Available online at www.sciencedirect.com
ScienceDirect
Transportation Research Procedia 14 (2016) 3456 – 3465
Transportation Research Procedia
www.elsevier.com/locate/procedia

6th Transport Research Arena April 18-21, 2016

Safety PL – a support tool for Road Safety Impact Assessment

Wojciech Kustra [a,*], Kazimierz Jamroz [a], Marcin Budzynski [a]

[a]*Gdansk University of Technology, 12 Narutowicza strs, 80-232 Gdansk, Poland*

Abstract

Published on 19 November 2008, the European Union's Directive 2008/96/EC is one of the most important EU documents setting out a road safety orientation, in particular, road infrastructure safety management. It identifies four main areas of activity: road safety impact assessment, road safety audit, ranking of high accident concentration sections and network safety ranking and road infrastructure safety inspection.

The Directive was implemented in Poland under the Act of 13 April 2012 "on amending the Public Roads Act and some other Acts". The Act implements three of the Directive's four actions: road safety assessment, road safety audit, ranking of sections and network ranking. The Directive is further implemented under documents issued by the Director of the General Directorate for National Roads and Motorways (GDDKiA).

In 2011 the GDDKiA commissioned the Gdansk University of Technology and Krakow University of Technology to prepare an Instruction for Road Safety Assessment. The document helps with conducting the procedure for all newly designed national roads. Having implemented these guidelines, the GDDKiA, in an effort to improve design quality, requires designers to prepare such assessments for all planned and newly designed national roads.

The road safety assessment uses a generalised model of linear regression to estimate the relations between selected road and traffic factors and selected road safety measures (number of accidents, injuries, fatalities and accident costs). The procedure comprises around twelve steps and differs depending on the type of road (class G, GP, A and S roads) and cross-section (1×2, 2×2, 2×3). It includes a number of variables representing road location, year of analysis and roadside.

The authors of this article present a concept of implementing computational procedures previously used for a road safety impact assessment in the PTV Visum application. As a result, it will be possible to include models used for assessing selected road safety measures into the traffic volume forecast tool. Thanks to this it will be possible to calculate the number of accidents, victims and

* Corresponding author. Tel.: +483471797.
E-mail address: w.kustra@fril.org.pl

Peer-review under responsibility of Road and Bridge Research Institute (IBDiM)
doi:10.1016/j.trpro.2016.05.308

accident costs for all analysed variants of traffic spatial distribution. By automating this process, we will be able to speed up work and reduce analytical errors.

Peer-review under responsibility of Road and Bridge Research Institute (IBDiM)

Keywords: road safety; PTV Visum; Road Safety Impact Assessment

1. Introduction

Over the last decade Poland has been one of the EU's worst performing countries for its total number of road deaths (F) and seriously injured (SI). Figures show that in Poland between 2010–2014 there were 186.770 accidents with 18.230 killed and 59.500 seriously injured.

Published in 2008, the EU Directive 2008/96/EC (Directive) on road infrastructure safety management is one of the main documents setting out a road safety orientation, including road network safety management (European Parliament and the Council, 2008). The Directive was preceded with extensive research such as studies conducted under the RIPCORD-ISEREST project (Ripcord-Iserest, 2005), PIARC initiative and others (Elvik and Vaa, 2004; Technical Committee 13, 2004; Technical Committee 18, 2004; Thora Arnadottir et al., 2008; Wegman et al., 1994).

The problems addressed by the Directive were subsequently reflected in road safety programmes in Europe and worldwide (European Commission, 2011, 2010; World Health Organization, 2009). The Directive identifies four main areas of action:

The problems addressed by the Directive were subsequently reflected in road safety programmes in Europe and worldwide (European Commission, 2011, 2010; World Health Organization, 2009). The Directive identifies four main areas of action:

- road safety impact assessment (RIA),
- road safety audit (RSA),
- ranking of high accident concentration sections (section rating) and network safety ranking (network ranking),
- road infrastructure safety inspection (RSI).

The Directive points out the need for research programmes in an effort to improve safety on the roads of the European Union. In point 7 it reads: "Research is vital to improving safety on the roads within the European Union. Developing and demonstrating components, measures and methods (including telematics) and disseminating research results play an important part in increasing the safety of road infrastructure" (European Parliament and the Council, 2008). Similar claims are made in road safety management research (Hagenzieker and Wegman, 2010; Hauer, 2005; Koßmann and Schulze, 2010). The authors stress the importance of research and its application in road safety programmes and strategies. Research is critical to reducing accidents and casualties.

