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THE CRITERIA DESCRIBING THE NEED FOR HIGHWAY RECONSTRUCTION BASED ON THE THEORY OF TRAFFIC FLOWS AND REPAY TIME

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Abstract. General data on the network of Ukrainian highways are presented. The analysis of design methods of highway reconstruction based on the theory of traffic flows and economic calculations of its repay time is made. The relationship between traffic intensity and speed is shown by considering the theory of traffic flows. The methods, taking into account the principle of effectiveness of highway reconstruction based on its repay time, are discussed.

Keywords: highway, reconstruction, repay time, cost, transport, vehicle, traffic intensity, traffic flow, speed, capital investments, transport expenses.

1. Introduction

Roads had already been built in the ancient time (BC), when the wheel was invented and the first vehicle was made. Methods of road construction were changing at various stages of mankind development, depending on the improvement of the production forces and the changes in production relations, as well as on the experience and knowledge gained in the related branches of technology. At the early stages, methods of road construction were mostly based on the more advanced technology of building construction. Roads as means of communication have always been one of the major factors in human life. The attitude to them has been changing, depending on the need for transportation, routes and the requirements to transportation regularity. The lack of the balance between freight volume, vehicle capacity and road quality either brought road construction to a stop or stimulated its further development. The requirements to roads were determined first by a messenger with an urgent message, then by a merchant with a pack of goods on the horse's back, troops of armed horsemen and, finally, by a motorized vehicle as the main means of transport.

Motor roads (highways) should secure freight transportation with the lowest power consumption and at low cost.

Highways make a national property, being a major component of the national transport system. Their state largely affects the country's social and economic development. Highways should be properly maintained and repaired to ensure safe and comfortable transportation.

The authors of the paper represent two countries – Ukraine and Lithuania, which have much in common. However, the structure of their highway networks differs to some extent. Therefore, the research centres on the analysis of the roads of one of the above countries – Ukraine.

The State Service of the Ukrainian Highways (in Ukrainian – *Державна служба автомобільних доріг України УКРАВТОДОР*) is the central body of the executive power for executing the control over the Ukrainian highways. This institution controls the road network for general use (Fig. 1) of about 169.1 thous. km of length, with 20.1 thous. km of roads of state importance. The roads also include 16 thous. bridges of the length of over 364 km.

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Table 1. Motor roads in Ukraine (the data on January 1, 2008)

The importance of motor roads	Total length of roads, km	Total length with rigid pavement, km	Including the type of road pavement, km					Roads with rigid pavement, %	Dirt roads, km	Roads with rigid pavement according to categories, km				
			cement-concrete roads	asphalt-concrete roads	black highway	white-broken stone, gravel roads	stone block			I	II	III	IV	V
Total in Ukraine	**169 422**	**165 612**	**2705**	**57 802**	**71 526**	**25 584**	**7 995**	**97,8**	**3 810**	**2 582**	**12 725**	**29 369**	**105 855**	**15 081**
Including:														
Roads of state importance *Including:*	**20 512**	**20 512**	**1 254**	**16 398**	**2 822**	**30**	**8**	**100,0**	**0**	**2 506**	**9 987**	**6 830**	**1 182**	**7**
International roads	8 200	8 200	970	6 856	366	0	8	100,0	0	1 768	4 621	1 716	89	6
national roads	4 811	4 811	109	4 301	401	0	0	100,0	0	514	2 810	1 380	107	0
regional roads	7 501	7 501	175	5 241	2 055	30	0	100,0	0	224	2 556	3 734	986	1
Roads of local importance *Including:*	**148 910**	**145 100**	**1 451**	**41 404**	**68 704**	**25 554**	**7 987**	**97,4**	**3 810**	**76**	**2 738**	**22 539**	**10 4673**	**15 074**
territorial roads	27 312	27 214	413	13 067	12 438	819	477	99,6	98	60	2 152	13 505	11 094	403
provincial roads	52 085	50 975	358	14 507	24 570	7 218	4 322	97,9	1 110	5	382	6 704	41 228	2 656
district roads	69 513	66 911	680	13 830	31 696	17 517	3 188	96,3	2 602	11	204	2 330	52 351	12 015

Fig. 1. The network of Ukrainian highways of general use
(Source – *Державна служба автомобільних доріг України*)

There are seven automobile transport corridors on the territory of Ukraine (see Table 2 and Fig. 2). The length of highways in the directions of these corridors is 5 240 km.

