LINKING RURAL ROAD ENVIRONMENT, SPEED AND SAFETY FACTORS WITH A 'TWO-STAGE' MODEL: A FEASIBILITY STUDY

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ABSTRACT

Speed on two-lane rural roads is a critical safety issue. In this regards various research perspectives have been adopted, including speed models (relating speed to design consistency factors) and safety models (which estimate safety using exposure data and design consistency variables). Unfortunately both approaches have often been carried out separately, and influences on speed choice have been limited only to geometrical variables. In contrast safety models are often expanded with wide array of exposure and risk factors.

The study aims to investigate the issue of speed and safety from a different perspective, using so called 'two-stage' model which estimates speed (using more explanatory variables) and further applies it in a simple safety performance function. This approach can be superior to the traditional approach as it preserves model parsimony while capturing the most important safety effects. The specific objective of the study is to prove feasibility of a 'two-stage' model in linking environment, speed and safety factors on a sample of Czech rural roads.

To this end, data collection was carried out on approx. 100 km (60 mi) of two-lane rural roads in the Czech Republic, using speed data from instrumented vehicle, manually collected road environment data, as well as crash and exposure data retrieved from national databases. Both models are developed, described and compared to the literature. It is concluded that approach is feasible, in spite of several current limitations. Planned further improvements and future practical applications are also listed.

1 INTRODUCTION

Operating speed models

Speed has been a critical issue within the traffic field; it was even described as one of the most important factors that road users consider in relation to convenience and efficiency of a certain route (*1*). Speed is also a key consideration in the geometric design and has a central role the road life cycle (*2*). At the same time speed has been recognized as the most influential risk factor (see *3*, *4* or *5* for a review) – on Czech roads speeding (e.g. excessive and inappropriate speed) has been attributed to almost half of fatal road crashes, making it the most frequent cause of road deaths.

A host of road environment factors have been known to influence speed choice, including effects of road geometry, alignment, cross-section and roadside (*6*, *7*, *8*). A synthesis of Dutch studies (*9*) sums up also other road features which lead drivers to higher speed, such as presence of road marking or low density of alongside vegetation.

Within the field of traffic engineering, the concept of operating speed is of high importance. According to seminal TRB synthesis (*1*), the assessment of operating speeds enables to assess the expected speed changes of individual vehicles over successive road elements (tangents and curves). Inconsistency of operating speeds (for example differences between speed in tangent and curve) is regarded one of the symptoms that violates driver's expectation. Because consistent operating speeds are thought to be a product of consistent design, variables for evaluating design consistency are usually derived from operating speed (*10*, *11*). With this focus large body of research has been devoted to modeling operating speed as a function of road parameters; among these horizontal curve radius or its transformations (inverse radius, degree of curve, curvature change rate, etc.) have been known as the most significant factor (*1*, *12*, *13*).

Therefore majority of models have included only horizontal curve radii or some of its derivatives; in spite of the fact that speed is very complex issue influenced by a number of other environmental variables, as mentioned in the previous text. For example the width (both road width and lane width) is regarded very influential cross-section parameter (*14*), however it has been included in few operating speed models only: a summary of North American operating speed studies (*1*, Table A-1) presents 23 models, of which 18 feature radius, while only 2 models consider road width.

It is worth noting that complete dependence of speed on road geometry is not always assured. For example Porter et al. (*2*) mention that geometric design decisions may not influence speeds unless very constrained dimensions are used.

Safety performance functions

Apart from the mentioned speed models, significant research efforts have also been devoted to development of so called safety performance functions (SPFs) or crash prediction models. These models provide relationships between crashes, exposure (e.g. traffic volume and segment length) and other potential risk factors (explanatory variables). Within focus of this study it is important that some SPFs also include variables related to speed, alignment or design consistency variables (for example *10*, *15 – 19*). Consistency variables, used in these models, are usually computed through operating speed models, which were mentioned in the previous paragraph. Development of these SPFs thus involves two models – in the further text they will be referred to as *speed* models and *safety* models. Table 1 shortly summarizes variables, which were used in the mentioned SPFs.

TABLE 1 Summary of Explanatory Variables Used in Several Speed and Safety Models

Study	Explanatory variables[1]	
	Speed model	Safety model
Anderson et al. (*10*)	*R*	*AADT, L,* 4 consistency measures
Ng and Sayed (*15*)	*R*	*AADT, L, V*
Cafiso et al. (*16*)	*W, CCR*	*AADT,* 4 consistency and alignment measures
Camacho-Torregrosa et al. (*17*)	*R*	*V*
de Oña et al. (*18*)	*R*	*AADT, L, V*
Montella and Imbriani (*19*)	*R, CCR, G,* L_T	*AADT*, up to 5 consistency and alignment measures

[1] Abbreviations: *R* – radius; *W* – width; *CCR* – curvature change rate; *G* – vertical grade; L_T – length of preceding tangent; *AADT* – traffic volume; *L* – length; *V* – speed consistency measure.

