SAFETY SCREENING OF CZECH CORE ROAD NETWORK

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ABSTRACT

Czech motorways and national roads present the core road network, which is critical in terms of ensuring operation and maintenance, as well as safety. In this context, there was an interest in safety screening of Czech core road network, which necessitated developing safety performance functions for all types of network elements, and using them to identify and rank hotspots. Unlike a number of international studies, which usually dealt only with a selected road category, the study focused on the whole network, including intersections and interchanges. The authors conducted their own traffic survey, collected and processed all necessary data, and used it to develop seven safety performance functions. These not only enabled identification of hotspots, but also interpretation of effect of statistically significant risk factors. Obtained results were mostly consistent with literature, for example as to the effects of exposure variables; on the other hand, several variables did not have sufficiently significant effect (for example intersection channelization, parking space along motorway, or urban/rural location) or yielded unexpected results, for example regarding the effects of traffic control devices.

INTRODUCTION

Czech core road network consists of motorways and national (1st class) roads. This network carries the highest portion of traffic and connects the most important political and economic centers and recreational areas. With 0.7 km of roads per one square km, the Czech Republic has one of the densest networks in Europe (*1*), with density equal to the United States (*2*). This is challenging in terms of ensuring sufficient operation and maintenance, as well as safety, especially when the oldest part of the core network is currently undergoing a large-scale renovation.

In this context, there is an interest in safety screening of Czech core road network. Consistently with state-of-the-art literature, this necessitates developing crash prediction models (or safety performance functions, SPFs) for all types of network elements (road segments, intersections, interchanges, etc.), and using them to identify hazardous road locations (or hotspots). While this process is known and applied internationally, usually it does not cover complete road networks, which comprise a variety of different elements and thus require different SPFs.

The study, reported in the presented paper, aimed to conduct safety screening of complete Czech core road network. To this end, authors conducted their own traffic survey, collected and processed all necessary data, and used them to develop SPFs. These not only enabled identification of hotspots, but also provided interpretation of influence of statistically significant risk factors. The final ranked lists of hotspots were handed over to the road agency, which will use them to prioritize and perform necessary steps to improve safety of Czech core road network.

BACKGROUND

Network safety screening (also referred to as identification of hotspots or sites with promise) is defined as the process by which a road network is screened to identify sites that require safety investigation. As the first step of road network safety management process, it is one of the most frequent tasks conducted by road agencies (*3*). According to state-of-the-art practices (*4* – *6*), network screening should be based on empirical Bayes (EB) approach; in the end the list is produced which enables ranking the locations based on their potential for safety improvement (*7*).

EB technique improves reliability of safety estimation by combining predicted and recorded crash frequencies (*8*), the former being estimated with a safety performance function (SPF). In 2010, *Highway Safety Manual* (HSM) was published, introducing a number of US-specific SPFs. It was found that these SPFs are well transferable between the States (*9* – *11*); however, transferability outside of the US may not always be successful, as indicated by studies in Canada or Italy (*12* – *14*).

In addition, two interchange safety analysis tools (ISAT and ISATe) were made available through FHWA (*15*, *16*). As with HSM transferability, calibration of these tools may be uncertain. An Italian study (*17*) found that number of injury crashes, predicted by ISAT, was underestimated at one interchange and overestimated at another interchange. In addition, specific ramp configurations are not distuinguished; Torbic et al. (*18*) attempted applying ISATe to both loop and diamond ramps, and concluded that each of them requires separate calibration.

At the same time, for example several European countries have developed their own SPFs. However, they differ in their level of complexity: sometimes they are rather crash rates (i.e., implying linear relationship between AADT and crashes) and they often consider either segments or intersections only (for example Finland, Sweden or Germany, *19 – 21*). In Norway (*22*), intersections are considered in terms of density (number per kilometer) within segments.

In terms of data requirements, motorways (freeways) can be even more challenging due to complexity of interchanges. This is probably why motorway safety studies usually omit interchanges or consider them part of segments (e.g., *23 – 27*).

Given the variety of Czech core road network types, it was decided to develop seven SPFs for following groups of elements:

Motorways

- Interchanges
    - Conflict points (*SPF 1*)
    - Ramps (*SPF 2*)
- Segments (*SPF 3*)

National roads

- Intersections
    - 3-leg (*SPF 4*)
    - 4-leg (*SPF 5*)
    - Roundabouts (*SPF 6*)
- Segments (*SPF 7*)

Before developing SPFs, following points needed to be resolved:

1. Data preparation
2. Network segmentation
3. Definition of variables
4. Selection of SPF function form

These steps will be described in the following sections.