As shown by the above data, Ukraine has a wide network of highways which need not only constant maintenance but reconstruction as well.

The relevant problem for the country's economy is the ability to take the proper decision about undertaking highway reconstruction. *Reconstruction* is perceived as the transfer of the road to a higher category by changing its geometric parameters and improving the quality of road pavement. Highway reconstruction requires the enhancement of all its elements. However, in reconstructing a highway, it is not necessary to rebuild all the elements according to design specifications for new roads.

Highway design is made for a certain period of time in the future, taking into account the yearly growth of traffic intensity. However, later, when a particular road grows in importance, the requirements to its specifications also become more stringent. Based on the calculations of the expected traffic intensity and the observations of the speed and type of traffic as well as taking into account the number and character of traffic accidents, the economic research into the need for highway reconstruction is carried out. One of the reasons for undertaking highway reconstruction may also be sharp deterioration of the ecological state of the roadside area. For this purpose, the following problems should be solved:

- to increase highway capacity;
- to increase traffic safety;
- to decrease the pollution of the environment;
- to save fuel;
- to use the resources effectively;
- to increase the comfort of road transportation within the framework of the developed highway reconstruction project.

Investments in transport are highly risky. This market sector needs great financial investments, while the profit is not quickly obtained. Therefore, it may be stated that transport is capital consuming business, requiring great amounts of money for investments.

2. A Survey of the Research Papers

The research into the problems associated with highway design and reconstruction, as well as the movement of single vehicles and traffic flows on the roads being reconstructed, is not new. These problems have been investigated for many years by the researchers from various countries, for example, Chomyak (Хомяк 1983); Palšaitis *et al.* (1990); Allen and Floyd (1991); Higgins (1993); Zavoritskij *et al.* (Заворицкий *и др*. 1996); Helbing and Greiner (1997); Beljatynskij *et al.* (Білятинський *и др*. 1997 and 1998); Fwa *et al.* (2002); Lee *et al.* (2005 and 2006); Yagi *et al.* (2005); Leden *et al.* (2006); Basu and Maitra (2007); Berezhnoy *et al.* (2007); Easa and Mehmood (2007); Jakimavičius and Burinskienė (2007 and 2009); Gintalas *et al.* (2007a and 2007b); Hugo *et al.* (2007); Junevičius and Bogdevičius (2007); Junevičius *et al.* (2007); Lee and Thomas (2007); Li (2007); Paliulis (2007); Sivilevičius and Šukevičius (2007 and 2009); Sužiedelytė-Visockienė (2007); Tanczos and Torok (2007); Tarel *et al.* (2007); Yu *et al.* (2007); Ziari and Khabiri (2007); Zavadskas *et al.* (2007 and 2008);

Table 2. Automobile transport corridors in Ukraine

Title	Towns (Countries)	Length
Pan-European Transport Corridor No 3	Berlin (Germany) – Dresden (Germany) – Wroclaw (Poland) – Lviv (Ukraine) – Kiev (Ukraine)	Length of the corridor – 1 640 km, including the section in Ukraine: • railway – 694 km; • motor roads – 611 km
Pan-European Transport Corridor No 5	Trieste (Italy) – Ljubljana (Slovenia) – Budapest (Hungary) – Bratislava (Slovakia) – Chop (Ukraine) – Uzhhorod (Ukraine) – Lviv (Ukraine)	Length of the corridor – 1 595 km, including the section in Ukraine: • railway – 266 km; • motor roads – 338 km (including branch roads – 47 km)
Pan-European Transport Corridor No 9	Helsinki (Finland) – St Petersburg (Russia) – Vitebsk (Belarus) – Kiev (Ukraine) – Moscow (Russia) – Odessa (Ukraine) – Kishinev (Moldova) – Plovdiv (Bulgaria) – Bucharest (Romania) – Alexandropoli (Greece)	Length of the corridor – 3 400 km, including the section in Ukraine: • railway – 1496 km; • motor roads – 996 km (including branch roads – 152 km and 242 km)
National Transport Corridor 'Baltic Sea – Black Sea'	Gdansk (Poland) – Odessa (Ukraine)	
National Transport Corridor 'Europe – Asia'	Krakovets – Lviv – Rivne – Zhytomyr – Kiev – Poltava – Kharkiv – Debaltsevo – Izvarino (Ukraine)	
Eurasian National Transport Corridor	Odessa – Mykolaiv – Kherson – Dzankoy – Kerch (Ukraine)	
National Transport Corridor 'Black Sea Economic Cooperation (BSEC)'	Reni – Izmail – Odessa – Mykolaiv – Kherson – Melitopol – Berdiansk – Novoazovsk (Ukraine)	