From Table 1 it is evident that some speed models rely on explanatory power of a single variable (horizontal curve radius). In contrast some of safety models introduce a large number of variables; some even applied the same variables in both models at the same time.

'Two-Stage' model

The above review on speed and safety models demonstrate that while speed models are usually kept parsimonious, safety models may be relatively complex. In this regards an interesting approach has been recently applied by Chen et al. (*20*) in studying interrelationships of geometry, speed and safety on roundabouts. They developed a 'two-stage' model – firstly approach speed was modeled, which is applied in a crash prediction model in the second stage. According to the authors, such an approach can be superior to the SPFs directly containing design variables as it preserves model parsimony while capturing the important safety effects of design changes. It means that, as opposed to the models in the previous paragraphs, speed model (stage 1) include more variables, while safety model (stage 2) is parsimonious.

The objective of this study is to prove feasibility of development and application of a combination of speed and safety models (in so called 'two-stage' model) in the study of environment, speed and safety factors on a sample of Czech rural roads. The two stages will be as follows:

1. Using road environment factors to estimate speed on a segment (speed model). Estimated speeds on individual tangents and curves will be used to compute indicator of speed consistency (as a difference between the speeds in tangent and curve).
2. Speed consistency indicator will be used as additional explanatory variable in safety performance function (safety model) in order to predict expected crash frequency.

Compared to previous applications of SPFs with design consistency variables (Table 1), the proposed approach will have some novel features.

- As opposed to simple speed models (often based on one variable only), speed model will consider influence of more variables, which are known to impact driving speed choice. Curvature change rate (CCR) will be used as one of explanatory factors, since is seen as the most successful parameter in explaining much of the variability in operating speeds (*21*); other factors will consider not only road geometry or alignment, but rather broader road environment. Different speed models will be developed separately for tangents and for curves.
- In contrast, safety model will be developed as much as simple as possible. The objective is to achieve parsimony (in a number of variables and one function form common for both tangents and curves), as opposed to some complex functions illustrated in Table 1, some of which are further distinguished between tangents and curves.

The following section 2 describes data collection and characteristics and methods used to develop the 'two-stage' model. Results are reported in section 3, together with descriptions of several comparisons. The final section 4 brings discussions and conclusions, aiming to assess the achieved feasibility, further improvements and potential practical applications.

2 DATA AND METHODS

Study location

The authors' intention was to apply the introduced concept on a sample, which will be representative of the most critical settings within Czech road network. To this end, disaggregated Czech Traffic Police data were studied. Figure 1 provides a division of Czech road fatalities counts by road settings (rural or urban roads), road network elements (segments or intersections) and their categories: motorways, national roads (1st class roads) or regional roads (2nd and 3rd class roads).

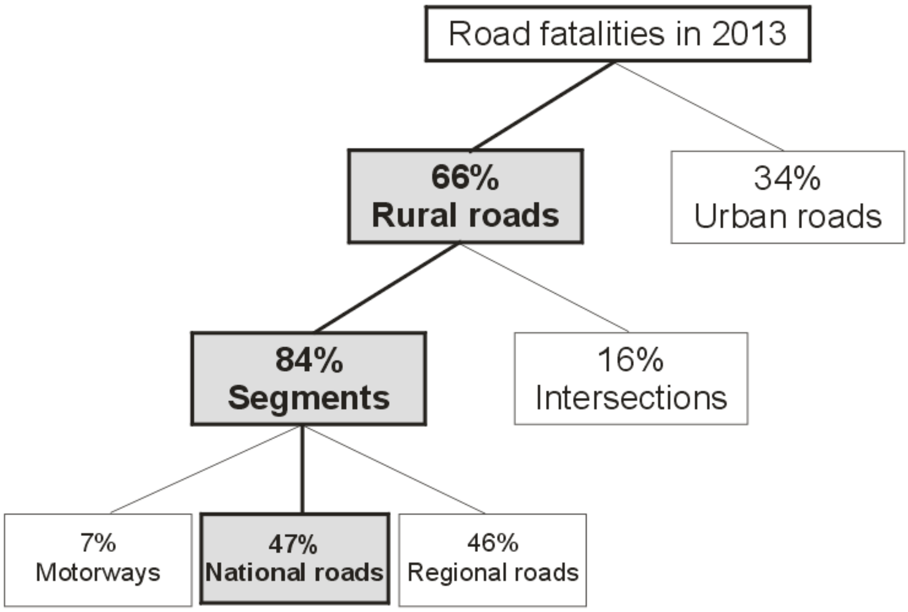

FIGURE 1 Division of Czech road fatalities counts by road settings according to 2013 police data.