Points 8 and 9 emphasise that the safety performance should be raised by targeting road sections with the highest accident concentration or the highest accident reduction potential. Network safety rating offers a strong potential for effective road safety treatment (European Parliament and the Council, 2008).

2. Poland's experience from implementing the directive

Just as other EU countries, Poland has a duty to implement the EU Directive 2008/96/EC on road infrastructure safety management. This was done under the Act of 2012 "on amending the Public Roads Act and some other Acts" (Polish Parliamen, 2012; Polish Parliament, 2007). The Act implements three of the Directive's four actions: road safety assessment, road safety audit, ranking of sections and network ranking. According to the Act road infrastructure safety management is required on roads that are part of the Trans-European Transport Network (TEN-T). The roads total more than 5 100 km, which represents more than 27% of Poland's national roads (Budzynski et al., 2014a; European Parliament and the Council, 2010).

The Directive is also implemented under regulations of the Director of the General Directorate for National Roads and Motorways (GDDKiA) on road safety impact assessment, audit and section rating (between 2009 and 2014).

In the period 2011-2013 the GDDKiA commissioned the Gdansk University of Technology and Krakow University of Technology to prepare guidelines to support the implementation of the Act and GDDKiA director's regulations:

- Instruction for Road Safety Assessment (2011). The document helps with conducting the procedure for all newly designed national roads. Having implemented these guidelines, the GDDKiA, in an effort to improve design quality, requires designers to prepare such assessments for all planned and newly designed national roads (Budzynski et al., 2011).
- Method for forecasting road safety indicators (2011). It is designed to predict accidents, victims and costs to support economic effectiveness analyses for infrastructure work on Poland's national roads (Budzynski et al., 2013b).
- Instruction for inspecting road safety (2013) consisting of two parts: Part One covers road infrastructure safety inspection. It is designed to identify errors on an existing road network and assess the hazard they pose to road user safety. Part Two gives guidance on rating of high-risk sites on national roads. It is designed to prepare section rating for fatality concentration and road network safety (Budzynski et al., 2013a).

3. Road Safety Impact Assessment (RIA)

3.1. Assumptions of RIA Method

In accordance with the assumptions of the paper (Budzynski et al., 2011) assessment of the impact of the planned road sections on road safety (RIA) *[… is a strategic comparative analysis of the impact of a new road or a substantial modification to an existing road on the safety performance of the road network and allows identification of the best solution for road safety...]*.

The main objective of RIA is to prepare a ranking of planned solutions indicating the best variant from the point of view of road safety. Ranking of road safety should take into account both the planned roads and their effect on the road network operation in the impact area. The subordinate objectives are:

- Rejecting, from further stages of design, the variants of planned roads that do not meet acceptable risk levels, considering the class and category of road.
- Estimating the road safety measures: number of accidents (*A*), number of injuries (*I*), number of seriously injured (*SI*), number of fatalities (*F*) and accident costs (*AC*) in the impact area of planned roads.
- Providing data on road safety for environmental and economic analyses.
- Including road safety measures as decision criteria in the multi-criteria analyses in selection of the most advantageous variant of planned roads (Budzynski et al., 2014a, 2011).

Road safety assessment should be performed under the "Corridor study with the multi-criteria analysis (CS)" (fig 1). In the absence of such an analysis at this stage of design, it should be performed at the stage of "Technical – Economic – Environmental Study". It is one of the necessary studies with the same status as the analysis of costs or impact on the environment and must be taken into account when evaluating and selecting variants of a planned road investment.

The validity of performing multi-criteria analyses. Implementation of road investment may have a very serious impact on the development of areas of the country for years to come. Therefore, the selection of the optimal variant of the investment is a process that requires a series of decisions at many stages of its execution, that will generate both costs and benefits when the investment becomes operational. Applying scientific methods to support this process allows for selecting a variant that is best in terms of selected criteria: finance, transportation, environment, road safety (Budzynski and Kaszubowski, 2014; Kaszubowski and Oskarbski, 2013).

In typical approach to such analysis, the cost-benefit analysis (CBA) is conducted. However, the results obtained by this method do not cover all aspects of the analysis (e.g. environmental loss, difficulties for residents, adjacent land use, etc.). As a result, more and more often the analysis is required that takes into account a greater number of variables affecting the choice of a variant, in which case it is necessary to apply multi-criteria analysis. However, this imposes the need to develop a reliable set of audit criteria and determine their importance in the decision-making process to obtain reliable and reproducible results (Budzynski and Kaszubowski, 2014; Kaszubowski and Oskarbski, 2013).

