IMPROVING THE SELF-EXPLAINING PERFORMANCE OF CZECH NATIONAL ROADS

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ABSTRACT

Improving the road network according to principles of self-explaining roads is a promising way to increase the level of safety; however, there are no universal guidelines on how to measure and improve the self-explaining performance of the existing roads. In order to apply this approach on Czech national roads, the presented study was conducted, consisting of five steps: (1) automated segmentation into tangents and horizontal curves; (2) collection of floating car data and calculation of speed; (3) development of multivariate speed models for estimation of speed also on segments not covered by floating car data; (4) network-wide application of the models and evaluation of speed consistency, i.e. differences of speeds on tangents and following curves; (5) identification of substandard curves, categorization and proposal of optimization in terms of consistent placement of traffic control devices or reconstructions. The paper describes all the steps as well as several checks conducted along the way, such as comparison of profile speed and floating car speed, interpretation of regression models, and validation of predicted speed consistency against long-term average of crash frequency. The methodology was certified for use in practice and will be applied by the Czech national road agency.

Keywords: road safety, self-explaining road, floating car data, speed consistency, horizontal curve

1 INTRODUCTION

The current level of road traffic safety on Czech roads is unsatisfactory. In 2011 the National road safety strategy was established with goals to reduce the number of fatalities by 60% and serious injuries by 40% until 2020. A variety of countermeasures has been proposed and continuously applied, such as infrastructural improvements, increase of police enforcement, and improvement of traffic safety education. In spite of the efforts, annual evaluations of the strategy fulfillment show that the goals are not met (*1*).

In this critical situation, new solutions and measures need to be adopted. An option, mentioned in the strategy, is to improve the road network based on the principles of self-explaining and forgiving roads. Self-explaining environment is such traffic environment which simply elicits safe behavior by its design (*2*) – the concept involves designing a road system in which the driver's expectations created by the road environment are implicitly in line with safe behavior. According to an international review (*3*), the self-explaining road concept and principles have been used world-wide and often in situations different from the original: e.g. in the UK self-explaining roads are mentioned as those where drivers naturally adopt the correct speed (*4*); in New Zealand, the concept was extended to an area-wide approach to traffic calming and speed management (*5*). In US, a term "self-enforcing design" was introduced, which reinforces established speed limits and reduces speeding opportunities; such road itself should induce drivers to adopt operating speeds that are within limits (*6*). In summary, there are no universal definitions or guidelines on how to measure and improve the self-explaining performance of the existing roads.

The paper summarizes a research project focusing on improving the self-explaining performance of Czech national roads. The project was conducted by CDV – Transport Research Centre according to the needs of the National road agency (Road and Motorway Directorate). The following sections describe data collection, development of methodology, and application on rural sections of national roads, followed by discussion and conclusions.

2 THE STUDY

According to Gitelman *et al.* (*7*), the tools applicable for creating self-explaining roads include: (1) setting a correct functional hierarchy of the road system; (2) providing consistency in the road design; (3) measuring a link between road characteristics and travel speeds. The second and third options were adopted in the presented project.

The idea behind consistency concept (also design consistency, alignment consistency or speed consistency) is as follows: drivers are more likely make fewer errors in the vicinity of geometric features that fit their expectations than in the vicinity of features that violate their expectations (*8*). The consistent design ensures that successive geometric elements are coordinated in a manner that minimizes variability in vehicle speeds, prevents critical driving maneuvers, and reduces crash risk (*9*). Consistent operating speeds are a product of consistent design (*8*); therefore, the variables for evaluating design consistency are usually defined in terms of an operating speed (*10*). Various consistency measures have been used, with the most used one, developed by Lamm *et al.*, which evaluates consistency in terms of the magnitude of speed reduction between successive design elements: design is regarded as ‘good’ if the magnitude of the difference in 85th speed percentiles is lower than 10 km/h; as ‘fair’ if the difference is between 10 km/h and 20 km/h; and as ‘poor’ if the difference is higher than 20 km/h (*11 – 13*).

