HOW TO SIMPLIFY ROAD NETWORK SAFETY SCREENING: TWO CASE STUDIES

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ABSTRACT

Network screening is the first step of rational road safety management; based on the state-of-the-art research, it utilizes crash prediction models or safety performance functions. However, their development is demanding, since they require knowledge of traffic volume data for all evaluated segments and intersections. In addition, the whole screening process as well as its output is separated into segments and intersections, which may not be the most practical step from the perspective of a road administrator as the end user. In this regard, using a number of intersections per a segment length is a potential simplification which allows omitting separate modeling for intersections; although its performance is rarely tested. The aim of the paper is to follow the original UK application of the concept, while extending it not only geographically, but also in various road conditions (regional and national road network samples) and adding an assessment of the method consistency, which is important for the quality of network screening. The method was found feasible: predictions from a simplified model were closely correlated with predictions based on a combination of segment and intersection models; goodness-of-fit even improved, and consistency, in terms of overlapping between two rankings of the final segment lists, was also satisfactory. The simplified approach may thus increase the efficiency of network screening and enable wider practical application for Czech regional agencies.

Keywords: road safety, network screening, segments, intersections, regions

1 INTRODUCTION

Traffic accident occurrence is influenced by both global factors, such as drivers' behavior, vehicle state or weather conditions, and local factors (*1*). From the perspective of the end user, i.e. road administrator, the former are more interesting, since they are related to specific locations which may subsequently be treated. The first step of the road network safety management process is network screening (also referred to as an identification of hazardous road locations, network safety ranking, or hotspot identification), defined as a process by which the road network is screened to identify sites that require safety investigation (*2*). According to recommended practices (*3* – *5*), network screening employs crash prediction models (or safety performance functions, SPFs) and empirical Bayes (EB) approach. In the end a list is produced which enables ranking the locations from the most likely to least likely to reach a reduction in crash frequency through the implementation of countermeasures (*5*).

It has become a standard to develop SPFs for separate entities, typically intersections and road segments between them (*5* – *9*); however, this custom leads to two issues:

1. Network screening, based on such SPFs, is also separate for intersections and segments, and yields two lists in the end. During the allocation of the budget to safety improvements, choosing between investments into countermeasures on 5 segments or 5 intersections may be difficult.
2. SPF input data include traffic volumes (AADT), which are usually available for all major roads (from periodical traffic censuses), but rarely available for all minor roads. In order to develop intersection SPFs, the modeler then has to conduct additional traffic surveys to complete AADT data on all intersection legs, which increases the time and budget demands.

For both analysts and funding road administrators it would thus be beneficial to use such SPF development approach that would allow considering intersections and segments jointly, without having to collect AADT data for all missing intersection legs. In fact, such approach was explored as part of study by Mountain *et al.* (*10*) in 1996 – using data for approx. 3800 km of UK roads with more than 5000 intersections with minor roads (i.e. local distributors or access roads), they developed and compared two approaches: (1) modeling of segment and intersection crashes separately while summing the predictions, and (2) modeling of total crashes on segments including a predictor of the number of minor intersections per a kilometer, i.e. intersection density. The conclusion was that "there is nothing to choose between these approaches in terms of the quality of the estimates obtained" (p. 705). It is of interest that, according to literature survey, this modeling design has not become widely used.

The paper presents a study that focused on proving feasibility of the original UK approach on Czech road network. In order to extend the application in a different country with different safety performance, vehicle fleet, weather, and under various conditions, case studies were conducted for the network of national and regional roads. Given the practical focus on road administrators' network screening, the method consistency was tested additionally. The following section presents the data and methods followed by results, discussion and conclusions.

2 DATA AND METHODS

Two datasets were used for developing SPFs, partly based on authors' recent studies (*11 – 14*) in two neighboring regions in the southeast of the Czech Republic: rural sections were sampled from regional roads in South Moravia region, and national roads in Zlín region (see Figure 1; further referred to as SM and ZL regions). In both samples roughly half of the intersections were not covered by the National Traffic Census, i.e. lacking AADT data – this was the original motive to explore simplified approaches to network screening.