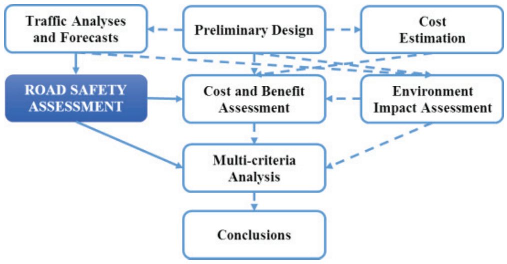

Fig. 1. RIA as an element of "Corridor study with the multi-criteria analysis" (Budzynski et al., 2011).

3.2. Measures of traffic safety assessment as part of a multi-criteria analysis

The authors (Budzynski et al., 2014b) proposed 7 main decision criteria: technical, functional, mobility, safety, economic, environmental protection and social protection using the AHP method. The paper (Budzynski and Kaszubowski, 2014) proposed 6 criteria: technical, transportation, safety, environment, complementarity and the accessibility of land. It can be seen in both cases that traffic safety is one of the key criteria that influences the selection of the preferred option of the road investment.

In case of the road safety criterion to evaluate the different options five measures were adopted as criteria for decision-making in multi-criteria analysis (Fig 2): *A*, *I*, *SI*, *F*, *AC*.

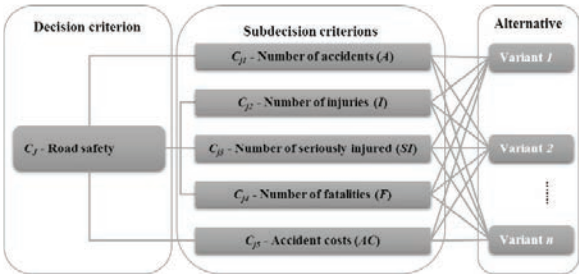

Fig. 2. Criteria and sub-criteria of road traffic safety in the AHP method.

3.3. The need to build tools to support the analysis of road safety

Development of the methodology and the construction of models for predicting accidents and casualties for both newly designed roads and the affected roads enabled the implementation of RIA as one of the elements of the road infrastructure safety management in Poland (Budzynski et al., 2013a, 2011). In the applied models of the relationship between sources of risk and losses in hazardous events, in addition to the exposure to risk variables (*L and ADDT*), the independent variables were included that could also have an effect on the risk level (share of trucks, built-up areas, the density of intersections or nodes etc.). This approach increases the quality of the fit of the estimated results from a model to empirical data. Additionally, in the case of analyses for newly designed roads, a designer is obliged to make such calculations for many variants and several forecasting periods. As a result the process of the analysis is long and complicated.

The Polish experience from conducted training in the implementation of the RIA manual have indicated a need for building tools to support the work of designers. Such tools will enable the automation of some calculation procedures which will improve the quality and reduce the time needed to perform such analyses.

For several years the PTV Group and other researchers have been working on the construction and implementation of tools to support the designers work, including elements of road safety (Basile and Persia, 2012; Brannolte and Münch, 2009; Laufer, 2014; McFarland, 2014) The PTV Visum Safety software package, in the initial phase, typically included a database of locations of accidents. The combination of the accident location data and road network data enabled both point and linear analyses. Software authors have developed two modules: the Black Spot Management (BSM) and Network Safety Management (NSM). BSM enables the identification of accident concentration, while NSM enables identification of sections with the highest risk level. Both of these modules are part of the solutions that are recommended in the Road Safety Directive (European Parliament and the Council, 2008).

The latest module in this tool is the Road Safety Impact Assessment (PTV Visum Safety's RIA). According to the description (Laufer, 2014) it enables the estimation of the risk level on both existing and newly design roads. Using PTV Visum Safety's RIA, developers can easily estimate the predicted number of accidents using simplified models of accident prediction depending on the adopted variants of road network development and traffic distribution in the network. The used models (developed for Switzerland) are based on traffic volume and road class. They do not include other independent variables that affect the number of accidents (e.g. share of built-up areas (*PBA*), share of heavy goods vehicles (*PHV*) or density of intersections (*DIS*)). In addition, this tool does not allow for the estimation of other road safety measures: the number of injuries and fatalities or accident costs. This approach does not allow for simple implementation of the PTV Visum Safety's RIA tool for Poland due both to the lack of selected road safety assessment measures and the necessity to use forecasting models built for Poland.

