



PHD THESIS

MODEL FOR THE SUBSTANTIATION OF ROAD SAFETY IMPROVEMENT
MEASURES ON THE ROADS OF LITHUANIA

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Abstract. This article gives the summary of the author's PhD Thesis supervised by Prof Dr Donatas Čygas and defended on 16 December 2009 at the Vilnius Gediminas Technical University. The thesis is written in Lithuanian and is available from the author upon request. Chapter 1 gives the main data on the road network of national significance of Lithuania, the change in the level of vehicle ownership, the basic accident indices and the essential factors influencing road safety. Chapter 2 gives a review of research methods used, review and evaluation of methodologies for the substantiation of road safety measures in Lithuania, Finland, Belarus, Poland and Sweden. Chapter 3 gives the evaluation of the effect of road safety measures implemented on the roads of Lithuania in 1999–2002. Chapter 4 describes the improved model for the substantiation of road safety measures under Lithuanian conditions. Chapter 5 presents the use of mathematical models for the forecasting of road accidents on the main roads of the Republic of Lithuania.

Keywords: road safety, high-accident road sections, road safety improvement measures, impact coefficients, accident prediction model.

State of the problem

After Lithuania joined the European Union (EU), due to the expanding economic relations with EU member-states, the flows of transit traffic on the roads of Lithuania and the vehicle ownership have been increasing every year. Based on data of international accident statistics Lithuania is one of those few countries where the number of people killed per one million inhabitants is the highest compared to other EU countries (Čygas *et al.* 2004). In 1994–2008 on the roads of Lithuania 10 681 people were killed and 102 850 were injured. Most often the victims are young people, road accidents cause large moral and material losses for the public (Ratkevičiūtė *et al.* 2008).

In September 2001 the White Book, approved by the European Commission, confirmed an ambitious objective to reduce the number of accident victims by 50% by 2010 (from 50 000 to 25 000 per year). This can be implemented by seeking to unify the amount of penalties, to implement additional measures to ensure road traffic safety and to introduce new modern technologies. Having joined the EU Lithuania also undertook this objective: until 2010 to reduce the number of people killed during road accidents by 50%. Unfortunately, statistical data shows that safety situation on the roads of Lithua-

nia is still one of the worst in the European Union. The number of black spots is high, therefore, it is necessary to develop an effective model for the substantiation of road safety improvement measures (further – road safety measures) which would allow to select road safety measures first of all for those road sections where accident indices exceed the limit values.

The results of accident data research showed that the currently used methodology for the substantiation of road safety measures in Lithuania does not allow to accurately select road safety measures for high-accident road sections, to forecast accidents and their preventive measures (Ratkevičiūtė *et al.* 2008). Thus, it is necessary to correct it taking into consideration the experience of Lithuania and other foreign countries, to use mathematical statistics and mathematical optimisation models for preventing road accidents. Improvement of this methodology describes the topicality of this dissertation.

Research object covers the injury accident concentration places, black spots, methodology for the substantiation of road safety improvement measures, mathematical statistics and optimisation models for preventing road accidents. Experimental object of the work is 1995–2008 accident data on Lithuanian roads.

Aim and tasks of the work are to improve methodology for the substantiation of road safety measures in order to eliminate black spots, to construct a draft mathematical model for predicting fatal and injury accidents and to form the optimization problem which enables to model the optimal selection of road safety measures for the main roads of Lithuania.

The following tasks must be solved to achieve the aim of the work:

- to make the analysis of the currently used Lithuanian methodology for the substantiation of road safety measures;
- to make the analysis and evaluation of road safety indices after implementation of special measures on the roads of national significance of Lithuania and to determine the effect of methodology used;
- to study and evaluate similar methodologies for the substantiation of road safety measures used in other foreign countries;
- having evaluated the experience of other countries and the shortcomings of methodology currently used in Lithuania, to construct the effective model for the substantiation of road safety measures;
- to carry out testing of a new computer program and experimental calculations;
- to study the use of mathematical methods for predicting fatal and injury accidents;
- to construct a draft mathematical model for predicting fatal and injury accidents and to form the optimization problem which enables to model the selection of road safety measures for the main roads of Lithuania.

Scientific novelty of the work consists of the development of the model for evaluating the effect of road safety measures and its adaptation to the roads of national significance of Lithuania, based on the existing traffic volume and traffic conditions.