DATA CONSIDERATIONS

Step 1: Data preparation

Firstly, 2010 was set as a reference year, due to two facts:

1. At the time of project launch (2015), the last available national traffic census data (the basic source for AADT) was 2010.
2. Since 2011, the main motorway D1 between two largest cities Prague and Brno has been renovated. Year 2010 may be thus considered the last “uninfluenced” year.

To develop SPFs, three basic datasets are needed, which will be described in the following paragraphs.

Traffic data

Regarding traffic data, Czech national traffic census covers most of the core road network; however, it was observed that it does not include interchange ramps on motorways. Since this data is required for developing interchange SPFs, manual traffic counts needed to be performed on all ramps of approx. 450 interchanges (in more than 1,000 profiles). Each profile was observed for 2 hours of a working day; results were factored up to AADT of a reference year 2010, using national guidelines (*28*, *29*).

Also on national roads, national traffic census data was found incomplete. AADT was missing on large number of minor roads, which intersect national roads – therefore it would not be possible to develop intersection SPFs. Due to immense number of these intersections, it was not feasible to complement it with own survey. Therefore, simplified approach was taken, similar to the mentioned Norwegian practice – i.e., not considering intersections with minor roads as individual units, but in terms of their frequency. Feasibility of this approach was previously tested in two Czech regions and found satisfactory (*30*).

Crash data

Geo-located crashes have been collected by Czech Traffic Police since 2007, which makes it a suitable network-wide data source. However, this data is not routinely linked to the units of interest, for example interchange conflict points and ramps. In this study, this linkage was done manually in GIS environment. Unfortunately, location precision was to some extent limited, and did not allow for example distinguishing crashes in acceleration/deceleration lanes or merging zones. Therefore, instead of using them to develop separate models, they were considered a subset of road segment crashes.

Typically, 3-year period of crash data is used (*31*). However, since motorways have relatively low crash frequencies, 7 years of crash data (2009 – 2015) were used in the study. Neither severity levels nor crash types were distinguished.

Road data

Road data is digitally maintained by Road and Motorway Directorate's Road Databank and updated twice a year. This data was imported to authors' own GIS environment and used to obtain selected road parameters. Additional information was collected manually from public online maps, such as Mapy.cz or Google Maps. It was also assured that parts of network under renovation were removed from the sample.

Step 2: Network segmentation

For segmentation of road network, it is necessary to realize the consequences of various segment lengths. In case of using homogeneity principle (keeping constant values of explanatory variables within a segment), one may obtain too short segments (*33*). For network screening, it should be kept in mind that the follow-up on-site visits require manageable lengths (say, in units of kilometers). Therefore, the goal was to define logical segments, while also trying to minimize differences within the segments.

On motorways, average length of sections between interchanges was 5 km. These sections were thus taken as motorway segments. Subsequently, each interchange was split into conflict points (merging, diverging, crossing, etc.) and segments between them (ramps). On national roads, segments were defined in following steps:

1. Intersections with complete AADT data (on both major and minor roads) were identified. Segments were defined between these intersections, usually between two settlements.
2. In case of segments over 10 km, some of intermediate intersections (even with incomplete AADT data) were used to split the segment into two segments.

Note that data contained both divided and undivided roads. On divided sections, segments in two directions were defined independently. Undivided segments comprised both directions.

Step 3: Definition of variables

Selection of explanatory variables should be guided by a theory, or previously documented evidence. Apart from exposure, literature review indicated following typically used variables:

- on interchanges: horizontal alignment, ramp type (on/off), ramp length, area type (rural/urban), etc. (*34, 35, 32, 36, 37*)

- on road segments: geometric characteristics (alignment), cross-section parameters (lane, median and shoulder widths), roadside hazard rating, speed-related variables, pavement quality (*38, 39, 25, 40, 41*)
- on at-grade intersections: number of legs, lanes, turn lanes, type of traffic control device (signalized/unsignalized), intersection angle, sight distance, etc. (*42 – 46*)

Based on the review and previously described datasets, following variables were defined in this study:

- 7-year total crashes frequencies (all severity levels, including property-damage-only).
- AADT in national traffic census is reported as bi-directional (both for divided and undivided segments); for analysis it was considered as follows:
    - in undivided segments: bi-directional AADT
    - in divided segments: daily volume in each direction, i.e., half of AADT
    - in interchange conflict points: AADT of individual conflicting streams
    - at intersections: daily sum of entering vehicles, separately for major and minor roads (i.e., half of AADT)
    - at roundabouts: daily sum of entering vehicles in all legs
    - in national road segments, consisting of sub-segments with different AADTs: maximum AADT or average AADT
- Interchange conflict points were described by their type, traffic control device, presence/absence of channelization by road marking, and number of driving directions.
- Interchange ramps were described by their length, type, curvature and radius.
- For intersections on national roads, traffic control device and presence/absence of turn lanes and bypass lanes was recorded. Following previous Czech studies (*47*, *48*), roundabouts were further described by number of legs, inscribed circle diameter, central island diameter, average of roundabout entry angles, average of deviation angles, width of circulatory lane, and width of truck apron.
- National road segments were described by length and curvature change rate (CCR). In order to consider minor intersections, their number was used; analogically, number of accesses from petrol stations or rest areas was used on motorways. Both variables were used to calculate density (frequency per 1 km). In addition, number of available parking space was used as a proxy for potential traffic flow to/from motorway rest areas.

Motorway network is located primarily outside of urban areas. Intersections on national roads were described according to their rural/urban location. Road segments, which comprised mix of both conditions, were described by a ratio of location in urban areas (e.g., 0.3 means 30% and 70% of length in urban and rural area, respectively). The list of all variables, including their symbol, unit and data source, is provided in Table 1.

TABLE 1 List of Variables, With Their Symbol, Unit and Data Source

Element type	Symbol	Variable [unit*]	Data source**
Interchange conflict points	*N*	7-year total crash frequency	Police
	AADT_maj	AADT in major conflicting stream [veh/day]	NTC + own survey
	AADT_min	AADT in minor conflicting stream [veh/day]	NTC + own survey
	Type	Type of conflict point (merging, diverging, etc.)	online maps
	Signal	Traffic control device (unsignalized/signalized)	online maps
	Channel	Channelization by road marking (no/yes)	online maps
	Directions	Number of driving directions	online maps
Interchange ramps	*N*	7-year total crash frequency	Police
	AADT	AADT [veh/day]	NTC + own survey
	L	Length [m]	RMD
	Ramp	Type (on-ramp, off-ramp, etc.)	online maps
	Curve	Horizontal curvature (straight/curved)	own GIS
	R	Horizontal radius [m]	own GIS
Segments between interchanges	*N*	7-year total crash frequency	Police
	AADT	AADT [veh/day]	NTC
	L	Length [km]	RMD
	Access	Number of accesses per kilometer	RMD
	Parking	Number of available parking space	RMD
Intersections on national roads	*N*	7-year total crash frequency	Police
	AADT_maj	Major road AADT [veh/day]	NTC
	AADT_min	Minor road AADT [veh/day]	NTC
	Location	Location in rural/urban areas	online maps
	Control	Traffic control device (yield, stop, signals)	online maps
	Bypass	Bypass lane (no/yes)	online maps
	Turn	Turning lanes (no/yes)	online maps
	Legs	Number of roundabout legs	online maps
	ICD	Roundabout inscribed circle diameter [m]	online maps
	Island	Roundabout central island diameter [m]	online maps
	Entry	Average of roundabout entry angles [°]	online maps
	Deviation	Average of roundabout deviation angles [°]	online maps
	Circ	Width of roundabout circulatory lane [m]	online maps
	Apron	Width of roundabout track apron [m]	online maps
Segments of national roads	*N*	7-year total crash frequency	Police
	AADT_max	Maximum AADT [veh/day]	NTC
	AADT_avg	Average AADT [veh/day]	NTC
	L	Length [km]	RMD
	Urban	Ratio of location in urban areas	own GIS
	Minor	Number of minor intersections per kilometer	online maps
	CCR	Curvature change rate [gon/km]	own GIS

* 1 m (meter) = 3.3 ft; 1 km (kilometer) = 0.6 mi; 1 gon = 9/10°
** NTC = national traffic census; RMD = Road and Motorway Directorate of the Czech Republic

Table 2 summarizes numbers of elements and descriptive characteristics of their crash data.