4. The concept of Safety PL – support tool for RIA

4.1. Methodology of RIA Implementation

The Road Safety Impact Assessment Method (Budzynski et al., 2011) in Poland consists of five stages. Each of the stages includes several consecutive detailed steps. The end result of the RIA is a report containing the results of analytical work on particular stages and the ranking of variants indicating the best variants in terms of road safety (fig 3):

- Stage I – Preparatory analyses. Their goal is to determine the impact area of a planned road and to prepare the input data that will be used in stages III and IV.
- Stage II – Analysis of the existing state of road safety. The purpose of this step is to identify existing road safety problems in the analysed area and to prepare information to describe the problems in the final RIA report.

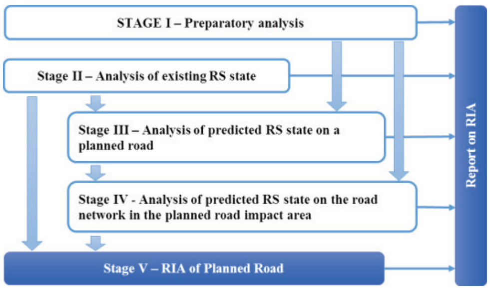

Fig. 3. RIA Stages (Budzynski et al., 2014a, 2011).

- Stage III – Analysis of the predicted state of road safety on the planned road, which together with stage IV, is the most important step in the RIA. The aim of the analysis is the calculation of road safety measures: *A*, *I*, *SI*, *F*, *AC* for the planned road, for a no-investment variant and to identify risk class. In the case of exceeding the risk limit level the particular variant of the planned road should be eliminated from further planning works or changes should be recommended that will allow for achieving an acceptable risk level.
- Stage IV – Analysis of the predicted state of road safety on the road network in the planned road impact area. The aim of the analysis is to determine the value of road safety measures for the network.
- Stage V – Road safety impact assessment of the planned road. The aim of the assessment is to calculate decrease in the level of road safety measures for the impact area of the planned road. This will enable the calculation of the number of points according to the adopted criteria for each of the variants, and establishment of the ranking of variants (Budzynski et al., 2011).

4.2. The concept of road safety measures modelling

4.2.1. The selection of road safety measures

The aim of building models (model construction) is to develop a tool that enables solving the task at hand, i.e. to answer the posed question (Leszczynski, 1990). In the RIA, modelling aims to create a tool using predictive models of accidents and casualties that will enable verification and evaluation of proposed solutions. Assessment and classification of variants for a new road together with the assessment of the impact of this road will offer the solution to the task.

An important element of a model construction process is correct selection measures for road safety impact assessment. Their choice is not arbitrary, it is contingent upon the adopted objectives of the works conducted and the available data (information about the site) that will help achieve this goal. According to the assumptions and multi--criteria analyses five measures of overall collective risk (CR_O) were adopted: *A, I, SI, F, AC,* representing the impact of road traffic elements on the level of road safety. To calculate them four measures of normalised collective risk (CR_N) will be used: *DA, DI, DSI, DF*.

An important element of a model construction process is correct selection measures for road safety impact assessment. Their choice is not arbitrary, it is contingent upon the adopted objectives of the works conducted and the available data (information about the site) that will help achieve this goal. According to the assumptions and multi--criteria analyses five measures of overall collective risk (CR_O) were adopted: *A, I, SI, F, AC,* representing the impact of road traffic elements on the level of road safety. To calculate them four measures of normalised collective risk (CR_N) will be used: *DA, DI, DSI, DF*.

The choice of methods used to predict the road safety measures is also conditioned by a set of available data describing the researched site. The most commonly used method for prediction of selected road safety measures is a statistical method. It consists in exploring the dependent variables based on trends and correlations observed while working on the model construction.

4.2.2. Design of the models

Drawing on the collective risk model methodology as described by Jamroz (Jamroz, 2011), partial models were developed to define collective risk on long road sections. This will help forecast these rates depending on the availability of factors:

- MCR_O-1 shows a two-component model used for calculating overall collective risk (CR_O^A). The estimated measures are the result of the risk exposure (E_L) and the probability of a dangerous event (P_{DA}) in a time unit. The model is described with the formula:

$$CR_O^A = E_L \cdot P_{DA} \tag{1}$$

- MCRO-2 shows a three-component model used for calculating overall collective risk (CR_O^I, CR_O^{SI}, CR_O^F). The estimated measures are obtained by multiplying the exposure to a risk of certain type (E_L), the probability of a dangerous event (P_{DA}) and the probability of occurrence of the selected victim type (C_{SVT}). The model is described with the formula:

$$CR_O = E_L \cdot P_{DA} \cdot C_{SVT} \tag{2}$$

Selecting the shape of the approximating function and its parameters. Based on a review of literature (Garber and Lei, 2001; Ivan et al., 2005; Ptak-Chmielewska, 2013; Rakha et al., 2010; Son et al., 2011; Wood, 2005; Ye et al., 2013), and previous research (Budzynski et al., 2011), it was agreed that selected measures of road safety on long road sections will be modelled using generalised models of linear regression. The model consists of three components: probability distributions of the dependent variable, linear predictor ηi and non-linear link function μ_i.