For the first time the constructed evaluation model was based on the results of analysis of engineering road safety measures implemented on the high-accident road sections of Lithuania in 1997–2008, and on the experience of foreign countries (Ratkevičiūtė *et al.* 2008). A new computer program *Evaluation of the Road Safety Measures* was created, its testing was carried out as well as experimental calculations.

For the first time in Lithuania a draft mathematical model is presented for predicting road accidents and modelling the optimal selection of road safety measures on the main roads of Lithuania.

The constructed model for the evaluation of road safety measures and the developed computer program which is used for the economic evaluation of road safety measures before their implementation on high-accident road sections and on the black spots of Lithuania is a practical value. The constructed draft mathematical stochastic model and the optimization problem is used for accident forecasting, selection of the optimal road safety measures to be implemented on the black spots of the main roads of Lithuania.

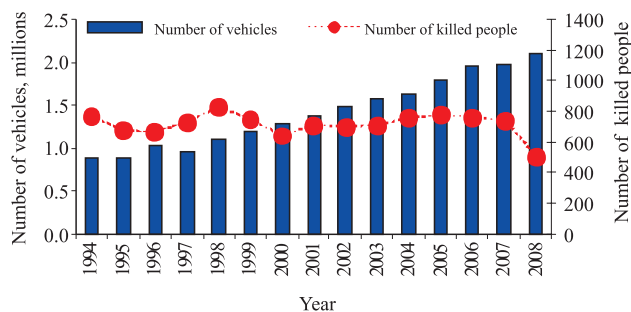


Fig. 1. Number of vehicles and people killed in 1994–2008

Road safety situation in Lithuania

Though the number of vehicles and the average annual daily traffic (AADT, vpd) has been increasing every year, the number of people killed on the roads is decreasing (Fig. 1). Due to a continuous improvement of vehicles (air bags, modern safety belts, anti-lock braking systems, reinforced vehicle body, etc.) accident severity becomes more slight.

From 2001 to 2009 the number of people killed on the roads of Lithuania was reduced by 26%. In 2008 the number of people killed during road accidents in Lithuania was one of the least in the recent 40 years. In the year 2008 on the roads of 27 EU member-states 39 thousand people were killed, however, this number has decreased by 15.4 thousand since 2001. Such a rapid decrease in the number of accidents was achieved merely by the united efforts of all the institutions concerned and their joint actions in saving human lives. A perfect result was achieved by a tightened road user control, gradual implementation of the engineering road safety measures for the number of years, active educational activities, therefore, the road users' culture and responsibility on the road has notably changed, and the executed scientific works allowed to more effectively work and adopt the best foreign practice (Ratkevičiūtė *et al.* 2008).

In order to select the most suitable road safety measures the causes of road accidents and their influencing factors were determined. This is the most important task for road safety specialists which is attempted to be strategically solved all over the EU in a way of creating common methodologies. The basis of these methodologies – identification of the accident-influencing factors and implementation of appropriate road safety measures on the high-accident road sections.

Analysis of methodologies for the substantiation of road safety measures used in Lithuania and foreign countries

When comparing methodologies for the substantiation of road safety measures used in Lithuania (TARVAL abbreviation from Finnish Turvallisuusvaikutusten Arviointi Vaikutuskertoimilla TARVA Lithuanian version), Finland (TARVA), Belarus and Poland the following main differences could be distinguished:

- Belarusian and Polish methodologies are more complicated than TARVAL and TARVA (Ratkevičiūtė *et al.* 2008);
- Polish methodology enables to predict the reduction of collisions (%) with vehicles, pedestrians and bicyclists (Ratkevičiūtė *et al.* 2008);
- Belarusian methodology enables to predict the probability for the reduction of accident number in parts of a unit from the total number of accidents as well as the probability for the reduction of fatal or injury accidents (Kapski *et al.* 2007; 2008; Ratkevičiūtė *et al.* 2008);
- TARVAL and TARVA versions enables to predict the impact coefficients for the accidents with motor vehicles, pedestrians/cyclists and animals;
- the impact coefficients for animal-involved accidents are used only in TARVAL and TARVA methodologies (but not in Belarusian or Polish methodologies).

The Finnish methodology for the substantiation of road safety measures TARVA is very close to the Lithuanian version TARVAL, however, at present it is much more new and differs from the initial TARVA version (Čygas *et al.* 2004). The specialists of the *Technical Research Centre of Finland* (VTT) have been continuously improving it and adapting to the current traffic situation on the national roads (Peltola 2000; 2007). The latest version of TARVA program also allows to forecast road accidents on the newly constructed or reconstructed road sections, to select road safety measures and to carry out accident prevention (Peltola 2007).