TABLE 2 Numbers of Elements and Descriptive Characteristics of Their Crash Data

Element type	#	Min	Max	Mean	Sum
Motorways					
- Interchange conflict points	2,550	0	172	2.39	6,095
- Interchange ramps	3,636	0	178	3.03	11,029
- Segments	390	0	308	62.13	24,232
National roads					
- 3-leg intersections	582	0	126	7.13	4,149
- 4-leg intersections	104	0	56	13.15	1,368
- Roundabouts	67	0	110	11.69	783
- Segments	1,797	0	635	39.94	71,776

Step 4: Selection of SPF function form

SPF equation consists of two parts: (1) exposure, i.e., AADT (and length, in case of segments), and (2) risk factors. In literature, various forms of considering road segment risk exposure may be found, for example:

- both length and AADT in a power form (*38*, *49*, *50*): $L^{\beta_1} \cdot (AADT)^{\beta_2}$
- length as an offset and AADT in a power form (*15*, *16*): $L \cdot (AADT)^{\beta_1}$
- length in exponential form (*32*, *51*): $\exp(\beta_1 \cdot L) \cdot (AADT)^{\beta_2}$

In a previous Czech study (*52*), several SPF function forms were compared in terms of proportion of explained systematic variation, and SPF with power function of segment length proved better. Therefore, it was also chosen for this study. For intersections or conflict points SPFs, there is a relative consensus in literature (*53 – 55*): exposure is defined as a product of conflicting flows, i.e. $(AADT\_major)^{\beta_1} \cdot (AADT\_minor)^{\beta_2}$. SPF function forms adopted for this study, together with their linearized form, which will be used for modeling, were as follows:

- for segments:

$$\hat{N} = \exp(\beta_0) \cdot L^{\beta_1} \cdot (AADT)^{\beta_2} \cdot \exp\left(\sum_{i=3}^{n}(\beta_i \cdot x_i)\right) \quad (1)$$

in linearized form:

$$\ln(\hat{N}) = \beta_0 + \beta_1 \cdot \ln(L) + \beta_2 \cdot \ln(AADT) + \sum_{i=3}^{n}(\beta_i \cdot x_i) \quad (2)$$

- for intersections:

$$\hat{N} = \exp(\beta_0) \cdot \left(AADT_{major}\right)^{\beta_1} \cdot (AADT_{minor})^{\beta_2} \cdot \exp\left(\sum_{i=3}^{n}(\beta_i \cdot x_i)\right) \quad (3)$$

in linearized form:

$$ln(\hat{N}) = \beta_0 + \beta_1 \cdot \ln\left(AADT_{major}\right) + \beta_2 \cdot \ln(AADT_{minor}) + \sum_{i=3}^{n}(\beta_i \cdot x_i) \quad (4)$$

where: $\hat{N}$ … predicted crash frequency
L … segment length
$AADT$ … annual average daily traffic
x_i … other explanatory variables (risk factors)
β_i … regression coefficients, to be estimated in modeling

SPF DEVELOPMENT AND APPLICATION

The previously described data were used to calibrate the mentioned function forms, i.e., to estimate regression coefficients β_i and obtain SPF equations. Explanatory variables (x_i) were added stepwise, while controlling for achieved statistical significance and discarding non-significant variables. The process was performed using generalized linear modeling (GLM) procedure in IBM SPSS, with a negative binomial error structure and logarithmic link function.

In the following text, parameters of the developed SPFs are reported, followed by interpretation of their effects. Interpretation is based on signs of regression coefficients β_i, which show the direction of statistical relationship between a variable and crash frequency:

- *Positive* relationship means that change of a variable is associated with change of response variable in the same direction.
- *Negative* relationship means that change of a variable is associated with change of response variable in the opposite direction.

Effects of categorical variables are to be interpreted in comparison to the reference category (i.e., the one with zero regression coefficient) of the relevant SPF. Note that the effect magnitudes are not directly comparable across different SPFs.

Following information is further reported for each SPF:

- Achieved level of statistical significance (*Sig.*) of each variable. With few exceptions, its values are below 5%, which means at least 95% confidence level.
- Overdispersion parameter; its use will be explained in a section on safety screening.
- Proportion of explained systematic variation. Some studies reported values up to 80 – 90% (*24*, *56*), while other authors achieved lower levels, such as 40 – 50% (*32*, *40*). The developed SPFs had satisfactory values between 60% and 90%.

Regarding the effect of exposure variables (AADT and length), the values in all SPFs are relatively consistent with literature, which reports coefficients 0.4 – 0.8 for intersection SPFs and 0.6 – 1.0 for segment SPFs (*53*, *54*).