The probability distribution of the dependent variable is from the exponential distribution family. For the purposes of this work the gamma distribution was used. (Hassett and Stewart, 2006; Penn State's Department of Statistics, 2006; Ptak-Chmielewska, 2013). In the case of the gamma, the logarithmic form of the copula function was used. Based on this relation, the transformed formula is:

$$\mu_i = E(Y_i) = \beta_0 \cdot X_{i1}^{\beta_{i1}} \cdot \exp^{(\eta_i)} \tag{3}$$

Linear predictor η_i – linear combination of explanatory variables (Fox, 2008; Kiec, 2009; Reurings et al., 2005; Schafer, 2006):

$$\eta_i = \varepsilon + \beta_2 \cdot x_{i2} + \beta_3 \cdot x_{i3} + ... + \beta_k \cdot x_{ik} = \varepsilon + \sum_{i=2}^{k} \beta_k \cdot x_{ik} \tag{4}$$

where: μ_i, – vale of expected dependent variable, η_i – linear predictor, x_{ik} – observed non-random independent variables, β_i, – equation coefficient, ε – unobservable variable representing a component of random error.

By transforming risk models *MCR$_O$-1* (formula 1) we obtain:

$$A_i = L \cdot DA = L \cdot (\beta_0 \cdot T \cdot AADT^{\beta_1} \cdot \exp^{(\eta_i)}) \tag{5}$$

By transforming risk models *MCR$_O$-2* (formula 2) we obtain:

$$S_k = L \cdot D_K = L \cdot (\beta_0 \cdot T \cdot DA^{\beta_1} \cdot \exp^{(\eta_i)}) \tag{6}$$

where: A – number of accidents, S_k – the sum of the victims of the selected type (injuries, seriously injured, fatalities), *DA* – accidents density, D_k – density of the victims of the selected type (*DI* – density of injuries, *DSI* – seriously injured, *DF* – fatalities), L – section length, *AADT* – annual average daily traffic, T – road type.

The costs of accidents is the total value of both material and human loss in an adopted unit of time. The cost of accidents for any year is calculated with the formula:

$$AC_i = A_i \cdot UA_i + I_i \cdot UI_i + SI_i \cdot USI_i + F_i \cdot UF \tag{7}$$

where: AC_i – accident cost in a year, *UA* – unit accident cost in a year, *UI* – unit injured cost in a year, *USI* – unit seriously injured cost in a year, *UF* – unit fatality cost in a year (Jazdzik-Osmolska et al., 2012)

4.2.3. Procedure for the calculation of road safety measures

Stage III and IV are the most important stages in the entire RIA procedure. They are preceded by stage I, in which the impact area of the planned road is identified. The boundaries of the impact area should be established so as to unambiguously determine the beginnings and ends of analysed roads and limit the difference in the traffic volume sums at boundary points between different variants. All major roads should be divided into homogenous sections in accordance with the criteria (cross section, type of road, the approximate AADT, the junction with the national or regional road). Calculated average values of the variables describing the characteristics associated with road geometry and roadside (e.g. *PHV, PBA*, *DIS$_N$*, *DIS$_R$*, *RLA*) should be assigned to each homogeneous section.

The procedure is performed in a 3-group division, taking into account the class and type of road: single carriageway (G, GP, S 1×2) dual carriageway (G, GP 2×2), motorways and expressways (A,S 2×2, A,S 2×3, S 2 + 1). This approach stems from the significant differences in safety indicators, cross section, traffic volume, and different characteristics of geometry, accessibility and roadside.

The procedure consisting of 12 steps includes the calculation of all selected RS measures for each homogenous section throughout the entire analysis period (fig. 4). Steps S1 – S5 are associated with the preparation of data for each homogeneous section, which are used in the subsequent stages of the analysis. In the following steps S6 – S7, RS measures of normalised collective risk (CR_N): *DA, DI, DSI, DF* are calculated, which are the components of CR_O models calculated according to the formula 5 and 6 for measures *A, I, SI, F* (step K8). Calculated values of these measures allow for the estimation of the *AC* measure (step K9, Formula 7). In steps K10 – K11 feedback occurs and calculations are conducted for the subsequent years and homogeneous sections. The end result of the analysis (step K12) is the calculation of the sum of the values of the measures for each homogenous section, every road and the whole impact area (the planned road and all affected roads).

