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From reactive to proactive: Czech examples of development and application of alternative road safety assessment approaches

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Abstract

Traditionally, road safety assessment has been based on accident history. However, this approach may be biased, since accident occurrence is statistically rare and partly random. In this regards, various alternatives have been sought worldwide. The paper presents two examples of development and practical application of alternative road safety assessment approaches in the Czech Republic. The first example describes accident prediction models, which were developed firstly for secondary roads in several regions and secondly for core road network (motorways and national roads), and used for identification of hazardous road locations. The second example describes a different proactive technique, using speed consistency in order to identify hazardous curves. The wider use of these approaches will enable shifting from traditional reactive accident-based approach to proactive alternatives, which will improve quality and efficiency of Czech road network safety management.

Keywords: road network; safety management; proactive assessment; accident prediction model; speed consistency

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1. Introduction

In recent years, European Union (EU) road safety orientation has been steered by the EU Directive 2008/96/EC on road infrastructure safety management. The Directive introduces four procedures, including the one focusing on existing roads, namely "safety ranking and management of the road network in operation" (in the paper, shorter label "road safety assessment" will be used). According to the Directive, the assessment should take into account the number of accidents that have occurred in previous years per unit of road length in relation to the volume of traffic; and it should result in a priority list of road sections where an improvement of the infrastructure is expected to be highly effective (EC, 2008, Annex III).

The Directive description is rather short and provides space for users in EU countries to apply their own approaches. In addition, the described process is depending on accident history, i.e. accumulated frequency of accidents, although research has shown that that accident occurrence is also influenced by random variation (Hauer, 1997). Due to this effect, known as regression-to-mean, the road units (segments or intersections) identified as critical in one period, may not be critical in another period. The effect of these random fluctuations around a long-term mean may be corrected for by adding information on safety of similar units. The combination of the information contained in accident counts with the information contained in knowing the safety of similar entities (through using an accident prediction model) is known as empirical Bayes (EB) method, and is considered a state-of-the-art method of road safety assessment (Hauer et al., 2002; Elvik, 2008; Montella, 2010).

Nevertheless, with using accident-based (reactive) methods, one has to "wait for accidents to happen" before any analysis and conclusions can be made. This is why also alternative (proactive) approaches have been used, including for example surrogate measures called "traffic conflicts". However, traffic conflict techniques (TCTs) are usually limited to specific locations, typically intersections (for a review of TCTs and surrogate measures, see e.g. Zheng et al., 2014; Laureshyn et al., 2016; Sohel Mahmud et al., 2017).

CDV – Transport Research Centre has been recently successful in developing and applying alternative (proactive) road safety assessment approaches for the needs of Czech road agencies. The paper presents two such examples, focusing on the level of regional or national road network:

1. The first case describes development of accident prediction models and their application for network screening according to the EB method. CDV conducted such studies firstly for secondary roads in several regions and secondly for core road network (i.e. motorways and national roads). The network screening resulted in a list of hazardous locations, which was ranked and adopted by regional road agencies, to conduct subsequent field reviews and proposal of measures.
2. The second example describes a different proactive technique, using speed consistency in order to identify hazardous curves. The project, applied on national road network, utilized floating car data from vehicle fleets in order to determine speeds and speed consistency. For the critical curves, categorization and optimization in terms of consistent placement of traffic signing and marking was also proposed, and adopted by a national road agency.

2. Road safety assessment using accident prediction models

As mentioned in the introduction, accident prediction models (or safety performance functions, SPFs, in short "models") are required for application of empirical Bayes method. This is why the models have been recommended as state-of-the-art tools, enabling rational road safety management (AASHTO, 2010). They are mathematical equations, which link risk factors to safety performance. The models express the expected accident frequency and/or severity of a site (e.g. road segment or intersection) as a function of explanatory variables. These variables (risk factors) describe exposure and other characteristics, related to cross section, road design and other attributes. The typical model form is:

$$accident\ frequency = \exp(\beta_0) \cdot (exposure)^{\beta_1} \cdot \exp(\textstyle\sum_{i=2}^{n}(\beta_i \cdot x_i)) \quad (1)$$

where x_i are explanatory variables, β_0 is intercept and β_i (i = 1, 2, …) are regression coefficients. The coefficients cannot be estimated by the traditional ordinary least squares. In order to consider discrete and nonnegative character of accident frequencies, and their negative binomial probability distribution, generalized linear modelling (GLM) methods are typically used.

