and consequently – appeal are increased.

Possibilities for establishing a large number of easily accessible work places in the periphery of the city are created.

Preconditions for alternative transport types (such as subway) are met due to the created points of large passenger concentration.

And finally, one of the most important features of the solution is the possibility to attract private sector finances for its implementation. Ordinary two or more level road junctions used nowadays in city bypasses give no extra value from the large territory they occupy. Meanwhile a large part of Pinavia-occupied land is fully utilizable for urbanization and has a significant commercial value due to its easy access and strategic location. Therefore, sales revenues of this land after the Pinavia construction may be many times larger than the investment.

5.3. Economical evaluation

Pinavia junction has a very high capacity (limited only by the number of lanes), high safety (no lanes intersect), it is ecological (no acceleration / deceleration) and economically efficient. By functional parameters it corresponds to a 4-level interchange, although Pinavia needs only 2 levels instead. According to the technical specification of Pinavia for projected speeds of 50 km/h (Viaprojektas Ltd. 2009), the estimated construction cost is 57.5 mil. LTL (16 mil. EUR). This junction could be compared to the Jakų junction currently being reconstructed close to Klaipėda city, where the first stage of its 3-stage reconstruction already required 101 mil.LTL (28 mil. EUR) (Vakarų Ekspresas 2010). Moreover, the Jakų junction is going to have 3 levels, the whole plot of land will be occupied and still there will be some conflict points left. In contrast, Pinavia has no conflict points on any of the roads, and the free land inside the junction can be commercialized and further reduce the investments for its construction.

The main drawback of the Pinavia junction – requirement for a sufficiently large territory – can be neutralized due to the possibility to enter and utilize its center area. This way it is possible to build Pinavia-like structures around already existing districts of any city by using existing streets on the sides of the district (limiting them to one-way traffic only) and building four small overpasses to eliminate transport flow intersections. It would be possible then to quickly pass by the district, and also – to enter it, all without any conflict points, without intersections, and with minimal construction costs.

Pinavia is most suited for intersections of circular city streets with main intercity roads, because these are the areas of the highest traffic flow, especially the left-turning traffic, when the usual clover-leaf type interchanges have problems.

5.4. Modeling the Pinavia interchange

When new interchanges are designed it is imperative to optimize their parameters in order to decrease building costs and the area of occupied land. The procedure is quite straightforward in the case of the usual interchanges, because the parameters of one road do not strongly affect the parameters of another.

The Pinavia interchange is quite simple from the first look; however, serious complications arise when designing it. Braiding of roadways creates strong dependencies between them and there are several junction variables making essential and non-trivial influence on its final construction parameters (such as its size, length or width of overpasses, size of the land suitable for urbanization, etc). In order to use computer optimization, a mathematical model of the interchange is needed.

Usually straight lines and circular arcs are used to model the geometry of roads. A spiral arc is used to smooth the change in centripetal acceleration experienced by a vehicle approaching a circular curve. On railroads during the 19th century, as speeds increased, the need for a track curve with gradually increasing curvature became apparent. Then equations of the so-called clothoid curve, where the curvature is exactly linear in arc-length, were derived by several civil engineers independently. The clothoid curve is also known under different names as Euler or Cornu spiral, and most likely it was introduced by Leonard Euler in 1744. Clothoid curve ($x(t)$, $y(t)$) can be parametrized using Fresnel integrals

$$x(t) = \frac{A}{\sqrt{\pi}} \int_0^t \cos\frac{\pi u^2}{2} du,$$

$$y(t) = \frac{A}{\sqrt{\pi}} \int_0^t \sin\frac{\pi u^2}{2} du ,$$

where A is called a clothoid parameter. Length L of this curve is

$$L = \int_0^t \sqrt{\dot{x}^2(u) + \dot{y}^2(u)}\, du = A\sqrt{\pi}t.$$

Curvature $k(t)$ of the clothoid can be computed as a derivative of the angle of rotation $\theta(t) = \pi t^2 / 2$ by length parameter L:

$$k(t) = \frac{d\theta}{dL} = \frac{d\theta}{dt}\frac{dt}{dL} = \frac{\sqrt{\pi}\, t}{A}.$$

Since a curvature radius is $R = 1/k$, we get formula

$$A = \sqrt{RL} .$$

The clothoid arc defined on the interval [0, t] blends a horizontal line (x-axis) with an osculating circle at point ($x(t)$, $y(t)$), see Fig. 8. Here angle θ, width w and height h of the dashed rectangle can be directly calculated:

$$\theta = \pi t^2 / 2 ,$$

$$w = x(t) - R\sin\theta ,$$

$$h = y(t) + R(\cos\theta - 1) ,$$

$t = \sqrt{L / R\pi}$ is easily found for any given R and L.