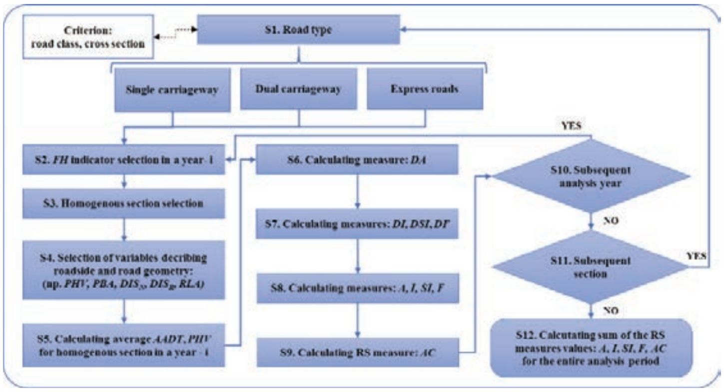

Fig. 4. Diagram of the procedure for calculating road safety measures.

4.3. Software PTV Visum as an element of Safety PL tool

The authors recommend using the PTV Visum software as one of the elements of the tool Safety PL – Support Tool for Road Safety Impact Assessment. The choice of the PTV Visum software has been dictated by the fact that it is the most commonly used tool for work related to the forecasts and analyses of traffic on newly designed roads in Poland. This approach will enable the use of the results of traffic forecasts for the entire impact area of the planned road, in the prepared models predicting accidents and casualties without the necessity to transfer them to other tools that support the calculation of road safety assessment.

The essential element preceding the calculation of road safety measures is preparation of data on homogeneous sections in the impact area. For this purpose, the PTV Visum programme will prepare attributes for all variables in the prepared prediction models of accidents and victims. These elements of work will correspond to steps S1–S5. Figure 5 shows an example of the assigned values in variables attributes and division into homogenous sections.

Calculation of road safety measures: DA DI, DSI, DF (step S6–S7), and A, I, SI, F, AC (step S8–S9) using prepared attributes will be conducted in the procedure sequence module. It allows for performing calculations with user defined equations (step S6–S8). The calculation process will be conducted for each of the three types of roads separately by using the automatic selection of the type of road.

Figure 6 shows an example of equation implementation to the A measure for single carriageway homogeneous sections in procedure sequence module (Kustra et al., 2015):

$$A_i = L \cdot DA = L \cdot 0{,}120 \cdot T \cdot AADT^{0{,}822} \cdot \exp^{(0{,}199 \cdot PBA - 0{,}230 \cdot PWS - 0{,}683 \cdot PAL + 0{,}453 \cdot (DIS_N + DIS_R) - 0{,}186 \cdot T + 0{,}624 \cdot RLA)} \quad (8)$$

where: *L* – length of road section, *T* – class, cross section, *AADT* – annual average traffic volume, *RLA* – location of road, *PBA* – share of built-up sections, *PAL* – share of sections with an additional lane for going straight ahead (additional), *PWS* – share of sections with wide pavement shoulder ⩾ 2m, DIS_N, DIS_R – density of junctions with national and regional roads.

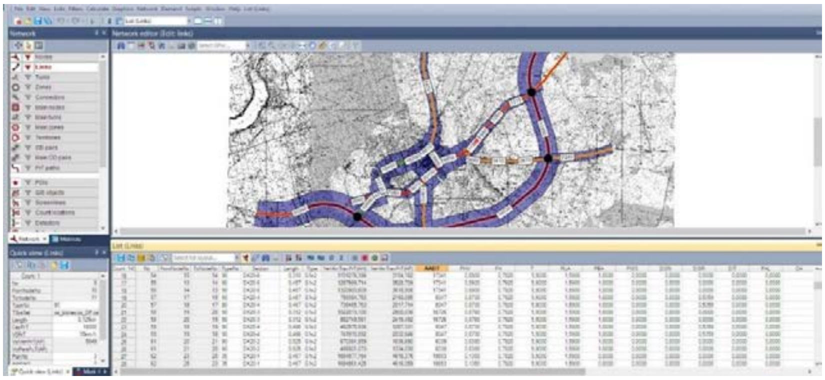

Fig. 5. Summary of variables describing the road traffic parameters on homogenous sections in the PTV Visum programme.