Sweden has no methodology for the substantiation of road safety measures, similar to that of TARVAL used in Lithuania. However, the Swedish methodology *Traffic Conflict Technique* (TCT) enables to identify conflict situations between different road users on the road section or junction before the occurrence of road accident. Having this type of data it is possible to select those road safety measures which would prevent from possible accidents (Jonsson 2005).

Research and evaluation of accident indices on the roads of Lithuania

For the evaluation of the effect of road safety measures implemented on the roads of Lithuania in 1999–2002 fatal and injury accidents were analyzed of 1995–2006. Accident data is compared before implementing road safety measures and 4 years after their implementation on the selected 48 high-accident road sections.

Economic evaluation was carried out using the cost-benefit analysis (Čygas *et al.* 2004; Hauer 2005). Based on this method benefits, consisting of savings in accident losses, were compared to the costs consisting of the implementation costs of road safety measures. Economic evaluation of safety measures was conducted for each black spot. Sensitivity analysis was carried out based on three sensitivity tests (growth of traffic volume, costs of safety measures and change in evaluation period). All 48 cases

showed that investments into road safety measures will pay back (Ratkevičiūtė *et al.* 2007; 2008).

Analysis of the effect of road safety measures implemented on 48 high-accident road sections showed that the expected results of the improvement of safety situation were not achieved on 24 road sections, i. e. 50%; the expected reduction in the accident rate was not achieved on 7 road sections, i. e. 15%; the implemented road safety measures have justified themselves on 24 road sections, i. e. 50% (Ratkevičiūtė *et al.* 2007).

In order to make an analysis of only partly justified road safety measures the visual investigations of high-accident road sections were carried out and a detail analysis of safety situation.

The use of research data in the models for the substantiation of road safety measures

Lithuania has a comprehensive accident databases and makes an accurate recording of accident locations. The amount and accuracy of other data required for the accident analysis has highly increased: traffic volume and its change, road safety measures, precise locations for their implementation, etc. All this allow collecting reliable data and based on this data to carry out a detail accident analysis, to correct the list of road safety measures and their impact coefficients, to more accurately forecast accident indices and to execute economic evaluation.

Analysis of accident research data showed that the currently used TARVAL software is not sufficiently accurate to evaluate safety measures to be implemented and to forecast accident indices. Therefore, it was necessary to correct it taking into consideration the experience in Lithuania and other countries and the current safety situation on the roads of Lithuania (Ratkevičiūtė *et al.* 2007).

Fig. 2 gives stages for the improvement of methodology used for the substantiation of road safety measures in Lithuania. For the improvement purposes the results of the analysis of effects of road safety measures implemented in Lithuania in 1997–2008 were taken into consideration, also the foreign experience and methodologies (Elvik 2009; Hakkert, Gitelman 2004; Kapski *et al.* 2007; 2008; Peltola 2000; Ratkevičiūtė *et al.* 2008; Yannisa *et al.* 2008), the road safety measures and their effect on road safety. The list of road safety measures has been supplemented with 59 new measures not earlier used.

Improvement of the method for the substantiation of road safety measures under Lithuanian conditions

The computer program *Saugaus eismo priemonių vertinimas* (*Evaluation of the Road Safety Measures*) for the evaluation of road safety measures consists of two parts:

- normative tables;
- data and calculations.

Before starting working with the program it is necessary to input the newest initial data into the already made-up normative tables. The cost of road accident is determined according to the unit prices approved by the Director General of the Lithuanian Road Administration