FIGURE 1 Location of South Moravia and Zlín regions within the Czech Republic (adapted from Wikimedia Commons).

The study approach followed the original UK study (*10*) in developing 3 SPFs:

1. for total crashes on segments, including intersection density (*'combined'* model)
2. for segment-only crashes, i.e. excluding intersection crashes (model *2a*)
3. for intersections (model *2b*)

The samples are visualized in Figure 2. The study objective was to compare predictions 1 (based on the combined model) and 2 (i.e. a sum of results from models 2a and 2b).

Explanatory values were

- for combined model: segment AADT, segment length, intersection density
- for segment-only model: segment AADT, segment length
- for intersection model: AADT on major and minor roads, number of legs, turn lanes

Consistently with the previous research (*6, 10, 15 – 19*), including authors' work (*13, 14, 20*), the following model forms were adopted:

$$N_{combined} = e^{b_0} \cdot \left(AADT_{segment}\right)^{b_1} \cdot (Length)^{b_2} \cdot e^{(b_3 \cdot Intersection\_density)} \quad (1)$$

$$N_{segment} = e^{b_0} \cdot \left(AADT_{segment}\right)^{b_1} \cdot (Length)^{b_2} \quad (2)$$

$$N_{intersection} = e^{b_0} \cdot \underbrace{\left(AADT_{major}\right)^{b_1}}_{F1} \cdot \underbrace{\left(\frac{AADT_{minor}}{AADT_{major}+AADT_{minor}}\right)^{b_2}}_{FR} \cdot e^{(b_3 \cdot \#Legs + b_4 \cdot Turn\_lanes)} \quad (3)$$

where $N_{combined}$, $N_{segment}$, $N_{intersection}$ are crash frequencies for combinations of explanatory variables segment AADT ($AADT_{segment}$), segment length ($Length$), intersection density, major and minor road AADT at intersections ($AADT_{major}$ and $AADT_{minor}$), number of intersection legs ($\#Legs$) and presence of turn lanes ($Turn\_lanes$); e is natural logarithm base, and b_i are regression parameters to be estimated in modeling. For the sake of brevity, AADT terms in Eq. 3 will be referred to as $F1$ and FR, as originally used in *17*.

Regarding the model form, it should be noted that more explanatory variables were often used in the literature. However, several authors also indicated that additional predictors were not always beneficial and using simple models may be sufficient (*21 – 23*). The same finding emerged from a recent authors' analyses (*12, 13*), which motivated the use of simple models, including only exposure (i.e. AADT and segment length) in Eqs. 1 and 2.

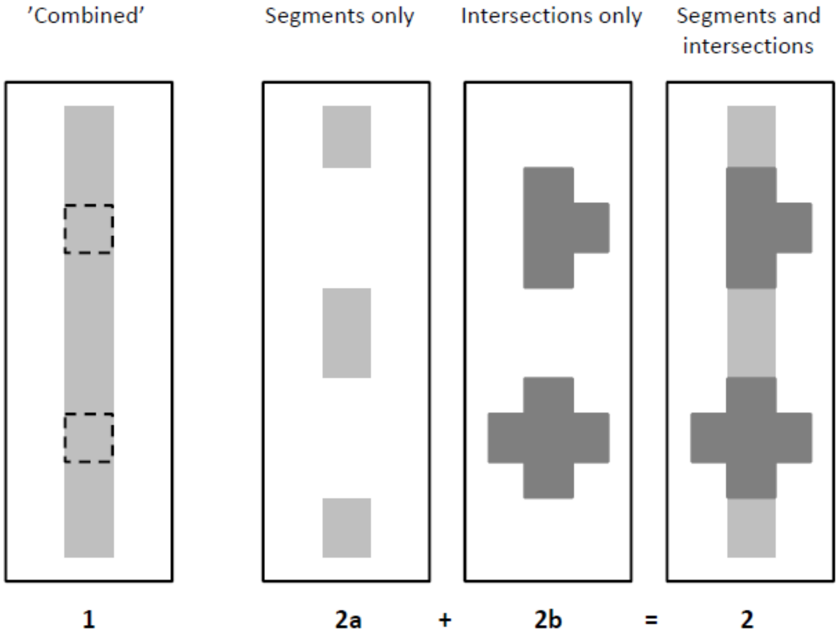

FIGURE 2 Visualization of principle of combined model, where intersections are considered only in terms of their frequency (1); segment model (2a); and model of individual intersections (2b).