Fig. 2. International transport corridors on the territory of Ukraine (Source – *Державна служба автомобільних доріг України*): 1 – Pan-European Transport Corridor No 3; 2 – Pan-European Transport Corridor No 5; 3 – Pan-European Transport Corridor No 9; 4 – National Transport Corridor 'Baltic Sea – Black Sea'; 5 – National Transport Corridor 'Europe – Asia'; 6 – Eurasian National Transport Corridor; 7 – National Transport Corridor 'Black Sea Economic Cooperation (BSEC)'

Akgüngör (2008a and 2008b); Bazaras *et al.* (2008); Brauers *et al.* (2008a and 2008b); Čygas *et al.* (2008); Gopalakrishnan (2008); Kapski *et al.* (2008); Kinderytė-Poškienė and Sokolovskij (2008); Lundkvist and Isacsson (2008); Raab and Partl (2008); Paslawski (2008a, 2008b and 2009); Sivilevičius *et al.* (2008); Sivilevičius and Vislavičius 2008; Šelih *et al.* (2008); Zavadskas (2008); Antov *et al.* (2009); Burinskienė (2009); Burinskienė *et al.* (2009); Burinskienė and Rudzkienė (2009); Šliupas (2009); Tampère *et al.* (2009), etc.

Let us consider some of these works.

The research by Allen and Floyd (1991) examines the alternative financing techniques in funding major highway reconstruction projects, using the I-285 perimeter freeway around the north side of Atlanta, Georgia as an example. The status of the I-285 freeway; factors creating the problems of raising the amounts needed to finance large-scale highway reconstruction projects in the U.S.

The research by Higgins (1993) examines the monitoring and evaluation of traffic management strategies during highway reconstruction. It discusses the overall purposes of monitoring and evaluation, including the ways of strategies' implementation, tracking costs and comparing these to budget as well as tracking the evaluation procedures set out in the traffic management plan. This is followed by examination of evaluation methods and considerations of each category of strategies in the light of the existing information about their nature and effectiveness. The author also offers some suggestions about the use of evaluation information for maintaining a cost-effective mix of strategies and planning future traffic management programmes.

Sivilevičius and Šukevičius (2007) investigated the dynamics of vehicle load impact on the asphalt pavement of European highways crossing Lithuania. The largest damage to the road pavement is caused by heavy goods vehicles (HGV's). Due to large axle loads, which often produce the dynamic effect, the HGVs account for almost total destructive impact on the road pavement, though they make about 15% of all traffic flows on the main roads of Lithuania. A continuous growth in the transit HGVs on the roads of Lithuania causes the development of permanent deformations of road pavement. Due to the insufficient pavement strength, the ruts, waves, displacements and potholes are initiated. Based on the analysis of traffic volume, it could be stated that the amount of vehicles on our roads has been annually growing. The largest loads are caused by HGVs, with their average annual increase making 17%. Based on the traffic volume measurement data provided by the Transport and Road Research Institute (TRRI), the annual average daily traffic (AADT) and the impact of the HGVs on the road pavement was identified on separate sections of the roads E85 and E67. The impact was determined by calculating the equivalent standard axle (ESA).

Gintalas *et al*. (2007a) investigated the longitudinal profile of the objects included in the *Gravel Roads Paving Programme* of Lithuania. For the implementation of the *Gravel Roads Paving Programme* on the Lithuanian roads the reconstruction projects of the existing gravel roads are being prepared. This article studies the problems caused by taking design solutions and correcting a longitudinal road profile of the objects included in the *Gravel Roads Paving Programme*. It also gives the results of longitudinal profile investigation of gravel roads under the supervision of the state enterprise 'Telšiai Regional Roads' (VĮ 'Telšių regiono keliai') Administration. Based on the investigation results, the design radii of vertical curves are suggested and recommended for use in the projects of paving gravel roads.