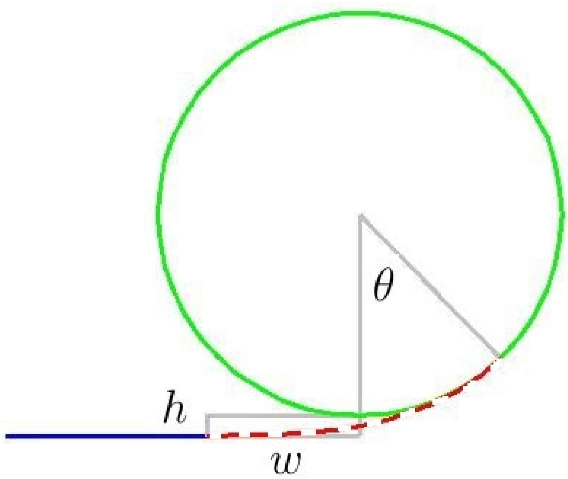

Fig. 8. Clothoid curve

We can apply rotation and/or reflection in order to create a transition curve between a line and a circle in an arbitrary position. This construction can be used twice in a case when two consequent turns are to be performed (see Fig. 9).

To model the driving through the Pinavia interchange it is necessary to make a sequence of several maneuvers: e.g. turn right, then left and finally once more right to drive straight (cf. Fig. 5). Any of these paths depend only on the center position and the radius of the big circular arc. Given the radius (it corresponds to the designed driving speed) and considering a symmetric case where all other directions are obtained by 90 degree rotations, this becomes a two parameter optimization problem. In practice, minimization of a cost function (a sum of land, road and overpass prices) is performed. The area of land is estimated by a ring bounded by the minimal and the maximal circles; the road price is calculated using the total length of roads, and the overpass prices are derived from their approximated area. Also, several other constraints should be applied: roads may not collide on the same level, and sufficient distance between the overpasses should be maintained (depending on the allowed slope of roads).

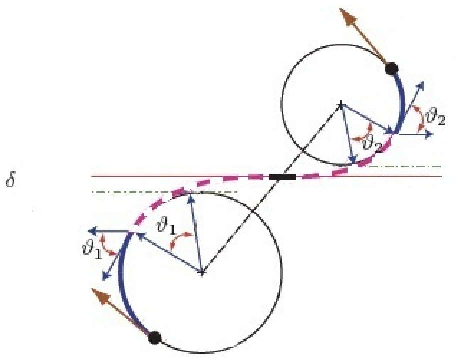

Fig. 9. Clothoids of two consequent turns

6. Conclusions

The main cause of Vilnius city transport congestion is the constantly growing flows of transport through the center part of the city arising due to the lack of bypass roads, asymmetric distribution of residential and work areas, and decreasing popularity of public transportation.

Application of any single one of the known solutions to the problem does not give the needed effect while application of several integrated solutions requires large resources and so it is slow and problematic.

The presented strategy for a city transportation system improvement suggests to surround the city by a full circle of bypass roads, and to construct new type Pinavia junctions at the points of the bypass intersections with major intercity roads, at the same time applying traffic limitations to the center part of the city. No changes in the inner city street infrastructure are needed. Due to unique features of the Pinavia junction (the possibility to urbanize the territory in its center: to create passenger attraction points, parking lots, and terminal points of public transport routes) it is possible to attract private capital for the implementation of the strategy, and also to perform a series of measures enabling high quality passenger transport and a decrease in traffic congestion.

References

BUTELIAUSKAS S. 2008. Patent No. US-2,941,454.

DEPARTMENT OF STATISTICS OF LITHUANIA. 2009. Number of registered passenger cars. [interactive]. Retrieved 29 Jan 2010: http://db1.stat.gov.lt/statbank/SelectVarVal/Define.asp?Maintable=M7030307.