Since the main objective was to verify the usefulness of intersection density, segments with at least 1 intersection were selected. However, AADT was not available for all intersections: 87% and 54% of them contributed to intersection SPFs for SM and ZL, respectively. For compatibility, intersection density was also computed using the number of intersections with available AADT only.

Crash frequencies related to injury crashes, which were reported to Traffic Police in a 6-year period (2009 – 2014). In order to determine intersection-related crashes, an influence area was defined using the radius of a circle around the intersection center. A radius threshold of 250 ft (approx. 76 m) was often used (e.g. *24 – 27*). However, Avelar et al. (*28*) studied the relationship between the crash locations and the probability of the crashes being associated with intersections and found that a threshold of 300 ft (approx. 92 m) minimizes the risk of underestimating the crash frequency. This threshold, rounded up to 100 m, was also used in the presented study: all crashes within 100-meter area around the intersection center were considered intersection crashes. The study only used typical (unsignalized) intersections – the signalized, interchanges, roundabouts and other types were discarded. The samples contained 3-leg intersections (in more than 75% cases) and 4-leg intersections.

A part of traffic volume data was retrieved from the National Traffic Census; the missing part was additionally surveyed using stationary radars. Collected short-term counts were adjusted according to Czech guidelines (*29*) in order to obtain the AADT. Other variables were gathered from Road and Motorway Directorate databases or on-line map sources. Table 1 lists descriptive characteristics of all explanatory variables.

TABLE 1 Descriptive Characteristics of Explanatory Variables for Both Samples

			SM (39 segments & 61 intersections)			**ZL (21 segments & 56 intersections)**		
			Min.	Max.	Mean	Min.	Max.	Mean
Continuous variables	Segment AADT [veh/day]		220	8,600	2,173	1,398	15,041	7,325
	Segment length [km]		0.50	9.70	2.61	0.23	9.81	3.11
	Intersection density [km^{-1}]		0.23	3.00	0.94	0.24	4.41	1.61
	Major road AADT [veh/day]		245	13,531	3,340	1,398	15,041	8,026
	Minor road AADT [veh/day]		16	3,570	600	27	4,131	887
				Freq.	%		Freq.	%
Categorical variables	Number of legs	= 3		48	78.7		49	87.5
		= 4		13	21.3		7	12.5
	Turn lanes	= Yes		7	11.5		23	41.1
		= No		54	88.5		33	58.9

In order to compare the samples with the original UK study (*10*), two comparable characteristics were selected. The UK study used road categories A-single, A-dual and B-single (urban and rural); only the rural were used for further comparisons:

- Mean intersection density (0.94 in SM, 1.61 in ZL) was approx. 1.2 for both A- and B-roads.
- Ratio of intersection crashes to all crashes (39.9% in SM, 15.2% in ZL) was approx. 25% for both A- and B-roads.

The values of both characteristics in the UK data are rough averages of values in SM and ZL samples.

Inter-correlations were checked and generally found low, therefore all explanatory variables were used. Models were built SPFs using a generalized linear modeling procedure in IBM SPSS, applying a negative binomial error structure with the logarithmic link function; explanatory variables with a power form in Eqs. 1 – 3 thus took the form of natural logarithms. Parameters of resulting SPFs are reported in Table 2.