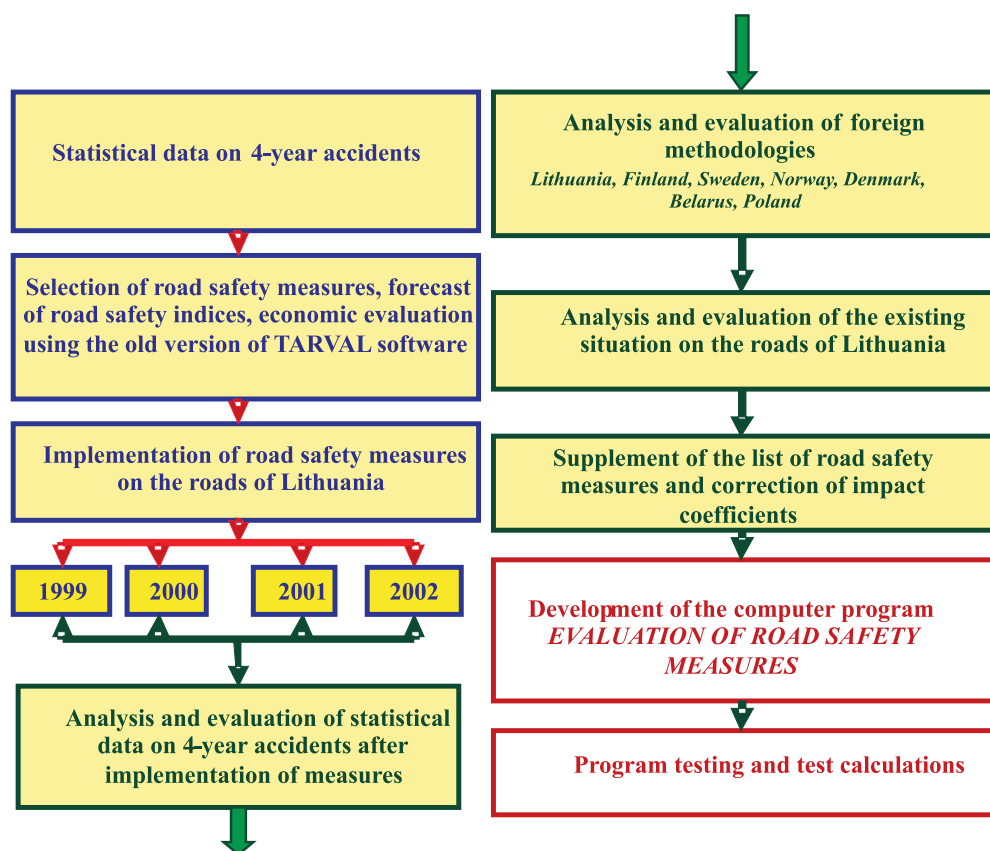


Fig. 2. Stages for the improvement of methodology used for the substantiation of road safety measures in Lithuania

under the Ministry of Transport and Communications of the Republic of Lithuania. The latest unit prices were approved by the order No. V-410 of 19 November 2008. In order to make the analysis of measures implemented in the previous years and the effect of those measures the unit prices of that period must be used. Road safety measures data stored in a table of the impact of road safety measures is the main input data of the road safety management system. Impact coefficients divided into three groups: vehicle-involved accidents, pedestrian-involved accidents and animal-involved accidents. Road safety measures are standard or individual. Individual road safety measures not yet included into the system, but there is a possibility to enter new safety measures.

Having entered **data** into normative tables the **calculations** are carried out. Calculations consist of three stages:

- data input;
- forecast calculations of road accidents and accident losses;
- economic calculations.

Data input is in detail described in the User's Manual presented in the dissertation. A very important feature of data input of a new program is that the data input area is joined to the *Lietuvos valstybinės reikšmės kelių informacinė sistema* (LAKIS) (*The Lithuanian State Road Information System of the Lithuanian Road Administration*).

Economic calculations show if the project is expedient to be implemented from the economic point of view. If several alternatives are studied it is determined which of them is the most acceptable.

Summary table of results gives data on the road section where a certain road safety measure is planned to be implemented, data on the traffic volume and accident rate of this road section, the planned road safety measures, summary data on the forecasted effect of measures after their implementation. Based on economic indices and the forecasted accident rate the software itself makes the evaluation of the project's attractiveness which can be:

- I – unsatisfactory;
- II – satisfactory;
- III – good;
- IV – very good.

A test of the improved model for the substantiation of road safety measures

Experimental calculations were carried out on those road sections where after implementation of road safety measures or their complex the expected decrease in the accident rate was not achieved. Based on the results of experimental calculations the impact coefficients of road safety measures were once again corrected.

Accident modelling

The developed computer program *Evaluation of the Road Safety Measures* is used for the evaluation of safety measures to be implemented on black spots. In order to make forecasts of the safety situation on the newly built or reconstructed road sections and to prevent the occurrence of black spots it is necessary to carry out a very comprehensive analysis of historical data on the change of road accidents and traffic volume on the roads of Lithuania, to divide the roads of Lithuania into plenty of homogenous sections and to adapt the methods of mathematical statistics and game theory.