2.1. Accident prediction models for regional roads

Exposure is typically expressed in terms of traffic volume (annual average daily traffic, AADT) and, in case of road segments, also segment length. Regarding further factors (x_i in equation 1), an effort was made to collect and use data on a number of explanatory variables, such as curvature change rate (CCR), road width, presence of paved shoulders, speed limits, etc. Next, several model variants were compared in terms of their explanatory power, function forms and consistency (Ambros and Sedoník, 2016). As a result, it was found that relatively simple models, involving only AADT, length and CCR, are sufficient. The form of models was:

$$accident\ frequency = \exp(\beta_0) \cdot (AADT)^{\beta_1} \cdot (length)^{\beta_2} \cdot \exp(\beta_3 \cdot CCR) \qquad (2)$$

More information on regional road segment models is provided in previous papers (Ambros and Sedoník, 2016; Ambros et al., 2016). In addition, models for intersections should also be developed. The intersection exposure is given by a product of AADT on major and minor roads; therefore developing such models requires knowledge of AADT on all intersection legs. This may be a problem, since the minor roads are often not covered by the national traffic census, which is used as the main source of AADT data. A follow-up study (Ambros et al., 2017a) attempted an alternative approach, based on using a number of intersections per segment length ("intersection density"). It was found that predictions from this 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. This approach provides a simplification, compared to separate modelling of intersection accidents, having to additionally collect AADT on minor roads.

2.2. Accident prediction models for core road network

Compared to regional roads, which may be simply divided into segments and intersections, the core road network (i.e. motorways and national roads) is more complex, comprising both divided and undivided roads and various intersection types, such as roundabouts or interchanges. For the needs of national road agency, it was decided to develop seven models (*APM 1* to *APM 7*), as follows:

Motorways	National roads

• Interchanges
  o Conflict points (*APM 1*)
  o Ramps (*APM 2*)
• Segments (*APM 3*)
	• Intersections
	  o 3-leg (*APM 4*)
	  o 4-leg (*APM 5*)
	  o Roundabouts (*APM 6*)
	• Segments (*APM 7*)

AADT on motorway ramps was not included in national traffic census, and thus had to be additionally surveyed. National road intersections with minor roads (in model *APM 7*) were used in terms of their density, as described in paragraph 2.1.

Unlike the regional roads, the core road network consisted of both divided and undivided roads. On motorways (which are completely divided) and divided sections of national roads, segments in two directions were defined independently. Undivided segments comprised both directions.

Data on various variables was collected, for example:

- Interchange conflict points: type, traffic control, presence/absence of channelization by road marking, number of driving directions.
- Interchange ramps: length, ramp type, curvature and radius.
- Intersections on national roads: traffic control, presence/absence of turn lanes and bypasses.
- Roundabouts: number of legs, inscribed circle diameter, central island diameter, average of roundabout entry angles, average of deviation angles, width of circulatory lane, width of truck apron.
- National road segments: length and curvature change rate (CCR).

- In order to consider minor intersections on national roads, their number was used; analogically, number of accesses from petrol stations or rest areas was used on motorways. In addition, number of available parking space was used as a proxy for potential traffic flow to/from motorway rest areas.

Not all variables were statistically significant and thus included in the final models. The model equations for 7-year accidents are provided in Table 1.

Table 1. Core road network model categories and equations.