Gintalas *et al*. (2007b) studied the problems of making design solutions in the projects of gravel road reconstruction due to taking of land for the right-of-way. The research was carried out in which the volume of taking the land due to the correction of the road plan and the costs of special planning related to the taking of land were predicted for the gravel road sections under the supervision of the state enterprise 'Telšiai Regional Roads' ('*Telšių regiono keliai*'). The article gives recommendations for the necessity to correct the road plan and the reduction of the related costs.

Zavadskas *et al*. (2007) propose multi-attribute assessment of road design solutions by using the COPRAS method. Multi-attribute analysis is a popular tool in solving a number of economical, managerial, constructional and other problems. The objective of this research is to develop and implement methodology for multi-attribute assessment of multi-alternative decisions in road construction. Based on a short overview of multi-attribute decision support for assessment of road design alternatives, the COPRAS approach was selected. This methodology is applicable to the problems with large numbers of scenarios and criteria. A case study is provided to demonstrate the concept of multi-attribute assessment of road design alternatives and the best road design alternative is determined. The research concluded that the COPRAS method is appropriate for use.

Brauers *et al*. (2008a) investigated multi-objective decision-making for road design. Based on a short overview of the articles dealing with the multi-objective decision and assessment of road design alternatives described by discrete values, method of Multi-Objective Optimization on the basis of the Ratio Analysis – MOORA (Brauers and Zavadskas 2006 and 2009; Brauers *et al*. 2008a and 2008b) – was selected. This method focuses on a matrix of alternative responses on the objectives. A case study demonstrates the concept of multi-objective optimization of road design alternatives and the best road design alternative is determined.

The work of Šliupas (2009) analyses the data on road traffic accidents on Lithuanian main and interurban roads in the years 2002–2006. The road network is divided into 341 road sections. The surrounding area and road parameters of each of the sections are measured. Then, the dependence of traffic accident rate on the above parameters is studied and described using linear and multiple regressions. The equations are built using 90% of the available data and tested by forecasting traffic accident rate for the rest of 10% of the data and comparing the results obtained with the real data.

Junevičius and Bogdevičius (2007) determine traffic flow parameters in the cases of interaction of different traffic flows. Modelling of a straight road section consisting of one traffic lane gives the opportunity to simulate 'follow the car' system. In general, it looks like a line of vehicles, going one after another. The kinetic theory used in this paper describes traffic flow system as a straight unbroken line with a limited flow speed and concentration. This model also gives the opportunity to derive traffic lane intersections. For example, an intersection could be derived like a point with traffic lanes coming and outgoing from this point by only changing the boundary conditions. A mathematical model is built using the characteristic method.

Fwa *et al*. (2002) analysed optimal vertical alignment for highway design. The critical length of grade control, fixed-elevation points, and non-overlapping of horizontal and vertical curves are three common requirements to the vertical alignment design of roads. These three forms of constraints are, however, usually not addressed in the conventional road alignment optimization analysis because of difficulties faced in considering them in mathematical formulation and solution of the problem. This paper shows that the artificial intelligence technique of genetic algorithms can be adopted to handle these three forms of constraints effectively. The formulation of the genetic-algorithm computer program and the method of solution are described. The validity of the optimization algorithm is verified against a dynamic programming solution. Some examples are presented to demonstrate the application of the genetic-algorithm program to problems involving critical length of grade requirements, fixed-elevation control, and non-overlapping of horizontal and vertical curves. These three constraints were found to have significant effects on the computed optimal alignments and the associated construction costs.

Lee *et al*. (2005) in their paper investigated the planning of urban highway reconstruction with traffic demand affected by construction schedule. This research introduces an integrated approach to the development of construction and traffic management plans for reconstructing high-volume urban freeways. The Devore project, which rebuilds a 4.2 km stretch of the deteriorated concrete pavement (truck lanes) on Interstate-15 (I-15) in San Bernardino County in southern California, is used as a case study. The alternative closure timing, closure duration, and a number of closed lanes were compared to identify the best rehabilitation strategy for the Devore reconstruction project. The perspectives of construction schedule, traffic inconvenience (road user cost and maximum delay), and agency costs were considered. The analysis concluded that full closure of one roadbed with counter-flow traffic during the repeated three or four continuous weekdays, utilizing round-theclock reconstruction operations, was the best strategy for both the public and the sponsoring agency. A delay in the start of construction from Spring to Fall 2004 is expected to cause a 5% seasonal traffic increase, which will result in a \$4.5 million increase in road user cost and a 20% increase in maximum queue delay per closure.