TABLE 2 Parameters of Crash Prediction Models for Both Samples

		SM			ZL		
	Parameters	B	SE	Sig.	B	SE	Sig.
Model 1	(Intercept)	-5.507	0.786	0.000	-3.047	1.076	0.005
	ln_AADT	0.685	0.110	0.000	0.448	0.114	0.000
	ln_Length	1.584	0.135	0.000	0.991	0.157	0.000
	Intersection density	0.274	0.173	**0.112**	0.207	0.104	0.046
	(Overdispersion)	0.026			0.025		
Model 2a	(Intercept)	-3.851	0.778	0.000	-2.512	1.227	0.041
	ln_AADT	0.477	0.106	0.000	0.417	0.134	0.002
	ln_Length	1.418	0.142	0.000	0.887	0.169	0.000
	(Overdispersion)	0.001			0.062		
Model 2b	(Intercept)	-8.247	1.447	0.000	-8.557	2.475	0.001
	Legs = 3	-0.639	0.288	0.027	-0.656	0.319	0.039
	Legs = 4	0			0		
	Turn lanes = Yes	-1.278	0.396	0.001	(N.S.)		
	Turn lanes = No	0					
	ln_F1	1.302	0.182	0.000	1.176	0.274	0.000
	ln_FR	0.696	0.218	0.001	0.344	0.144	0.017
	(Overdispersion)	0.112			0.266		

Note: B – regression parameters, SE – standard errors, Sig. – level of statistical significance (N.S. reported for insignificant variable). Parameters of categorical variables are to be compared to a reference category, for which B = 0.

All variables have systematic influence at the level of statistical significance ≤ 5% (0.05). The only exception is intersection density (in bold), which achieved the level of statistical significance of 11.2% – this value may be accepted as approx. 10%. The signs of regression coefficients confirm expectations: AADTs and lengths are positive, i.e. their increase is associated with increasing crash frequency; the same holds for intersection density. The number of intersection legs has a negative coefficient suggesting that 3-leg intersections have lower crash occurrence compared to 4-leg ones; similar vein intersections with turn lanes seem safer than those without turn lanes. (Note that effect of turn lanes was found insignificant for the ZL sample.)

Regression coefficients may also be compared to the values in the original UK study. However, note that road categories may not be fully compatible, since UK A-roads were described as “roads of national or regional importance”, i.e. a potential mixture of national roads (ZL sample) and regional roads (SM sample), and B-roads “typically connect smaller centers of population” (*10*, p. 697). For the purpose of a comparison, A-roads values (averages of values for A-single and A-dual roads), were considered alternative to national roads in the ZL sample, and B-roads were considered alternative to regional roads in the SM sample. Regression coefficients of explanatory variables AADT, length, intersection density were compared, i.e. b_1, b_2, b_3 from Eqs. 1 and 2. The values are reported in Table 3 and visualized in Figure 3. The magnitudes are relatively comparable, with exceptions of regression coefficients for the segment length on regional roads (b_2) and for intersection density on both regional and national roads, which are higher compared to the same coefficients in UK models.

TABLE 3 Regression Coefficients of Described Models

		Combined models			Segment models	
		b_1	b_2	b_3	b_1	b_2
Regional roads	SM	0.685	1.584	0.274	0.477	1.418
	B-roads	0.614	0.808	0.104	0.644	0.808
National roads	ZL	0.448	0.991	0.207	0.417	0.887
	A-roads	0.614	0.986	0.104	0.644	0.957