SPF 1: Interchange conflict points

TABLE 3 SPF 1 Parameters

Variable		β_i	*Sig.*
(Intercept β_0)		–7.760	0.000
Type	3-leg	1.267	0.000
	4-leg	1.761	0.000
	roundabout	1.327	0.000
	merge	0.198	0.001
	diverge	0	
Signal	unsignalized	–0.585	0.000
	signalized	0	
ln (*AADT_major*)		0.679	0.000
ln (*AADT_minor*)		0.324	0.000
Overdispersion		0.880	
Explained sys. var.		89.8%	

The SPF does not contain insignificant variables: Channelization by road marking and Number of driving directions.

Regarding types of conflict points, 4-leg points are associated with the highest risk. It is expected, as these are the crossing points, which are known as the most risky. On the contrary, minimal risk is associated with diverge and merge conflict points.

Unsignalized points are associated with lower risk, compared to signalized. While it may sound unexpectedly, the same was found also by other authors (e.g., *57*, *58*). The reason may be that signalization is usually applied in more complex conditions, with previous crash history, i.e. it is endogenous. Another explanation is that since the study uses crashes of all severity levels, which includes rear-end (usually property-damage-only) crashes, that are known to increase after introduction of new signals (*59*).

SPF 2: Interchange ramps

TABLE 4 SPF 2 Parameters

Variable		β_i	***Sig.***
(Intercept β_0)		–5.845	0.000
Curve	curved	0.291	0.000
	straight	0	
Type	collector	–0.322	0.174
	crossroad (two-way)	–0.726	0.000
	crossroad (one-way)	–0.660	0.000
	on-ramp	0.489	0.000
	two-way	0.246	0.026
	roundabout	–0.455	0.100
	mainline (two-way)	0.360	0.011
	mainline (one-way)	0.199	0.206
	off-ramp	0.743	0.000
	on-ramp + off-ramp	0	
ln (*AADT*)		0.926	0.000
ln (*L*)		0.649	0.000
R		0.001	0.012
Overdispersion		1.195	
Explained sys. var.		84.9%	

Curved ramps are associated with higher risk than straight ramps, as well as off-ramps, compared to on-ramps. Both findings are consistent with previous research (*32*, *36*, *60*). On the contrary, crossroads (i.e., the minor road segments above the mainline motorway) are associated with the lowest risk.

SPF 3: Motorway segments

TABLE 5 SPF 3 Parameters

Variable	β_i	***Sig.***
(Intercept β_0)	–6.402	0.000
ln (*AADT*)	0.981	0.000
ln (*L*)	0.758	0.000
Overdispersion	0.214	
Explained sys. var.	69.9%	

Neither density of accesses nor available parking space was statistically significant. AADT coefficient is close to 1, which indicates approximately 1:1 relationship to crashes.

SPF 4: 3-leg intersections on national roads

TABLE 6 SPF 4 Parameters

Variable		β_i	***Sig.***
(Intercept β_0)		–6.274	0.000
Turn	yes	–0.173	0.031
	no	0	
ln (*AADT_major*)		0.637	0.000
ln (*AADT_minor*)		0.362	0.000
Overdispersion		0.435	
Explained sys. var.		76.8%	

Presence of bypass lane and location in rural/urban areas were not statistically significant variables. Presence of turn lanes is associated with lower risk, compared to condition without turn lanes, which confirms their anticipated safety effect.

SPF 5: 4-leg intersections on national roads

TABLE 7 SPF 5 Parameters

Variable		$\boldsymbol{\beta_i}$	***Sig.***
(Intercept β_0)		–4.663	0.000
Control	yield	–0.242	0.070
	signals	–0.293	0.088
	stop	0	
ln (*AADT_major*)		0.399	0.000
ln (*AADT_minor*)		0.480	0.000
Overdispersion		0.201	
Explained sys. var.		64.3%	

Presence of bypass lane and location in rural/urban areas were not statistically significant variables. Neither presence of turn lanes was included in the SPF. Compared to the 3-leg intersection SPF, the reason may be in different safety effect of turn lanes at 3-leg and 4-leg intersections, as reported in literature (*59*).

Type of traffic control device suggests the highest risk at STOP signs. This may again be due to endogenous background of STOP sign installation, similarly to the previously mentioned effect of signalization.