Each level of graph provides several blocks describes in terms of percentages of road fatalities in 2013. The most critical settings (in grey blocks) is rural segments of national roads. Specifically in this category, approximately 40% of fatalities are related to curve crashes; within these crashes on national roads speeding was attributed as the main cause of almost 40% of fatalities.

Given this focus, the study sample was chosen in one of the Czech regions (Kraj Vysočina). Of 5 national roads in this region, the two roads (No. 19 and 34) with the highest traffic volumes and risk were selected for the study. The roads are paved, two-lane, undivided, approximately 7 meters (23 ft) wide. Approximate traffic volume (AADT) is between 5,000 and 10,000 vehicles and general speed limit is 90 km/h (54 mph). After excluding the road sections in built-up areas (through-roads), their total length was approximately 100 km (60 mi).

Speed and alignment data

The roads in question were driven through in two weekdays in November 2013, in one direction, as close as possible to free-flow speed. The inspection vehicle of CDV – Transport Research Centre (Centrum dopravního výzkumu, v.v.i.) was used for this purpose, instrumented with several position sensors (gyroscope, accelerometer, odometer) as well as controller area network (CAN) bus, whose data are synchronized and positioned using a precise GPS with the frequency of 10 Hz. At the typical speed of 90 km/h (54 mph) the speed synchronization period equals to 2.5 m (8.25 ft) of driven distance.

In the Czech Republic it is difficult to obtain periodically updated and precise road design plans. Thus a method had to be developed in order to obtain alignment parameters and conduct segmentation into tangents and curves. The development and the pilot (non-automated) application of the methodology is described elsewhere (*22*); for this study it was programmed into an in-house web module in order to ensure its semi-automation and wider application. The employed calculation procedure consisted of several steps:

- Transformation of GPS data points into the Czech planar coordinate system JTSK.
- Calculation of distances and angles between points in order to calculate radii and lengths for each three consecutive points.
- Calculation of curvature change rate (CCR).
- Segmentation of data points into tangent and curve sections using CCR threshold; based on several sensitivity tests, its value was set at 80 gon/km. The process resulted in 316 segments: 158 tangents and 158 curves.

In terms of design consistency, each segment may be characterized by its values of speed and CCR. Given the sampling frequency of used GPS technology, both speed and CCR change continuously within segments. In order to smooth out the speed and CCR values 85th percentile of speed (V_{85}) and 85th percentile of CCR (CCR_{85}) were determined for each segment.

Road environment data

Based on the review of speed factors in the first section of the paper, several of them were chosen as candidate explanatory variables. To this end, data on following variables for each segment were manually collected using Google Maps (with in-house web environment based on Street View, developed with Google Maps API) and categorized as follows:

- *Roadside vegetation:* none or bushes; single trees; trees in a row or forest.
- *Road marking* (separation of driving directions): no line or broken line; solid line.
- *Delineator posts:* absent; present.
- *Guardrails:* absent; present.
- *Vertical grade:* absent (flat); present (slope).
- *Roadway width.* This data were extracted from road database data maintained by Czech Road and Motorway Directorate and assigned to individual segments. Where values were changing within a segment, an average value was used. Afterwards it was categorized, based on Czech road width categories (7.5, 9.5, 11.5 meters; i.e. approx. 25, 31 and 38 ft) into following four width classes: 7.5 m or less; 7.6 – 9.5 m; 9.6 – 11.5 m; 11.6 m or more.

Crash and exposure data

In studies related to driving behavior, speed and alignment, various authors use different crash types for their analyses. For example Anderson et al. (*10*) used both single- and multi-vehicle crashes but excluded, among others, crashes with animals. Turner et al. (*23*) combined loss-of-control and head-on crashes; as well as Dietze and Weller (*24*) who used only single-vehicle and overtaking crashes. In this study all single-vehicle crashes were used. In total 5 years (2009 – 2013) were considered, taking into account crashes of all severity levels (property damage only, slight/severe/fatal injury). Using this definition, georeferenced crashes on selected roads were retrieved from the Police database and assigned as a crash frequency to each segment.