In their research, Easa and Mehmood (2007) considered highway horizontal alignment as a means of maximizing design consistency. Highway design consistency is one of the most important criteria in selecting the geometric features of the proposed or existing alignments of two-lane rural highways. Operating-speed (OS) profile models have been used to evaluate design consistency by trial and error. For the proposed new highway, however, there may be geometric and physical constraints, and the selection of these elements by trial and error to achieve optimal design consistency would be difficult, if not impossible. This research presents an optimization model that uses highway horizontal alignment to achieve maximum design consistency based on the OS profile. The decision variables of the model include the radius of horizontal curves, spiral curve lengths, length of speed-change (SC) segments, and acceleration and deceleration rates. The objective function of the model minimizes the mean OS difference or the maximum OS difference for successive geometric features along the highway section. Application examples and sensitivity analysis are presented to illustrate the capabilities of the model in evaluating improvement strategies and to ensure that the model produces sound optimum alignments. The proposed model, which complements the existing optimization models mainly addressing highway construction cost, should be of interest to highway practitioners and engineers.

Li (2007) carried out the research into pavement preventive maintenance for highway based on cost-benefit analysis. Cost-benefit analysis is adopted to study preventive maintenance treatment for asphalt pavement. The definition of preventive maintenance of pavement is clarified by investigation and comparison. The technical-economic characteristics of pavement maintenance treatments typically used for asphalt pavement in Shanghai are defined. Cost-benefit analysis for preventive maintenance treatments including maintenance cost, traffic benefit and performance benefit, using the equivalent annual cost method, is performed. Cost-benefit analysis is brought forward to determine optimum maintenance methods and time. The costs include treatment cost, major maintenance cost and reconstruction cost. The benefit is represented by the area under the pavement performance curve. The results obtained show that cost-benefit analysis is the key technique of the preventive pavement maintenance, which is the guarantee to save costs during the pavement cost life. These theories, methods, technologies and parameters are the basis to build pavement preventive technique system and can be used as a reference for further research and application.

Šelih *et al*. (2008) investigated a multiple-criteria decision support system in highway infrastructure management. Highway infrastructure represents a significant part of the public assets, which in its lifetime is exposed to various deterioration processes leading to the depreciation of its value. It is therefore of vital importance to manage these assets, aiming to reduce the loss of their value with time to a minimum. A typical task of road managers is making decisions related to maintenance, repair and rehabilitation based on data regarding the existing road condition, risk of its use, life cycle costs and age. Road infrastructure is complex, and therefore the optimal choice of planned interventions is a delicate task often left to the road managers' subjective judgment. The main goal of the research work presented in the paper is the development of a multiple criteria decision support system to determine the priority ranking of asset rehabilitation projects. The results are presented for a selected case study that consists of 27 overpasses for a highway section. The data on the condition of crossovers obtained by regular inspection along their contribution to a structured database are essential. The selection of the set of asset rehabilitation projects is carried out by using the developed decision support system that includes the budget constraint option. The selected set of asset maintenance/rehabilitation projects meets best the pre-defined combination of several criteria and therefore yields the maximized overall benefit. The results showing the selection criteria employed in the decision process and relative importance are crucial in obtaining the targeted goals. The selected criteria should therefore reflect the needs of the users and the actual conditions related to the assets.

The above investigations make only a fraction of research carried out in the discussed area.

The authors of the present paper study the criteria of the need for highway reconstruction, taking into account the theory of traffic flow and repay time.

3. Methods Suggested for Analysis

A decision for undertaking highway reconstruction is made, when the intensity of traffic achieves the lower limit of a higher category highway. According to specifications (ДБН В.2.3.4:2007), the above traffic intensity is as follows:

- Category I – over 14 000 veh/24 h;
- Category II – 14 000 veh/24 h;
- Category III – 5 000 veh/24 h;
- Category IV – 2 500 veh/24 h;
- Category V – 300 veh/24 h.

However, the above figures are not always decisive for making a decision for reconstruction.