Model category *(model number)*	**Model equation for 7-year accident frequency** (with coefficients of categorical variables)
Motorway interchange conflict points (*APM 1*)	$\hat{N} = \exp(-7.760) \cdot \left(AADT_{major}\right)^{0.679} \cdot (AADT_{minor})^{0.324} \cdot \exp(type) \cdot \exp(signal)$ $type$: 3-leg 1.267, 4-leg 1.761, roundabout 1.327, merge 0.198, diverge 0 $signal$: unsignalized -0.585, signalized 0
Motorway interchange ramps (*APM 2*)	$\hat{N} = \exp(-5.845) \cdot AADT^{0.926} \cdot length^{0.649} \cdot radius^{0.001} \cdot \exp(curve) \cdot \exp(type)$ $curve$: curved 0.291, straight 0 $type$: collector -0.322, 2-way crossroad -0.726, 1-way crossroad -0.660, on-ramp 0.489, 2-way 0.246, roundabout -0.455, 2-way mainline 0.360, 1-way mainline 0.199, off-ramp 0.743, on-ramp + off-ramp 0
Motorway segments (*APM 3*)	$\hat{N} = \exp(-6.402) \cdot AADT^{0.981} \cdot length^{0.758}$
National road 3-leg intersections (*APM 4*)	$\hat{N} = \exp(-6.274) \cdot \left(AADT_{major}\right)^{0.637} \cdot (AADT_{minor})^{0.362} \cdot \exp(turning\ lane)$ $turning\ lane$: yes -0.173, no 0
National road 4-leg intersections (*APM 5*)	$\hat{N} = \exp(-4.663) \cdot \left(AADT_{major}\right)^{0.399} \cdot (AADT_{minor})^{0.480} \cdot \exp(control)$ $control$: yield -0.242, signals -0.293, stop 0
National road round-abouts (*APM 6*)	$\hat{N} = \exp(-4.560) \cdot (entering\ vehicles)^{0.714} \cdot \exp(-0.156 \cdot apron\ width) \cdot \exp(legs)$ $legs$: 3-leg -0.328, 4-leg 0
National road segments (*APM 7*)	$\hat{N} = \exp(-2.797) \cdot (AADT_{max})^{0.579} \cdot length^{0.808} \cdot \exp(0.114 \cdot minor)$ $AADT_{max}$ is maximum of involved sub-segments' AADT $minor$ is density of minor intersections (number per 1 km)

More details on Czech core road network modelling are available in a paper by Ambros et al. (2018).

2.3. Using accident prediction models in network screening

In case of both regional road network and core road network, the developed models were used to obtain predicted accident frequency for each segment (i). Empirical Bayes estimate of expected accident frequency (EB) was then calculated, using predicted accident frequency ($\hat{N}$), reported accident frequency (N) and length-dependent overdispersion parameter (Hauer, 2001). Finally potential for safety improvement (PSI) was obtained as a difference between EB estimate and predicted accident frequency (Persaud et al., 1999):

$$EB_i = w_i \cdot \hat{N}_i + (1 - w_i) \cdot N_i \qquad (3)$$
$$w_i = k_i/(k_i + \hat{N}_i) \qquad (4)$$
$$k_i = k \cdot L_i \qquad (5)$$
$$PSI_i = EB_i - \hat{N}_i \qquad (6)$$

where:

where:	EB_i	empirical Bayes estimate
	w_i	weight
	P_i	predicted accident frequency
	N_i	reported accident frequency
	k_i	overdispersion parameter
	L_i	segment length
	PSI_i	potential for safety improvement

Values of PSI were used for network screening and ranking. Descendent ranking enabled identifying hazardous locations in each category. The ranked list of locations were visualized in an online map and given to the road agency, which uses them to prioritize and perform necessary steps to improve safety of respective road networks.

3. Road safety assessment using speed consistency

The idea of consistency is that drivers are more likely to make fewer errors in the vicinity of geometric features that fit their expectations than in the vicinity of features that violate their expectations (Anderson et al., 1999). The variables for evaluating consistency are usually defined in terms of an operating speed (Gibreel et al., 1999). Various consistency measures have been used, with the most used one, developed by Lamm et al. (1999), defined in terms of speed reduction between successive design elements (tangents and horizontal curves). Using this concept, the Czech study, applied on rural sections of national road network, consisted of five steps:

1. In order to divide the studied network into tangents and curves, a novel method of automated segmentation was developed and applied (for details see Andrášik and Bíl, 2016).
2. Floating car data (FCD) were purchased and processed in order to obtain free-flow speed. The dataset consisted of GPS data points from approx. 1000 company vehicles, collected over 8 months. The speed was calculated from GPS location and the time interval between the points, given by the recording frequency 4 times per second. The speed was assigned to data points of each individual drives. Free-flow speed was estimated using cluster analysis and weighted average, based on number of data points. Regarding representativeness of speed data, only segments with at least 100 drives were used. The estimates were also compared to spot speed, which was measured by a roadside radar. In seven profiles, FCD-speed was on average by 2 km/h higher than the radar-speed.
3. Since floating car data did not cover the whole analyzed network, speed prediction models were developed, separately for tangents and curves, using data on length, cross slope, road/shoulder width, etc. In order to prove the models quality, validity of differences of estimated (predicted) speeds (i.e. speed consistency) against EB estimate of single-vehicle accident frequency was checked. Validation results, in terms of absolute values of speed difference (consistency), are displayed in Fig. 1. Values of EB averages form a clear rising trend, with the last bar (ΔV > 6 km/h) being by more than 50% higher than the first bar (ΔV < 2 km/h). This confirms that roads with minimal speed differences, i.e. maximal speed consistency, are the safest.

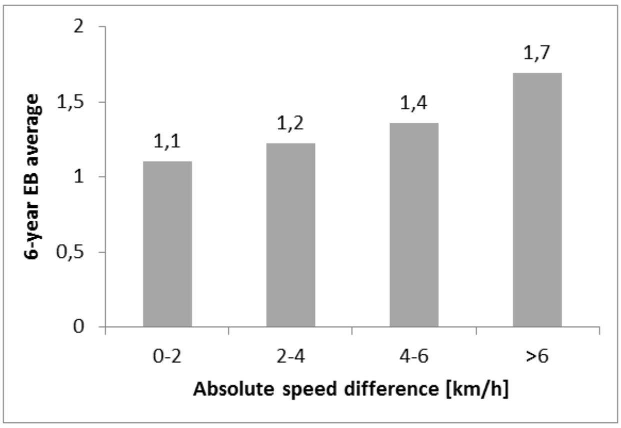

Fig. 1 Results of validation of absolute speed difference against long-term accident frequency (EB average)

4. The models were applied to obtain speed in the whole studied network. Subsequently, speed consistency ΔV was evaluated as follows:

$$\Delta V = V_c - V_t \qquad (7)$$

   where V_c is predicted speed in curve and V_t is predicted speed in preceding tangent.
5. Substandard curves were identified, using a procedure inspired by German design guidelines (FGSV, 2012), which introduce two fundamental graphs: (1) relationship of tangent length and following curve radius (L and R), and (2) relationship of two consecutive curve radii R_1 and R_2 (in case that the intermediate tangent length does not exceed 300 m). Conforming to these relation design rules assures that single design elements are not put together just arbitrarily. The adopted assessment approach consisted of the following steps:
   a. “Single element” assessment based on empirically set thresholds of speed consistency (Number 1 in Fig. 2).

b. "Relation design" assessment based on speed consistency adapted according to the German guidelines (Numbers 2 and 3 in Fig. 2).
c. Field inspection of assessed curves in order to investigate other influences, such as sight conditions, vertical alignment, vegetation, road surface, etc. Historical accident record may also be considered.
d. Combined assessment based on steps 1 to 3. For example when a curve is categorized as A class (in steps 1 and 2), but an adverse condition is identified during step 3, class is changed to B.