As a risk exposure indicator, traffic volume data (AADT) were retrieved from the National Traffic Census data of the Czech Road and Motorway Directorate. For curves, length of preceding tangent was added as another factor. Descriptive statistics for all the mentioned data are listed in following Tables 2 and 3, separately for curves and tangents.

TABLE 2 Descriptive Statistics of Collected Data (Scale Variables)

	Variables[1]	N	$AADT$ [veh/day]	L [m][2]	CCR_{85} [gon/km]	V_{85} [km/h]	L_{pre} [m]
Curves	Min.	0	1,122	21	19,75	48.01	0
	Max.	4	12,096	2,403	984.77	95.55	2,924
	Mean	0.31	5,050.43	188.94	216.82	77.84	406.41
	SD	0.69	2,966.09	269.76	162.39	11.03	519.90
Tangents	Min.	0	1,122	30	17.77	48.17	
	Max.	10	12,096	2,924	177.01	111.67	
	Mean	0.78	5,061.64	423.24	60.70	79.02	
	SD	1.66	3,023.87	541.07	23.33	11.30	

[1] Abbreviations: N – 5-year frequency of single-vehicle crashes; $AADT$ – traffic volume; L – length; CCR_{85} – 85th percentile of curvature change rate; V_{85} – 85th percentile of speed; L_{pre}– preceding tangent length (for curves only)

[2] Units: 1 m (meter) = 3.3 ft; 1 km (kilometer) = 0.6 mi; 1 gon = 10/9°

TABLE 3 Descriptive Statistics of Collected Data (Categorical Variables)

Variable	Categories	Curves		Tangents	
		Freq.	%	Freq.	%
Roadway width	1 (up to 7.5 m)	66	41.77	67	42.41
	2 (7.6 – 9.5 m)	19	12.03	20	12.66
	3 (9.6 – 11.5 m)	60	37.97	60	37.97
	4 (11.5 m +)	13	8.23	11	6.96
Vegetation	0 (none / bushes)	25	15.82	27	17.09
	1 (single trees)	58	36.71	52	32.91
	2 (trees / forest)	75	47.47	79	50.00
Road marking	0 (none / broken)	77	48.73	44	27.85
	1 (solid)	81	51.27	114	72.15
Delineator posts	0 (absent)	15	9.49	10	6.33
	1 (present)	143	90.51	148	93.67
Guardrails	0 (absent)	116	73.42	116	73.42
	1 (present)	42	26.58	42	26.58
Vertical grade	0 (flat)	115	72.78	92	58.23
	1 (slope)	43	27.22	66	41.77

The collected data may be grouped as following variables, according to the two stages of modeling (see Table 4):

TABLE 4 Overview of Variables Used in Speed and Safety Models

	Explanatory variables	Response variable
Speed model	Environment factors Length of preceding tangent (for curves only) Curvature change rate	Speed
Safety model	Exposure (length and AADT) Speed consistency	Crash frequency

Note that speed models will be developed separately for tangents and curves, while safety model will be one for both tangents and curves. Both models will be developed using generalized linear modeling feature in SPSS (procedure GENLIN). Segment number is referred to as i. Speed model was considered in a following form:

$$V_{85,i} = \beta_0 + \sum_{i=1}^{n} \beta_i \cdot x_i \qquad (1)$$

where:

$V_{85,i}$ … speed

x_i … explanatory variables (from Table 3)

β_i … regression coefficients to be estimated

For safety model negative binomial distribution with logarithmic link function was used. The model has following form:

$$P_i = \exp(\beta_0) \cdot AADT_i^{\beta_1} \cdot L_i^{\beta_2} \cdot \exp(\beta_3 \cdot |\Delta V_{85,i}|) \quad (2)$$

where:

P_i … expected crash frequency
$AADT_i$ … traffic volume [veh/day]
L_i … segment length [km]
$|\Delta V_{85,i}|$ … speed consistency indicator [km/h]
β_i … regression coefficients to be estimated

Speed consistency was quantified as absolute difference of 85th percentile speeds ($|\Delta V_{85}|$) between curve i and tangent $i+1$.

3 RESULTS

Stage 1: Speed model

The results related to speed model (Stage 1) are listed in Table 5. Only variables with statistical significance at 5% level ($p \leq 0.05$) are reported; two of original variables were not significant at this level (presence of delineator posts and preceding tangent length).