A decisive factor for undertaking highway reconstruction depends on economic calculations. Economic calculations help us to determine the repay time of capital expenses on reconstruction:

$$T = \frac{K}{\Delta E} \le 8.4 \text{ year}, \tag{1}$$

where: T is repay time; K denotes capital expenses on reconstruction; ΔE denotes the savings obtained in the 1st year of highway maintenance.

Transport expenses are perceived as the difference in the annual cost of veh/h before and after reconstruction:

$$\Delta E = E_{before} - E_{after}, \quad (2)$$

where: E_{before} is the cost of veh/h a year before highway reconstruction; E_{after} is the cost of veh/h a year after highway reconstruction.

The annual cost of veh/h is found by the formula:

$$E = \frac{L}{V_{aver\,24\,h}} \cdot N \cdot 365, \quad (3)$$

where: L is the highway length, km; $V_{aver\,24\,h}$ is the average speed, veh/24 h; C is the cost of a vehicle per hour of operation, UAH (Ukrainian Hryvnia); N is traffic intensity in 24 hours, veh/24 h.

Let us consider the dependence 'traffic intensity – speed' in terms of the theory of traffic flows. This dependence was established based on the 'hydrodynamic' theory and the theory of 'following the leader'. As a result, the functional relationship was obtained:

$$N = V_{average} \cdot \frac{q_{\max}}{l^{(V_{average}/V_0)}}, \quad (4)$$

where: N is traffic intensity, veh/h on the traffic lane; $V_{average}$ is the average speed of a traffic flow, km/h; V_0 is the average speed corresponding to the capacity of the traffic lane ($V_0 = 25$ km/h); $q_{\max}$ is the maximum traffic flow density in a jam, veh/km; l is the vehicle's length.

Any mathematical model should have a constraint or a particular application area. In this case, the speed of vehicles in free motion may be considered a constraint (Fig. 3).

The curve $F(N, V)$ represents the traffic of a column of vehicles on the lane. Thus, traffic intensity – N_{II}, N_{III} and N_{IV}, corresponds to the motion of vehicles in column at the speed corresponding to the speed of free motion of a vehicle on a highway of the respective categories.

In the intervals of vehicle travel from level N_0 to N_{II}, N_{III} and N_{IV}, the traffic modes of vehicles vary from free to column. When traffic intensity values are equal to the values of N_{II}, N_{III} and N_{IV}, the speed of the traffic flow V_{IV}, V_{III} and V_{II} is reduced respectively.

It is clear that, when these values are reached, the dynamic clearance limit follows another dynamic clearance limit without any interval, as shown in Fig. 4.

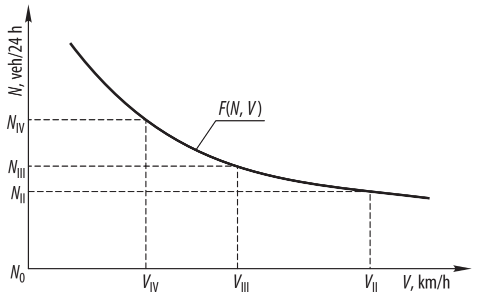

Fig. 3. The relationship between traffic intensity and speed of traffic flow

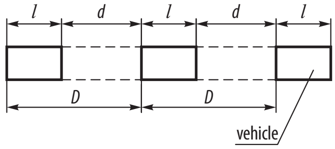

Fig. 4. The relationship between the dynamic clearance limits for traffic in column: l is the vehicle's length; d is the distance between the vehicles corresponding to a particular traffic speed; D is the dynamic clearance

In this case, the increase in traffic intensity causes the decrease in distance and speed.

Highway reconstruction may be undertaken if traffic intensity is as follows:

- 1000 veh/24 h on the highways of category IV or 100 veh/h – 50 veh/h on a traffic lane;
- 3000 veh/24 h on the highways of category III or 150 veh/h on a traffic lane;
- 7000 veh/24 h on the highways of category II or 350 veh/h on a traffic lane.

The intervals between the values of traffic intensity allowing for highway reconstruction and transfer to another category should be as follows:

- from category IV to category III – 1 000 veh/h – N_{III};
- from category III to category II– 3 000 veh/h – N_{II};
- from category IV to category II – 3 000 veh/h – $N_{II.}$

The transfer of a highway to category I may be made if traffic intensity on a traffic lane is equal to or exceeds 4 500 veh/h.