Forecasts of accident number

In order to forecast the number of road accidents on the main roads of Lithuania a statistical mathematical model of time series was used. Since in the analysis of statistical data of the number of accidents in a time series the clear seasonal variations were observed (Figs 3, 4) a search for regression curve was made which would well reflect the seasonal variations. A random quantity – the number of accidents in 3 months (in a quarter of the year) – is marked by Y :

$$\hat{y} = a_0 + at + a_1t_1 + a_2t_2 + a_3t_3, \tag{1}$$

where \hat{y} – forecasted average Y value; t – trend variable; t_i – variable taking the value 1 in the quarter i of the year and the value 0 in other quarters (the fourth quarter of the year is corresponded by the values of variables $t_1 = t_2 = t_3 = +$).

Seasonal variations are described by the regression equations (obtained using the *Microsoft Excel* tool *Data Analysis*) (Table 1):

$$\hat{y} = 190.19 + 0.69t - 76.64t_1 - 81.63t_2 - 22.11t_3, \tag{2}$$

(1997–2006)

$$\hat{y} = 187.32 + 0.60t - 72.92t_1 - 74.70t_2 - 16.49t_3, \tag{3}$$

(1997–2007)

$$\hat{y} = 193.52 + 0.02t - 67.78t_1 - 69.54t_2 - 14.48t_3, \tag{4}$$

(1997–2008)

Fig. 3 gives the dependency of the observed (1997–2008) and forecasted (based on 1997–2006 data) Y values in time. Accident data studied in 1997–2007 showed that

Table 1. Reliability and adequacy of forecasting results

Statistical data	Number of observations (quarters)	R	R^2	Standard deviation	p
1997–2006	40	0.92	0.85	16.59	8.41E–14
1997–2007	44	0.90	0.80	18.19	2.41E–13
1997–2008	48	0.79	0.63	25.31	8.23E–09

where p – probability to make an error after rejecting a hypothesis that the variables t, t_1, t_2, t_3 are insignificant if the values of a random quantity Y is taken into consideration; R^2 – determination coefficient showing in what proportion, %, the variables t, t_1, t_2, t_3 explain a dispersion of values of the random quantity Y (the more R^2 is close to 1 the more regression curve is suitable to experimental data); R – correlation coefficient, the measure of correlation strength between the variables (the more R is close to 1 or –1 the stronger is correlation between the studied variables).

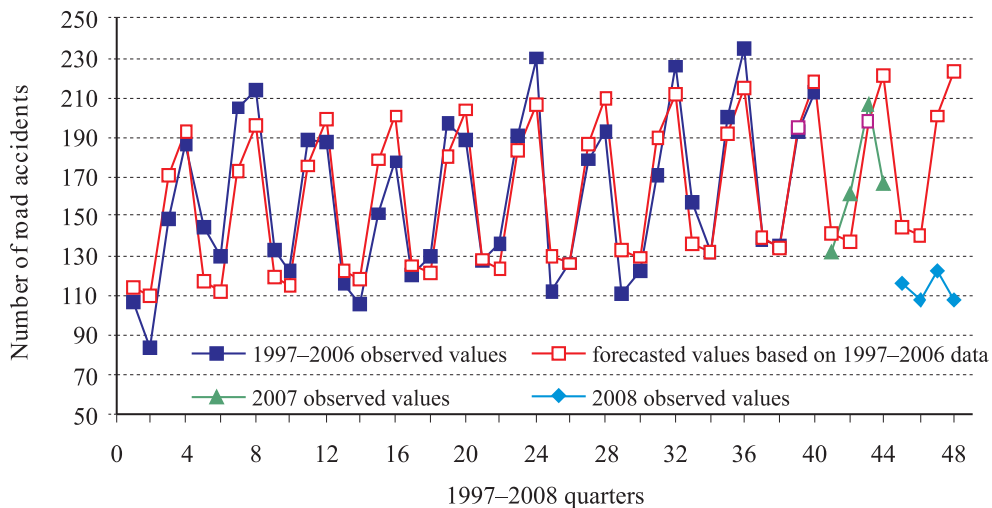


Fig. 3. Y values obtained by the regression Eq (1)