TABLE 5 Regression Coefficients and Statistical Significance of Explanatory Variables in Speed Models

Variable	Category	Regression coefficients		p-values*		Interpretation
		Curves	Tangents	Curves	Tangents	
Roadway width	1	0	0	0.002	0.000	
	2	0.50	3.12			
	3	-0.36	4.26			
	4	9.78	14.01			Positive
Vegetation	0	0	0	0.011	0.050	
	1	-0.56	1.56			
	2	4.01	4.80			Positive
Road marking	0	–	0	n.s.	0.002	
	1	–	5.37			Positive
Guardrails	0	0	0	0.015	0.005	
	1	4.05	4.89			Positive
Vertical grade	0	0	0	0.023	0.052	
	1	-3.62	-3.03			Negative
CCR_{85}	–	-0.03	-0.07	0.000	0.031	Negative

* n.s. – not significant

Interpretation in the last column is based on signs of regression coefficients (i.e. directions of relationships between predictor and predicted variable):

- Increase of road width is associated with higher speed. This is generally in line with literature (*14*, *25*, *26*).
- Speed increases with increasing density of vegetation, which is not completely consistent with past knowledge (*9*). However it was reported that 'continuous wall of overgrowth' may lead to speed increase, compared to bushes along the road, which may decrease speed, (*25*).
- Presence of solid line is associated with higher speeds in tangents. This may be consistent with a finding fact that presence of road marking (in contrast to no marking) is related to higher speed (*9*).
- Higher speeds in segments with guardrails also confirm previous findings studies (*9*).
- Both vertical grade and increase of curvature change rate are associated with decrease of speed, which is consistent with previous studies (*1*, *25*).

Stage 2: Safety model

The results related to safety model (Stage 1) are listed in Table 6. Statistical significance at 5% level ($p \leq 0.05$) was reached for AADT and length, but not for speed consistency, which achieved statistical significance at 13.4% level. Nevertheless due to its presumed causal role, it was kept in the model.

TABLE 6 Regression Coefficients and Statistical Significance of Explanatory Variables in Safety Model

Parameter	Regression coefficients	95% confidence interval boundaries		p-values
(Intercept)	-6.725	-9.427	-4.023	0.000
$\ln(AADT)$	0.838	0.523	1.154	0.000
$\ln(L)$	0.941	0.778	1.104	0.000
$\lvert \Delta V_{85} \rvert$	0.030	-0.009	0.068	**0.134**

Signs of all regression coefficients are positive. The exception of $|\Delta V_{85}|$ – although majority of its confidence interval is in positive values, it is also partly below zero. However overall the regression coefficients are positive, i.e. increasing values of predictors are associated with higher crash frequencies. This confirms expectations based on general knowledge from crash prediction modeling.

In addition sizes of individual regression coefficients may be compared to past studies, which used the same model form. Table 7 compares the above results with 4 studies – the values are not identical, but mostly relatively close. The consistent values are in bold text: for $\ln(AADT)$ between 0.6 and 0.9, for $\ln(L)$ between 0.8 and 1.0, for $|\Delta V_{85}|$ between 0.02 and 0.05. Potential inconsistencies may arise from variable conditions between individual studies: for example different crash types or incomparable ranges of explanatory variables.

TABLE 7 Comparison of Regression Coefficients with Several Other Studies

Variable	This study	Fitzpatrick et al. (*27*, equation 35)	Ng and Sayed (*15*, model 2)	Dietze and Weller (*24*, Table 9)	de Oña et al. (*18*, Table 8, average)
$\ln(AADT)$	**0.838**	**0.922**	**0.585**	**0.585**	1.129
$\ln(L)$	**0.941**	**0.842**	**0.887**	0.216	**0.955**
$\lvert \Delta V_{85} \rvert$	**0.030**	0.066	**0.048**	**0.033**	**0.015**

Overall performance of safety model may be quantified in terms of various indicators, for example Akaike information criterion (AIC), overdispersion parameter or ‘proportion of systematic variation in the original crash dataset explained by the model’ or *%SV* (*28*). Contribution to model’s explanatory power, which is caused by inclusion of additional variable, then equals the difference in values of these indicators. Both original model (with AADT and length) and full model (with AADT, length and $|\Delta V_{85}|$) were compared this way. The results are listed in Table 8.

TABLE 8 Comparison of Performance of Original and Full Models

Model variant	This study[1]			Anderson et al. (*10*, model 2)
	AIC	*O.d.p.*	*%SV*	*%SV*
Original model	480.682	0.281	91.306	65.86
Full model	480.526	0.260	91.956	66.51
Difference	-0.156	-0.021	+0.650	+0.66

[1] Abbreviations: *AIC* – Akaike information criterion; *O.d.p.* – overdispersion parameter; *%SV* – proportion of systematic variation explained.