SPF 6: Roundabouts on national roads

TABLE 8 SPF 6 Parameters

Variable		$\boldsymbol{\beta_i}$	***Sig.***
(Intercept β_0)		–4.560	0.067
ln (*AADT*)		0.714	0.002
Legs	3-leg	–0.328	0.037
	4-leg	0	
Apron		–0.156	0.032
Overdispersion		0.306	
Explained sys. var.		75.0%	

The SPF does not include several variables, which were not statistically significant: inscribed circle diameter, central island diameter, entry angles, deviation angles, circulatory lane width.

3-leg roundabouts are associated with lower risk, compared to 4-leg roundabouts, which is consistent with anticipated effect of number of conflict points. Increasing width of truck apron seems to decrease risk, which is consistent with a previous study (*47*). This effect may be due to reducing circulatory lane width and thus reducing driving speeds.

SPF 7: Segments of national roads

TABLE 9 SPF 7 Parameters

Variable	β_i	*Sig.*
(Intercept β_0)	–2.797	0.000
ln (*AADT_max*)	0.579	0.000
ln (*L*)	0.808	0.000
Minor	0.114	0.000
Overdispersion	0.365	
Explained sys. var.	75.0%	

Location in urban areas and curvature change rate were not statistically significant. Neither average AADT was significant, thus maximum AADT is used in the SPF. Effect of minor intersection density is associated with increasing risk, as expected, since these accesses create additional conflict points.

Using SPFs for safety screening

The developed SPFs were used to obtain predicted crash frequency ($\widehat{N}$) for each segment (i). Empirical Bayes estimate of expected crash frequency (EB) was then calculated, using predicted crash frequency, reported crash frequency (N) and length-dependent overdispersion parameter (*61*). Finally potential for safety improvement (PSI) was obtained as a difference between predicted crash frequency and EB estimate (*4*):

$$EB_i = w_i \cdot \widehat{N}_i + (1 - w_i) \cdot N_i \qquad (5)$$

$$w_i = \frac{k_i}{k_i + \widehat{N}_i} \qquad (6)$$

$$k_i = k \cdot L_i \qquad (7)$$

$$PSI_i = EB_i - \widehat{N}_i \qquad (8)$$

where:

EB_i	empirical Bayes estimate
w_i	weight
$\widehat{N}_i$	predicted crash frequency
N_i	reported crash 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. Given smaller sizes of 3-legs, 4-legs and roundabouts samples, they were combined into one group. Thus, descendent ranking enabled identifying hot spots in following five groups:

1. Interchange conflict points
2. Interchange ramps
3. Motorway segments
4. Intersections on national roads
5. Segments of national roads

The ranked list of locations were visualized in an online map and handed over to the road agency, which will use them to prioritize and perform necessary steps to improve safety of Czech core road network.

DISCUSSION AND CONCLUSIONS

The paper described the study, which focused on developing SPFs for safety screening of Czech core road network. Unlike a number of similar international studies, which usually dealt only with a selected road category, the study collected data and developed SPFs for complete motorway and national road network, including intersections and interchanges.

Final seven SPFs not only enabled identification of hotspots, but also provided interpretation of influence of statistically significant risk factors. Effect of exposure variables (AADT and length) was consistent with literature, as well as for example number of legs, ramp curvature or ramp type. On the other hand, several variables did not have sufficiently significant effect (for example channelization, parking space along motorway or intersection bypass lanes). Unexpectedly, this was also a case of location (urban/rural). Nevertheless, previous studies (e.g., *62*) indicated that common urban/rural dichotomy may not fully capture the real differences. Alternatives include for example using population density of commuting flows.

The SPFs also indicated effects of selected categories, for example STOP sign or intersection signalization, which were not in line with expected safety benefits. This may be due to endogeneity, i.e., the fact that these devices are often installed at locations with crash history or other risk factors, which were not controlled for in the SPFs. In addition, using total numbers of crashes may mask the effect of such factors which influence specifically one of severity levels.

It is important to note, that the reported effects are only associations; in order to capture causal effects, one would need to conduct before-after studies. Another caveat is that although original dataset was relatively large, there is always a risk of omitted variable bias. Examples of variables, which were not taken into account, may include for example speed behavior.

Nevertheless, the current study helped establishing the ranked list of hotspots to be selected for further treatment. Follow-up studies may focus on future SPF updating and improvements (for example by adding some less available data such as grade, vertical alignment, pedestrian traffic or land use), as well as development of crash modification factors to be used in selecting the most suitable countermeasures.

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