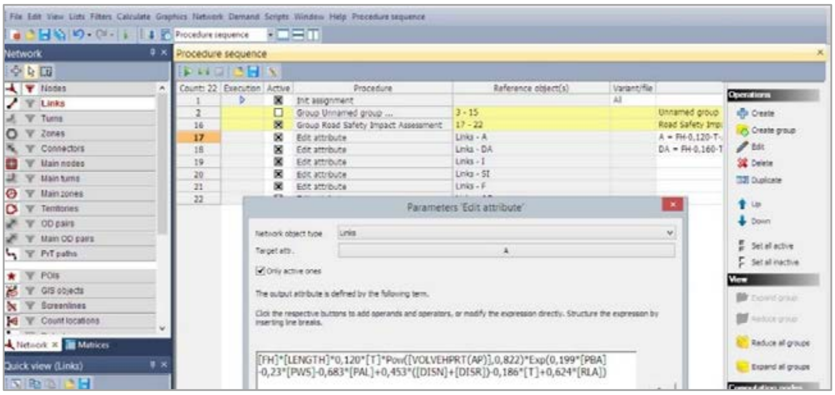

Fig. 6. Example of calculation procedure for the *A* measure in PTV Visum programme.

5. Summary

Implementation of the provisions of the EU Directive on the road safety management in Poland contributed to the development of selected tools and procedures. The impact assessment on the safety of the newly designed roads, audit procedures and safety inspections and classification of hazardous sections are developed and used for the national road network. In the case of the road safety assessment it is necessary, however, to implement prepared procedures for systems that facilitate and accelerate the process of conducting this analysis. The authors have presented the possibilities offered by the tool PTV Visum, combined with a prepared concept to include the results of undertaken research (models for predicting accidents, casualties and costs) in the calculation process of road safety assessment by the Safety PL module.

The next step might be the extending of the Safety PL module with models for specific types of accident (collision with a pedestrian, side, head-on and run-off-road collisions), and developing methods of estimating real hazards on the road network based on the characteristics of the roads and traffic.

References

Basile, O., Persia, L., 2012. Tools for Assessing the Safety Impact of Interventions on Road Safety. In: Procedia – Social and Behavioral Sciences. Elsevier B.V., pp. 682–691.

Brannolte, P.U., Münch, A., 2009. Software-based road safety analysis in Germany. In: 4th IRTAD Conference, Seoul, Korea. pp. 207–218.

Budzynski, M., Jamroz, K., Kustra, W., Gaca, S., Michalski, L., 2011. Instructions for road safety auditors – Part One Assessing the effects of road infrastructure projects on road safety, Part Two Road safety audit – for the GDDKiA. Gdansk University of Technology, Krakow University of Technology, Gdansk.

Budzynski, M., Jamroz, K., Kustra, W., Gaca, S., Michalski, L., 2013a. Instruction for rating high-risk sections on national roads – for the GDDKiA. Gdansk University of Technology, Krakow University of Technology, Gdansk.

Budzynski, M., Jamroz, K., Kustra, W., Michalski, L., 2014a. Tools for road infrastrukture safety management – Polish expiriences. Transp. Res. Procedia 3, 730–739.

Budzynski, M., Kustra, W., Jamroz, K., Gaca, S., Michalski, L., Guminska, L., 2013b. Method for forecasting road safety indicators for the purposes of economic effectiveness analyses for projects on Poland's national roads – for the GDDKiA. Gdansk University of Technology, Krakow University of Technology, Gdansk.

Budzynski, M., Kustra, W., Kaszubowski, D., 2014b. Multi-criteria analysis and expert assessment of variants of the location of the desinged new course of national road No. 91 – section of the east route from Daszyński Square to Grudziądzka St. in Toruń, with indication of the optimal variant. Gdansk University of Technology, Gdańsk.

Elvik, R., Vaa, T., 2004. The Handbook of Road Safety Measures. Elsevier.

European Commission, 2010. New road safety programme 2011-2020. Off. J. Eur. Union.

European Commission, 2011. Roadmap to a single European transport area – Towards a competitive and resource efficient transport system – White Paper. Off. J. Eur. Union.

European Parliament and the Council, 2008. Directive 2008/96/CE on road infrastructure safety management.

European Parliament and the Council, 2010. Decision 661/2010/EC on EU guidelines for the development of the trans-European transport network.

Fox, J., 2008. Applied Regression Analysis and Generalized Linear Models. SAGE Publications, Inc.