The differences in all indicators are small. Nevertheless such small contributions have also been reported in other similar studies (e.g. *10*), as reported in the last column of Table 8; therefore $|\Delta V_{85}|$ was kept in a model.

One potential application of model results may be in network screening, i.e. identification of hazardous road segments. Traditionally estimates from crash prediction models are used for this purpose; should we prove valid relationship of $|\Delta V_{85}|$ to safety, speed consistency may be used as a surrogate measure in a proactive way (before occurrence of crashes). Preliminary results from the same road sample, but using observed speeds and limited to curves only, were reported in a recent paper (*29*). Both trends were found to be relatively similar, with Pearson correlation coefficient between ranking both assessments equal to 0.62 in the preliminary study, and improved to 0.68 while using modeled speeds and both tangents and curves.

4 DISCUSSION AND CONCLUSIONS

Speed on two-lane rural roads is a critical safety issue. Within traffic and safety engineering, speed has been studied from several different perspectives. Two of them are referred to as speed models (relating speed to design consistency factors) and safety models (where safety is estimated using exposure data, also enriched by design consistency variables).

However research in both domains has often been carried out separately; their combination would be useful (*2*). What is more, although it is well known that a host of road environment factors influences speed choice, speed models have usually employed only few selected variables. In contrast, safety models often use wide array of exposure and risk factors. At the same time in a different field – studying roundabout safety – an opposite approach has been applied. So called ‘two-stage’ model estimates speed (using more explanatory variables) which is further applied in a relatively simple safety performance function (SPF). According to the authors (*20*), such an approach can be superior to the SPFs directly containing design variables as it preserves model parsimony while capturing the important safety effects.

The objective of this study was to prove feasibility of development and application of a combination of speed and safety models (in a ‘two-stage’ model) in the study of environment, speed and safety factors on a sample of Czech rural roads. To this end, data collection was carried out on approx. 100 km of two-lane rural roads in one of Czech regions. Using instrumented vehicle, speed and alignment data were obtained – 316 segments were created (158 tangents and 158 curves). These segments were assigned road environment data, based on their expected relation to speed choice (roadside vegetation, road marking, delineation, guardrails, vertical grade, roadway width), as well as single-vehicle crash frequency and exposure data (AADT and length). Data were used to develop and study speed and safety models in the following steps:

- Speed model utilized 8 potential explanatory variables; all but 2 of them were statistically significant at 5% level. All these variables had expected direction of relationship to speed.
- Modeled speeds were used to compute indicator of speed consistency $|\Delta V_{85}|$.
- Safety model was developed using AADT, length and speed consistency. 5% statistical significance was achieved for AADT and length, but not for speed consistency, which achieved statistical significance at 13.4% level. Nevertheless due to its presumed causal role, it was kept in the model. Sizes of regression coefficients were compared to 4 past studies and found to be in relative agreement. Also overall model performance was tested; however improvements due to added speed consistency were small, which was found also in other studies.

To sum up, final results are maybe less relevant than expected. Significances of variable influence and model performance could be higher. Nevertheless the findings seem plausible and are mostly comparable to other similar studies. Differences may results from the following limitations of the presented study:

- *Road environment data.* There are other variables, which were not used in this study, and could potentially improve the quality of speed models, such as pavement quality or superelevation in curves. Vertical grade could be used in a more quantitative way. In addition road environment data could be registered while riding, rather than from Google Maps, as was done in this study.
- *Speed data collection.* Data were collected within a single drive only in a single direction. Although there was an attempt to adapt driving speed to the free-flow as close as possible, the collected data may not be representative of the driving population and are considered as an approximation of operating speed only. In this regard, more drives, possibly with more drivers, could offer more reliable data, leading to different results.
- *Speed consistency measure.* Several studies recommended not to rely on a simple indicator of $|\Delta V_{85}|$, which was used in the presented study, since it may underestimate the real speed reduction (*30*). Other measures, such as 85^{th} percentile of maximum speed reduction, may circumvent the issue (*31*). Speed may be also collected in several points of speed profile, from the approach tangent through the curve and departure tangent (*1*).
- *Crash sample.* The sample of modeled crashes was generally small, and further reduced by using single-vehicle crashes only. Low numbers may influence quality of safety modeling, due to low statistical significances and also a ‘low mean problem’ which biases estimate of overdispersion (*32*).