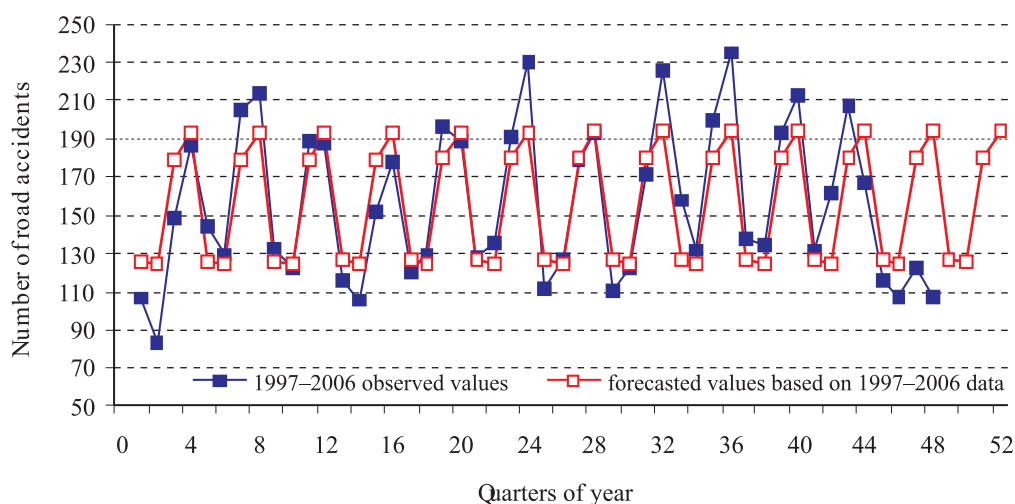


Fig. 4. Y values obtained by the regression Eq (4)

in the quarters III and IV the number of recorded accidents was significantly larger compared to the quarters I and II. Accident statistics of 2008 breaks even this regularity. The observed dispersion of the random quantity Y in the quarters III and IV is also larger compared to the quarters I and II.

The decrease in the number of accidents only in one year, i. e. 2008, is not statistically important to obtain a downward linear trend or a certain non-linear trend. This requires further observations of the accidents on the roads of Lithuania.

A detail analysis of the dependency of the number of accidents on the length of road section and its traffic volume is given. A detail statistical analysis of data about the black spots is presented too.

With the help of a high-volume sample ($n = 7095$) the main numerical characteristics of people killed and injured in one road accident were found. Forecasts were based on the fatal and injury accidents on the main roads of Lithuania in 1997–2008.

When analyzing the number of accidents on the black spots of the main roads in 2004–2007 data was grouped according to the type t of a black spot:

- t_1 – group I – black spots having no junctions;
- t_2 – group II – black spots having at-grade junctions;
- t_3 – group III – black spots having two-level junctions.

The number of black spots of the group I was 26, of the group II – 70, of the group III – 14. Such grouping enabled to rather reliably forecast the average number of accidents of each group (marked with X_1, X_2, X_3), separately of vehicle-involved accidents and accidents with pedestrians and cyclists (marked with X_{1m}, X_{2m}, X_{3m} and $X_{1dp}, X_{2dp}, X_{3dp}$) and the average number of people killed or injured in a 4-year period (marked with Z_1, Z_2, Z_3 and S_1, S_2, S_3). Regression equations of the statistical models of these parameters are:

$$X_i = aN^bL^c, \tag{5}$$

$$X_{im} = aN^bL^c, \tag{6}$$

$$X_{idp} = aN^bL^c, \tag{7}$$

$$Z_i = aN^bL^c, \tag{8}$$

$$S_i = aN^bL^c, \tag{9}$$

where $a = 1$; N – AADT on the studied road section, vpd; L – length of the studied road section, km; b – linear regression coefficient depending on traffic volume; c – linear regression coefficient depending on the length of road section; $i = 1, 2, 3$.

Regression equations, obtained for the black spots of all types ($t = 1, 2, 3$), forecast the averages of the studied random variables with the errors in the interval (1; 2.3), determination coefficients R^2 get the values in the interval (0.69; 0.99), thus, it could be stated that the dependency of random variables on the traffic volume and the length of the black spot gives a fairly good explanation of the dispersion of random variables $X_1, X_2, X_3, X_{1m}, X_{2m}, X_{3m}$ and $X_{1dp}, X_{2dp}, X_{3dp}, Z_1, Z_2, Z_3$ and S_1, S_2, S_3 .