Garber, N.J., Lei, W., 2001. Stochastic Models Relating Crash Probabilities With Geometric And Corresponding Traffic Characteristics Data. University of Virginia, Charlottesville.

Hagenzieker, M., Wegman, F., 2010. Editorial safety science special issue road safety management. Saf. Sci. 48, 1081–1084.

Hassett, M.J., Stewart, D.G., 2006. Probability for Risk Management.

Hauer, E., 2005. The Road Ahead. J. Transp. Eng. 131, 333–339.

Ivan, J.N., Lord, D., Washington, S.P., 2005. Poisson, Poisson-gamma and zero-inflated regression models of motor vehicle crashes: balancing statistical fit and theory. Accid. Anal. Prev. 37, 35–46.

Jamroz, K., 2011. Method of risk management in highway engineering. Gdansk University of Technology, Gdansk.

Jazdzik-Osmolska, A., Kretkiewicz, B., Brenska, U., 2012. Methodology and valuation of road accident costs on the road network in Poland. IBDiM, Warsaw.

Kiec, M., 2009. The impact of the accessibility of the road on conditions and traffic safety – PhD thesis. Cracow University of Technology.

Koßmann, I., Schulze, H., 2010. The role of safety research in road safety management. Saf. Sci. 48, 1160–1166.

Kustra, W., Budzynski, M., Jamroz, K., Zukowska, J., 2015. Modelling of traffic safety indicators on Polish national road network. In: ESREL 2015 25th European Safety and Reliability Conference. Zurich, p. 7.

Laufer, J., 2014. Network management and the forecast of accident blackspot locations. In: 26th ARRB Conference – Research Driving Efficiency. Sydney, pp. 1–14.

Leszczynski, J., 1990. Modelling of Transport Systems and Processes. Warsaw University of Technology.

McFarland, K., 2014. Road infrastructure safety management. In: International Road Safety Seminar GAMBIT 2014. Gdansk, p. 10.

Penn State's Department of Statistics, 2006. STAT Lecture.

Polish Parliament, 2007. ACT of 25 January 2007 on the announcement of a uniform text of the Public Roads Act.

Polish Parliamen, 2012. ACT of 13 April 2012 amending the Public Roads Act and some other acts.

Ptak-Chmielewska, A., 2013. Generalised linear models. Warsaw School of Economic, Warsaw.

Rakha, H., Arafeh, M., Abdel-Salam, A.G., Guo, F., Flintsch, A.M., 2010. Linear regression crash prediction models: issues and proposed solutions, Virginia Tech Transportation Institute.

Reurings, M., Jannsen, T., Eenink, R., Elvik, R., Cardoso, J., Stefan, C., 2005. Accident Prediction Models and Road Safety Impact Assessment a state of the art, Ripcord. Ripcord – Iserest.

Ripcord-Iserest, 2005. Road Infrastructure Safety Management.

Schafer, J., 2006. Penn State Department of Statistics [WWW Document]. Dep. Stat. Eberly Coll. Sci. URL sites.stat.psu.edu

Son, H. "Daniel," Kweon, Y.-J., Park, B. "Brian," 2011. Development of crash prediction models with individual vehicular data. Transp. Res. Part C Emerg. Technol. 19, 1353–1363.

Technical Committee 13, 2004. Road Safety Manual. PIARC.

Technical Committee 18, 2004. Study on Risk Management for Roads. PIARC.

Thora Arnadottir, A., Barton, B., Chambon, P., Cullen, H., Gingell, D., Heuchenne, D., Jahn, C., La Monica, S., La Torre, F., Le Du, Y., Lerta, C., Ludvigsen, H., Magaro, G., Mangen, P., Marques, P., Matena, S., Moning, H., Muskaug, R., Passafiume, A., Pavcic, T., Rolland, N., Tsaglas, A., Ude, R., Breyer, G., M. Eichinger-Vill, E., 2008. Tools for Infrastructure Safety Management Fact Sheets and Common Conclusions. CEDR.

Wegman, F., Roszbach, R., Mulder, J., Schoon, C., Poppe, F., 1994. Road Safety Impact Assessment. SWOV Institute for Road Safety Research.

Wood, G.R., 2005. Confidence and prediction intervals for generalised linear accident models. Accid. Anal. Prev. 37, 267–73.

World Health Organization, 2009. European status report on road safety. WHO Regional Office for Europe, Copenhagen.

Ye, Z., Zhang, Y., Lord, D., 2013. Goodness-of-fit testing for accident models with low means. Accid. Anal. Prev. 61, 78–86.