DEPARTMENT OF STATISTICS OF LITHUANIA, 2001. Vilnius census data. Retrieved 8 Feb 2010: http://vilniustsv.stat.gov.lt/lt/pages/view/?id=1864.

GREEN PAPER: Towards a new culture for urban mobility. 2007. European Commision. COM(2007) 551 final, Brussels.

MASTER PLAN OF VILNIUS DEVELOPMENT. 2007. Vilnius municipality. ISBN 9986-508-97-5.

PLAVIČIŪTĖ A. 2010. Vakarų Ekspresas, No. 213 (5575) 2010-09-18.

SUSISIEKIMO PASLAUGOS, Municipality Owned Company. 2010. Vilnius public transportation scheme. Retrieved 8 Feb 2010: http://www.vilniustransport.lt/images/mrweb_1.gif.

TRANSPORT AND ROAD RESEARCH INSTITUTE, LITHUANIA. 2008. Annual Report.

VIAPROJEKTAS LTD. 2009. Final report V1.1. Four-road city-type Pinavia junction for projected speed of 50 km/h. Vilnius, 2009.

VILNIAUS PLANAS GOC, INFRAPLANAS LTD. 2004. Economic evaluation of the IXB transport corridor continuation – the western Vilnius bypass. Kaunas, 2004.

Dr. Aušrius Juozapavičius, Assoc. professor, chief of the Department of Engineering Management, he General Jonas Žemaitis Military Academy of Lithuania
Main research areas: transport engineering management, problems of safe and rational transport.
Address: Šilo 5A, LT-10322, Vilnius, Lithuania
E-mail: ausrius.juozapavicius@mil.lt

Stanislovas Buteliauskas, Lector at the Department of Engineering Management, The General Jonas Žemaitis Military Academy of Lithuania.
Main research areas: transport engineering management, problems of safe and rational transport.
Address: Šilo 5A, LT-10322, Vilnius, Lithuania
E-mail: stasysbut@gmail.com

Dr. Rimvydas Krasauskas, Assoc. professor at the department of Mathematics and Informatics, Vilnius University, Lithuania.
Main research areas: geometry of real rational surfaces and their applications to computer aided geometric design, 3D web visualization, geometric modeling for CAD applications.
Address: Naugarduko 24, LT-03225, Vilnius, Lithuania
E-mail: Rimvydas.Krasauskas@mif.vu.lt

Miesto transporto sistemos tobulinimo galimybės naudojant PINAVIA sankryžą

Aušrius Juozapavičius[1], Stanislovas Buteliauskas[1], Rimvydas Krasauskas[2]
[1]*Inžinerinės vadybos katedra, Generolo Jono Žemaičio Lietuvos karo akademija*
[2]*Matematikos ir informatikos fakultetas, Vilniaus universitetas*

(gauta 2010 m. rugpjūčio mėn.; atiduota spaudai 2010 m. rugsėjo mėn.)

Straipsnyje nagrinėjamos miesto transporto sistemos problemos (pavyzdys – Vilniaus miestas), atskleidžiami eismo organizavimo ir infrastruktūros trūkumai, kurie ir lemia daugelio miestų transporto spūstis. Pristatoma nauja didelio pralaidumo dviejų lygių sankryža Pinavia, aprašomas jos matematinis modelis, leidžiantis ją optimizuoti ir pritaikyti konkrečiai vietovei. Unikalios šios sankryžos savybės (galimybė urbanizuoti jos centrą: sukurti ten keleivių traukos centrus, automobilių stovėjimo aikšteles ir galutines viešojo transporto stoteles) leidžia jos statybai pritraukti privatų kapitalą ir įgalina miesto infrastruktūros plėtros strategiją, kurioje aplinkkelio ir magistralinių miestą kertančių kelių sankryžose pastatomos Pinavia sankryžos, taip pat vykdomi kiti vadybiniai eismo reguliavimo miesto centre sprendimai (nekeičiantys miesto vidinės infrastruktūros). Strategijos įgyvendinimas įmanomas santykinai nedidelėmis valstybės lėšomis ir sudaro visas prielaidas miesto transporto spūsčių problemai išspręsti.

DOI: 10.5755/j01.erem.53.3.89