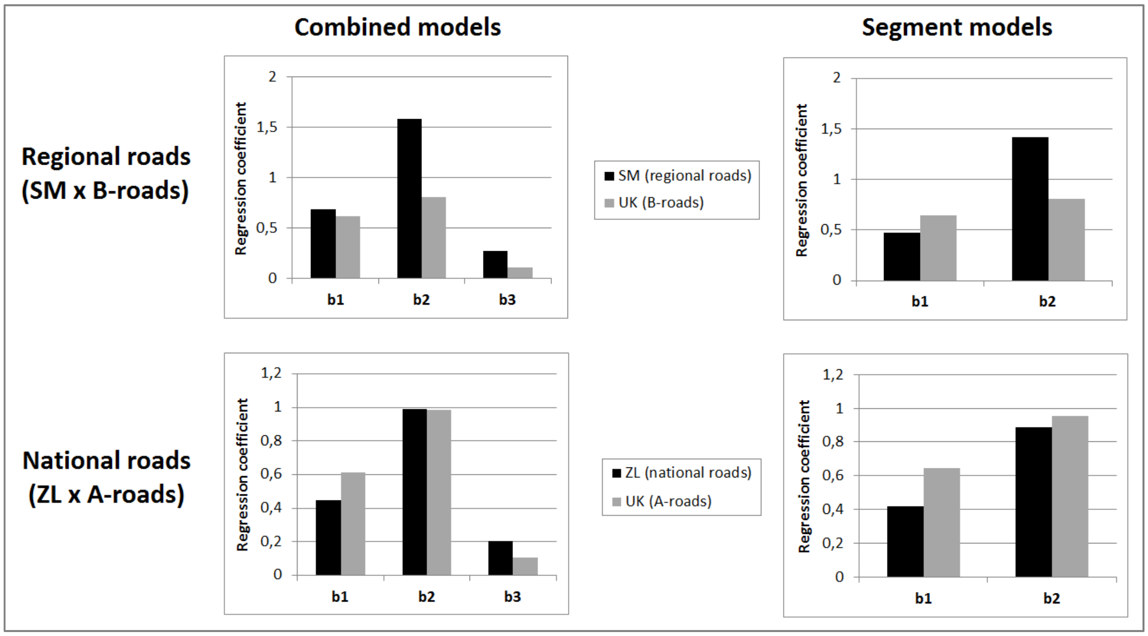

FIGURE 3 Graphical comparison of regression coefficients of described models.

In order to further investigate model quality, various goodness-of-fit measures may be used. For example Oh et al. (*25*) used five different measures to assess the external validity (Pearson correlation coefficient between observed and predicted crash frequencies, mean prediction bias, mean absolute deviation, mean squared prediction error, mean squared error), while noting that they all should be considered jointly. For the sake of brevity, a single indicator was used here – proportion of systematic variation in the original crash dataset explained by the model, also called Elvik index (*30*). This indicator was computed for models 1 and 2a in both regional samples.

Using the developed SPFs, *mean* crash frequency predictions (m) were obtained (m_1 and m_{2a} for each segment, m_{2b} for each intersection). However, as mentioned before, the objective was to assess the performance of the proposed simplified approach in terms of network screening. For this purpose, mean predictions were further adjusted according to empirical Bayes (EB) methodology (for explanation see *31*), which combines predicted and reported crash frequencies:

$$EB_i = w_i \cdot P_i + (1 - w_i) \cdot R_i \qquad (4)$$

$$w_i = \frac{k_i}{k_i + P_i} \qquad (5)$$

$$k_i = \frac{k}{Length_i} \tag{6}$$

where EB_i are EB estimates computed using the weighted average (with weights w_i) of predicted and reported crash frequencies (P_i and R_i). The overdispersion parameter (k_i) was computed as dependent on segment $Length$ (*32*). The obtained EB estimates for two segment models (1 and 2a) were compared in terms of consistency – i.e. an overlap between the segment list rankings based on models 1 and 2 (for more information on consistency tests see *12, 33 – 35*).

3 RESULTS AND DISCUSSION

The values of Elvik index are reported in Table 4, including a comparison with the UK study. The numbers are higher for combined models, which indicates their improvement compared to segment-only models. Explained systematic variance increases by 4% in both samples, which is comparable to 5% increase reported in the UK study.

TABLE 4 Values of Elvik Index of Described Models

Elvik index of…	SM sample	ZL sample	UK sample (*10*, Table 3)
- combined model (1)	99%	94%	60%
- segment-only model (2a)	95%	90%	55%

Predictions m_{2a} and m_{2b} were summed together and the results (m_2) were compared to predictions m_1. Graphs in Figure 4 display the relationship between predictions for both samples, in terms of the coefficient of determination (R^2). The results confirm a close positive relationship, with R^2 = 0.873 and 0.897 for SM and ZL, respectively. Pearson correlation coefficients were significant at the 0.01 level (2-tailed) for both datasets.