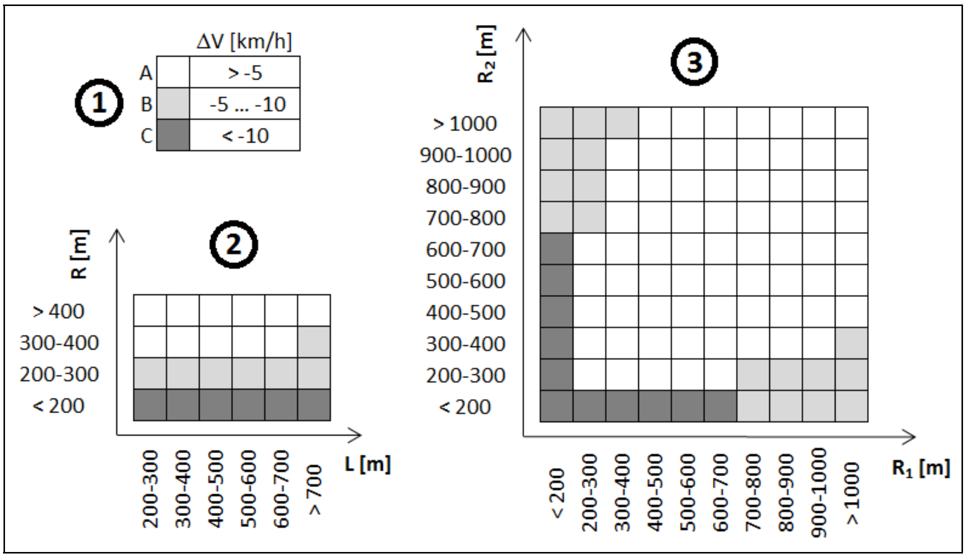

Fig. 2 Three assessment steps: (1) speed consistency, (2) tangent length *L* and following curve radius *R*, (3) radii of two consecutive curves

For A to C classes, consistent application of traffic control devices (signing and marking) was proposed (see Table 2); for D class, a reconstruction was recommended.

Table 2. Proposal of traffic control devices for each consistency class.

Class	Traffic control devices
A	broken centreline
B	warning sign, chevrons, solid centreline
C	retroreflective warning sign with advisory speed, retroreflective chevrons, double centreline

Note: Default traffic control devices (not listed in the table) are delineator posts and solid edgeline.

More details on the described speed consistency study are available in a paper by Ambros et al. (2017b).

4. Discussion and conclusions

As mentioned in the introduction, road safety assessments have traditionally relied on accident history (reactive approach). In contrast, the paper presented two examples of alternative (proactive) approaches. The empirical Bayes (EB) method, combining historical accidents with predicted accidents, is able to identify also potential hazardous road locations, where no accidents have yet occurred, which provides both proactive and reactive perspectives. The second example introduced speed consistency, obtained from floating car data, which was found to be statistically related to EB estimates, and thus providing a non-accident alternative of road safety assessment. Nevertheless, there is currently number of issues to be resolved in future, some of which will be listed:

- Czech road network length is limiting in terms of necessary sample sizes for developing accident prediction models. This also reduces chances of disaggregation models into individual severity levels or accident types. In addition, for models of specific intersection accident types, directional traffic volumes should be used instead of aggregated AADT.

- Compared to traditional spot-speed measurements, FCD has benefits of unlimited spatial coverage, as well as availability of historical data. However, data may not be sufficient in case of low traffic volumes. In addition, anonymity of FCD may limit the possibility of distinguishing different vehicle types or driver characteristics.
- Adopted speed consistency measure is relatively simple and may underestimate the real speed reduction (McFadden and Elefteriadou, 2000). Other indicators or speed profiles may be thus used to provide better insight. In addition, representativeness of speed behaviour may be biased by convenience sampling, uncertain definition of free-flow speed, or even the possibility of adapted behaviour. These may be reasons of relatively low explanatory power of developed speed prediction models, as also evidenced by other studies, for example Gaca and Kieć (2016) or Gitelman et al. (2017).

All pros and cons of the presented alternative approaches need to be carefully weighed, based on the requirements of specific tasks. For example, simple accident prediction models are sufficient for network screening, while for example multifactor analyses may require more detailed models. In the same vein, using FCD to illustrate speeding differences and trends may not be as data-hungry as using FCD to assess specific driving styles.

Nevertheless, the presented examples focused on using data for identification of hazardous road locations. This is especially valuable in current conditions of scattered accident occurrence, where traditional accident-based approaches do not perform well. Given these clear benefits, the results based on both presented methods have been approved by Czech road agencies and supplemented their decision making processes.

Other applications, such as road safety impact assessments, comparative evaluations or effectiveness studies, may also benefit from wider uptake of such proactive approaches. It is expected that future improvements will help shifting from traditional reactive accident-based approach to proactive alternatives, which will improve quality and efficiency of Czech road network safety management.

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