The optimization of the selection of measures which was conducted to reduce the number of black spots on the roads also is described. In the result different mathematical models were constructed. One of them allows the specialists to optimally select road safety measures to maximally reduce the number of people killed under unrestricted amount of funds (10), the other – under restricted financial possibilities (11).

$$\max \sum_{i=1}^m d_i,$$

$$\sum_{i=1}^m \sum_{j=1}^n x_{ij} \leq k,$$

$$\sum_{j=1}^n (\overline{\alpha}_m d_{imj} + \overline{\alpha}_{dp} d_{idpj}) x_{ij} \geq d_i, i = 1, 2, \dots, m,$$

$$\sum_{j=1}^n x_{ij} \leq 1, i = 1, 2, \dots, m,$$

$$0 \leq x_{ij} \leq 1, i = 1, 2, \dots, m, j = 1, 2, \dots, n_1,$$

$$x_{ij} = \begin{cases} 0 \\ 1 \end{cases}, j = n_1 + 1, \dots, n, i = 1, \dots, m \quad (10)$$

and

$$\max \sum_{j=1}^m d_i,$$

$$\sum_{i=1}^m \sum_{j=1}^n c_{ij} x_{ij} \leq C,$$

$$\sum_{j=1}^n (\overline{\alpha}_m d_{imj} + \overline{\alpha}_{dp} d_{idpj}) x_{ij} \geq d_i, i = 1, 2, \dots, m,$$

$$\sum_{j=1}^n x_{ij} \leq 1, i = 1, 2, \dots, m,$$

$$0 \leq x_{ij} \leq 1, i = 1, 2, \dots, m, j = 1, 2, \dots, n_1,$$

$$x_{ij} = \begin{cases} 0 \\ 1 \end{cases}, j = n_1 + 1, \dots, n, i = 1, \dots, m, \quad (11)$$

where $\overline{\alpha}_m, \overline{\alpha}_{dp}$ – average number of people killed in one vehicle-involved road accident ($\overline{\alpha}_m$) in one road accident with pedestrians and cyclists ($\overline{\alpha}_{dp}$); k – number of preventive measures; d_{imj}, d_{idpj} – average decrease in the number of vehicle-involved accidents (d_{imj}) and in the number of accidents with pedestrians and cyclists (d_{idpj}) after implementation of the measure j in the black spot i ; c_{ij} – cost of implementation of the measure j in the black spot i . Parameter C is the amount of money allocated for the implementation of measures.

Conclusions

Having made the analysis of the effect of road safety measures implemented it was determined that from the studied 48 high-accident road sections the expected improvement results in safety situation were not achieved on 50% of road sections; the expected reduction in accident rate was not achieved on 15% of road sections; the implemented road safety measures were justified on 50% of road sections.

Examination of 1995–2006 results of the substantiation of road safety measures implemented on the roads of national significance of Lithuania, the analysis of accident indices after implementation of special measures and the detail analysis of only partly justified road safety measures

showed that methodology for the substantiation of road safety measures, currently used in Lithuania, does not allow to accurately enough select road safety measures for the high-accident road sections.

Having made the analysis and evaluation of foreign methodologies for the substantiation of road safety measures and based on the *Microsoft Office Access* program the database was created operating as a separate program or as a sub-program *Evaluation of the Road Safety Measures*.

The created and tested calculation program *Evaluation of the Road Safety Measures* gives a possibility to determine the effect of the engineering road safety measures planned to be implemented on a certain high-accident location or black spot, using the suggested forecast coefficients of the impact and elasticity of road safety measures, of traffic volume and the growth in prices of preventive measures and taking into consideration the country's economic situation the program enables to forecast road accidents and accident losses.

In the result of research activities the list of road safety measures has been expanded by 59 new measures. A new program *Evaluation of the Road Safety Measures* uses already 131 safety measure. It gives a possibility to enter individual road safety measures.

With the use of high-volume sample $n = 7095$, data on the fatal and injury accidents on the main roads in 1997–2008, the main numerical characteristics of the number of people killed and injured in one road accident were found. The performed accident modelling allows constructing mathematical models for the optimum selection of preventive measures for the main roads.

In order to make forecasts of the safety situation on the newly built or reconstructed road sections and to prevent the occurrence of black spots it is necessary to carry out a very comprehensive analysis of historical data on the change of road accidents and traffic volume on the roads of Lithuania, to divide the roads into plenty of homogenous sections and to adapt the methods of mathematical statistics and optimization methods.

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