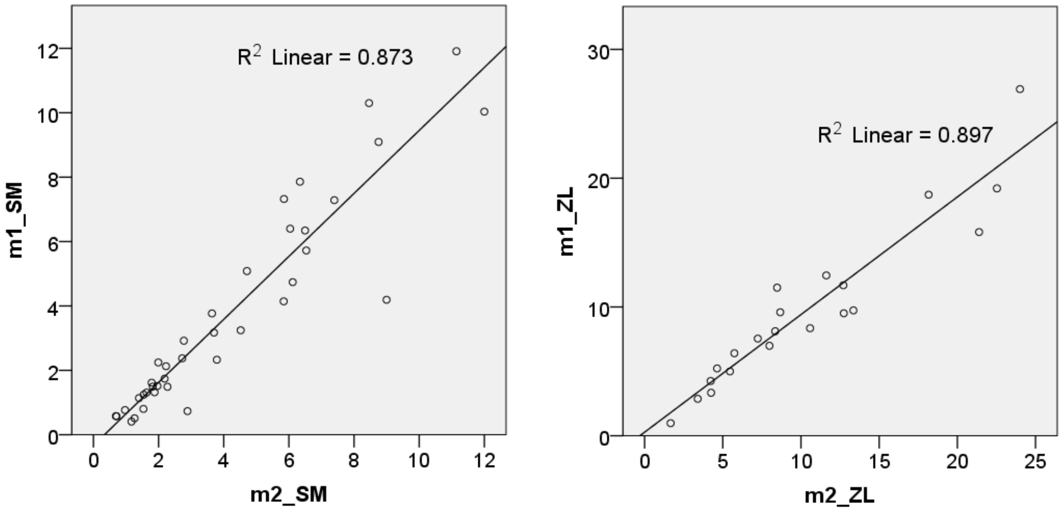

FIGURE 4 Relationships between segment-only predictions (m2) and simplified predictions (m1) for both South Moravia (SM) and Zlín region (ZL) samples.

Consistently with the original UK study, the developed simplified models seem to perform sufficiently in terms of both goodness-of-fit and correlation with traditional models. In addition, the method consistency was assessed for top segments with the highest EB estimates. The selected 10 segments in list 1 (segments ranked according to model 1) overlapped with 8 and 10 segments in list 2a (segments ranked according to model 2a), for SM and ZL samples, respectively. This equals to consistency is 80% and 100% for top 10 segments.

While the results seem encouraging, there is a limiting small size of the used samples. Nevertheless, the 3800-km UK sample from the original study is incomparable with conditions in the Czech regions, which include on average approx. 400 km of national roads and 1000 km of regional roads. In addition, neither all segments (only the ones which contained at least 1 intersection) nor all intersections (since part of them was discarded as non-standard) in selected regions were used in the presented study. Nevertheless, these reductions reflect real conditions and the study is thus illustrative. While the sample extension may be beneficial, it would need to rely on data from other conditions (road categories, intersection categories, regions, etc.), which could reduce the sample homogeneity.

4 CONCLUSIONS

For state-of-the-art network screening, as the critical first step of road safety management, safety performance functions (SPFs) are needed. However, their practical development is demanding, since it requires having AADT data for all evaluated units, i.e. road segments and intersections. In addition, the output, as well as the whole screening process, is separated into segments and intersections, which may not be the most practical from the road administrator's perspective. Using the number of intersections per a segment length (i.e. intersection density) is a potential simplification which would allow omitting data collection for intersection SPF – however, its performance has rarely been tested.

The aim of the paper was to follow the example of the original UK study (*10*) and verify the applicability of this approach in Czech conditions, both for regional and national road networks. The method was found feasible – simplified predictions with intersection density were very close to predictions based on a combination of segments and intersections; goodness-of-fit of simplified models even improved, and consistency, in terms of an overlap between two rankings of the final segment lists, was also satisfactory.

Based on these results, the approach based on intersection density seems promising. It allows performing the network screening without having to conduct additional traffic surveys to complement the missing AADT data on intersections. This simplification will increase efficiency of network screening and allow a wider practical application for Czech regional administrators. These will in turn provide material for study extensions in the future using bigger sample sizes.

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