These limitations are being addressed in further stages of the projects: study sample is enlarged in both time and space, using vehicle fleet speed data from repeated drives in both directions (*33*). An improvement of evaluation methodology is planned as well, considering more data collection spots in curves and their surroundings. It will enable improving the study quality and testing the validity of the findings presented in this feasibility study, as well as comparison to other studies.

Future practical applications of an improved concept may include proactive network screening (i.e. identification of hazardous road segments) without having to rely on crash occurrence only. Once hazardous segments are identified, potential countermeasures may be proposed. Common countermeasures in horizontal curves include warning signs, road marking, recommended speeds or reduced speed limits (*34*). A number of them have been recommended as safety-beneficial and low-cost (*35*). Joint analysis of environment, speed and safety factors, as proposed in this paper, will help decide on the most suitable countermeasures in order to tackle the issue of Czech rural roads safety.

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REFERENCES

1. TRB. *Modeling Operating Speed: Synthesis Report*. Transportation Research Circular E-C151, Transportation Research Board of the National Academies, Washington, D.C., 2011.
2. Porter, R. J., E. T. Donnell, and J. M. Mason. Geometric Design, Speed, and Safety. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2309,* Transportation Research Board of the National Academies, Washington, D.C., 2012, pp. 39–47.
3. Kloeden, C. N., A. J. McLean, V. M. Moore, and G. Ponte. *Travelling Speed and the Risk of Crash Involvement*. Report CR 172. Federal Office of Road Safety (FORS), Canberra, 1997.
4. Aarts, L., and I. van Schagen. Driving speed and the risk of road crashes: A review. *Accident Analysis and Prevention*, Vol. 38, 2006, pp. 215–224.
5. Hauer, E. Speed and Safety. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2103,* Transportation Research Board of the National Academies, Washington, D.C., 2009, pp. 10–17.
6. Fildes, B. N., and S. J. Lee. *The Speed Review: Road Environment, Behaviour, Speed Limits, Enforcement and Crashes*. Report CR 127. Federal Office of Road Safety (FORS), Canberra, 1993.
7. Silcock, D., K. Smith, D. Knox, and K. Beuret. *What limits speed? Factors that affect how fast we drive*. AA Foundation for Road Safety Research, 2000.
8. Edquist, J., C. M. Rudin-Brown, and M. G. Lenné. *Road design factors and their interactions with speed and speed limits*. Report 298. Monash University Accident Research Centre (MUARC), Victoria, 2009.
9. SWOV. *Speed choice: the influence of man, vehicle, and road*. SWOV Institute for Road Safety Research, Leidschendam, 2012.