Since the difference in traffic speed on the highways of categories III and IV ranges from 0.1 to 2.0 km/h, the reconstruction would be economically ineffective for any traffic intensity values, while because of slight reconstruction of transport expenses, the repay time would considerably exceed 8.4 years.

Thus, we may conclude that:

- highways of categories III and IV may be reconstructed when their traffic intensity corresponds to the vehicle's free motion speed on the highway of category II (N_{II});
- if traffic intensity on a highway corresponds to the traffic speed on a highway of a particular category (IV, III and II), it should be transferred to category I (N_I);
- traffic speed on the highway of categories IV, III and II will not change until the values of N_{IV}, N_{III} or N_I are achieved.

4. The Application of the Suggested Methods

Let us analyse a real case of the assigned reconstruction of the highway of category III with traffic speed of 3 000 veh/24 h or 150 veh/h on a traffic lane, based on the calculations made by the authors.

The traffic flow consists of:

- 50% of cars;
- 50% of trucks.

Free motion speed is:

- 64.2 km/h on highways of category III;
- 69.5 km/h on highways of category II.

The road length is 1 km.

The reduction of transport expenses per year is as follows:

- ΔE_1 = 1 294.29 UAH, when C = 1 UAH for 1 veh/year;
- ΔE_5 = 6 471.45 UAH, when C = 5 UAH for 1 veh/year;
- ΔE_{10} = 12 942.9 UAH, when C = 10 UAH for 1 veh/year.

Therefore, the maximum capital investments to the reconstruction of 1 km of highway will be:

$K_1 = E \cdot 8.4.$

5. The Novelty of the Methods Presented

The reconstruction of a highway is assigned when the upper traffic intensity limit on a particular category highway is reached for a long-term perspective.

From economic perspective, highway reconstruction should be assigned when the repay time is ≤8.4 years.

The repay time is calculated by the formula:

$$T_{repay} = \frac{K}{E_{before} - E_{after}}, \quad (5)$$

where: E_{before} denotes annual transport expenses before reconstruction, UAH; E_{after} means transport expenses after reconstruction, UAH; K denotes capital investments, UAH.

Transport expenses depend on the average speed of a traffic flow. The methods presented allow us to solve the problems of highway reconstruction based on determining the repay time (i.e. the ratio of capital investments to the reduction of transport expenses). This allows us to get some variants of transferring the highways of categories IV–II to category I, if their traffic intensity at that time makes ≥7 000 veh/24 h. The transfer to a higher category can be made only when the repay time is determined. If the repay time exceeds 8.4 years, highway reconstruction will be economically ineffective.

Based on the research performed, a functional describing the difference in current state expenses before and after highway reconstruction was chosen as a criterion determining the need for changing a particular state of the system 'traffic (highway) conditions – traffic flow – the environment' into another.

For the ideal case:

$$\Delta B = B_{before} - (B_{after} + B), \quad (6)$$

where: B_{before} denotes current state expenses before highway reconstruction, UAH; B_{after} denotes current state expenses after highway reconstruction, UAH; B denotes the expenses on highway reconstruction, UAH.

Taking into account the difficulty in providing a concrete mathematical definition to the above functional, the parameters defining the system were considered separately. The determining of the minimum of parameters usually does not yield the optimization of a general criterion, allowing us, however, to arrive at a rational, nearly optimal, solution.

6. Conclusions

When a highway is reconstructed, it should be transferred to a category for which the functional (6) will assume the maximum value. The functional's value close to maximum may be obtained by minimizing the parameters and the number of traffic accidents and providing economically rational traffic mode and intensity. Therefore, transferring the lower category highways to higher categories, the following factors, including the provision of economically rational traffic intensity and the number of overtakings, as well as higher traffic safety and protection of the environment, should be taken into account.

The methodology considered in the presented paper is based on the principle of assigning highway reconstruction, taking into account the economic effect of reconstruction depending on its repay time, which should not exceed 8.4 years. It may be recommended to undertake highway reconstruction, taking into consideration all economic expenses of the state.

It follows that a decision about highway reconstruction should be taken only if the appropriate economic calculations are made. When state expenses do not comply with the repay time of reconstructed highway, the reconstruction can hardly be economically effective, even if various methods of analysis showed that it was required. In this case, the solution could be a revision of traffic conditions on a highway, as well as its improvement or partial reconstruction of its component parts.

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