10. Anderson, I. B., K. M. Bauer, D. W. Harwood, and K. Fitzpatrick. Relationship to Safety of Geometric Design Consistency Measures for Rural Two-Lane Highways. In *Transportation Research Record: Journal of the Transportation Research Board*, *No. 1658*, Transportation Research Board of the National Academies, Washington, D.C., 1999, pp. 43–51.
11. Gibreel, G. M., S. M. Easa, Y. Hassan, and I. A. El-Dimeery. State of the Art of Highway Geometric Design Consistency. *Journal of Transportation Engineering*, Vol. 125, 1999, pp. 305–313.
12. Castro, M., J. F. Sánchez, and J. A. Sánchez. Operating speed models for two-lane rural highways. *Proceedings of the ICE – Transport*, Vol. 165, 2012, pp. 107–118
13. Montella, A., L. Pariota, F. Galante, L. L. Imbriani, and F. Mauriello. Prediction of Drivers' Speed Behavior on Rural Motorways Based on an Instrumented Vehicle Study. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2434*, Transportation Research Board of the National Academies, Washington, D.C., 2014, pp. 52–62.
14. Gatti, G., C. Polidori, I. Galvez, K. Mallschützke, R. Jorna, M. van de Leur, M. Dietze, D. Ebersbach, C. Lippold, B. Schlag, G. Weller, A. Wyczynski, F. Iman, and C. Aydin. *Safety Handbook for Secondary Roads.* RIPCORD-ISEREST project deliverable D13, 2007.
15. Ng, J. C. W., and T. Sayed. Effect of geometric design consistency on road safety. *Canadian Journal of Civil Engineering*, Vol. 31, 2004, pp. 218–227.
16. Cafiso, S., A. Di Graziano, G. Di Silvestro, G. La Cava, and B. Persaud. Development of comprehensive accident models for two-lane rural highways using exposure, geometry, consistency and context variables. *Accident Analysis and Prevention*, Vol. 42, 2010, pp. 1072–1079.
17. Camacho-Torregrosa, F. J., A. M. Pérez-Zuriaga, J. M. Campoy-Ungría, and A. García-García. New geometric design consistency model based on operating speed profiles for road safety evaluation. *Accident Analysis and Prevention*, Vol. 61, 2013, pp. 33–42.
18. de Oña, J., L. Garach, F. Calvo, and T. García-Muñoz. Relationship between Predicted Speed Reduction on Horizontal Curves and Safety on Two-Lane Rural Roads in Spain. *Journal of Transportation Engineering*, Vol. 140, 2014.
19. Montella, A., and L. L. Imbriani. Safety performance functions incorporating design consistency variables. *Accident Analysis and Prevention*, Vol. 74, 2015, pp. 133–144.
20. Chen, Y., B. Persaud, E. Sacchi, and M. Bassani. Investigation of models for relating roundabout safety to predicted speed. *Accident Analysis and Prevention*, Vol. 50, 2013, pp. 196–203.
21. Lamm, R., B. Psarianos, and S. Cafiso. Safety Evaluation Process for Two-Lane Rural Roads: A 10-Year Review. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1796,* Transportation Research Board of the National Academies, Washington, D.C., 2002, pp. 51–59.
22. Ambros, J., and V. Valentová. Identification of road horizontal alignment inconsistencies – A pilot study from the Czech Republic. *The Baltic Journal of Road and Bridge Engineering*, in press.
23. Turner, S., R. Singh, R., and G. Nates. *The next generation of rural road crash prediction models: final report*. Research report 509. NZ Transport Agency (NZTA), Wellington, 2012.
24. Dietze, M., and G. Weller. *Applying speed prediction model to define road sections and develop accident prediction models: A German case study and a Portuguese exploratory study*. RISMET project deliverable 6.2, 2011.
25. Martens, M., S. Comte, and N. Kaptein. *The Effects of Road Design on Speed Behaviour: A Literature Review*. MASTER project report 2.3.1, 1997.
26. Aarts, L., S. Brandenburg, S., and N. van Nes. The Influence of Environmental Factors on Speed Choice. In *2011 IEEE Forum on Integrated and Sustainable Transportation Systems* (FISTS), Vienna, Austria, June 29–July 1, 2011.

27. Fitzpatrick, K., L. Elefteriadou, D. W. Harwood, J. M. Collins, J. McFadden, I. B. Anderson, R. A. Krammes, N. Irizarry, K. D. Parma, K. M. Bauer, and K. Passetti. *Speed prediction for two-lane rural highways*. Report FHWA-RD-99-171. Federal Highway Administration (FHWA), Washington, D.C., 2000.
28. Kulmala, R. *Safety at rural three- and four-arm junctions: Development and application of accident prediction models*. Publication No. 233. VTT Technical Research Centre of Finland, Espoo, 1995.
29. Ambros, J., V. Valentová, and P. Oríšek. Safety Ranking of Rural Curves Based on Design Consistency Measures. In *5th International Symposium on Highway Geometric Design* (ISHGD), Vancouver, B.C., Canada, June 22–24, 2015.
30. McFadden, J., and L. Elefteriadou. Evaluating horizontal alignment design consistency of two-lane rural highways: Development of new procedure. In *Transportation Research Record: Journal of the Transportation Research Board*, *No. 1737*, Transportation Research Board of the National Academies, Washington, D.C., 2000, pp. 9–17.
31. Park, Y., and F. Saccomanno. Evaluating speed consistency between successive elements of a two-lane rural highway. *Transportation Research Part A*, Vol. 40, 2006, pp. 375–385.
32. Lord, D. Modeling motor vehicle crashes using Poisson-gamma models: Examining the effects of low sample mean values and small sample size on the estimation of the fixed dispersion parameter. *Accident Analysis and Prevention*, Vol. 38, 2006, pp. 751–766.
33. Ambros, J., O. Gogolín, J. Kubeček, R. Andrášik, and M. Bíl. Proactive identification of risk road locations using vehicle fleet data: exploratory study. In *28th ICTCT Workshop*, Ashdod, Israel, October 29–30, 2015.
34. Elvik, R., A. Høye, T. Vaa, and M. Sørensen. *The Handbook of Road Safety Measures, Second Edition*. Emerald, Bingley, 2009.
35. McGee, H. W., and F. R. Hanscom. *Low-Cost Treatments for Horizontal Curve Safety*. Report FHWA-SA-07-002. Federal Highway Administration (FHWA), Washington, D. C., 2006.