The following sub-sections describe five study steps:

1. In order to divide the studied network (rural sections of national roads) into tangents and horizontal curves, a novel method of automated segmentation was developed and applied.
2. Floating car data were purchased and processed in order to obtain free-flow speed.
3. Since floating car data did not cover the whole analyzed network, multivariate regression models (relationships between speed and explanatory variables) were built. The purpose of these models is to enable future network-wide application, without forcing users to collect their own data. In order to prove the models quality, validity of differences of estimated (predicted) speeds (i.e. speed consistency) against long-term average of crash frequency was checked.
4. Models were applied on the whole Czech road network – speed was estimated for each segment and consistency was evaluated.
5. Substandard curves were identified. Consistency assessments were categorized into five classes; a specific optimization was proposed for each class.

Step 1: Segmentation

Various authors have used different approaches to obtain alignment parameters and to make segmentation into tangents and curves (*14 – 16*). Nevertheless, each method has its disadvantages, such as limited accuracy or dependency on manual processing. Often a combination of manual and automatic identification is used. Recently, a novel fully automated segmentation methodology was developed (see *17* for details). It consists of four steps:

1. Pre-processing with Douglas-Peucker algorithm for data generalization.
2. Calculation of geometrical explanatory variables.
3. Classification of tangents and curves with the use of a classification tree on the basis of explanatory variables.
4. Post-processing with least squares method for radii computation.

The average error of identification is below 5%, which is more precise than commonly used techniques. The method was applied in the presented study to distinguish between tangents and curves. Since a number of segments were relatively short, two rules were considered:

- Lamm *et al.* (*11*) marked tangents shorter than 200 m as “dependent” – speeds on such tangents are influenced by speeds on previous segments.
- For crash-based analyses (i.e. also for planned validation), AASHTO *Highway Safety Manual* (*18*) recommends using minimal segment length of 0.1 mi (160.9 m). In a similar vein Czech hotspot identification guidelines (*19*) use a 250 m length.

Based on these two criteria, minimal length of 200 m was chosen; shorter segments were discarded.

Step 2: Determination of speed

The floating car data (FCD) were purchased from a private company Princip a.s. The dataset consisted of GPS data points from 1172 company vehicles, collected over 8 months (October 2014 – May 2015). The speed was calculated from GPS location and the time interval between the points, given by the recording frequency 4 times per second. This way, speed was assigned to data points of each individual drives.

Regarding the analyses of relationships between speed, road geometry and traffic safety, it is necessary to use free-flow speed (FFS), i.e. the speed which is not constrained by congestion, traffic devices or adverse weather conditions. The traditional approach to estimating FFS relies on field studies, where speeds of single (uninfluenced) vehicles are detected using hand-held speed guns, roadside traffic counters, and fixed loops or tubes (*20*). However, with area-wide collected FCD, a different approach is necessary. Typically, the data from off-peak hours are believed to represent FFS (*21 – 23*); however, since company vehicles often travel during peak hours, this approach could lead to enormous data loss. A different method was therefore applied, consisting of the following steps:

1. Each data point was assigned to the nearest vertex of the road centerline.
2. For each vertex, speed values were calculated and divided into two groups (influenced/uninfluenced speed) based on cluster analysis.
3. Free-flow speed was calculated as the 85th percentile of uninfluenced speed.
4. Weighted average of free-flow speed per segment was used, with weight given by the number of data points assigned to each vertex.

In order to obtain representative information, data from more drives in selected sections were needed. A TRB synthesis (*20*) reports the parameters of operating speed studies, including the number of observations; a large number of them used the criterion of “at least 100 per site”. The same criterion was applied in this study; the segments with fewer than 100 drives were discarded (in case there were 100 or more drives in both directions, both were used).

The representativeness of speed estimated from FCD was compared to spot speed, which was measured by a statistical radar SR 4. In seven profiles, FCD-speed was on average by 2 km/h higher than the radar-speed.

Step 3: Development and validation of speed models

Given the traditional links between geometric design and operating speed studies, speed models are usually simple, only introducing horizontal curve radii (or some of the derivatives, such as degree of curve or curvature change rate) as predictors. On the other hand, speed is a very complex issue influenced by a number of other environmental effects, such as cross-section, roadside, road marking or roadside vegetation density (*24 – 27*). Recent studies (*28, 29*) indicate that speeds are affected by a number of characteristics normally neglected in operating speed models.

Values of the following explanatory variables (potential speed choice attributes) were assigned to each segment:

- Traffic volume (half of bi-directional AADT)
- Road geometry (curvature change rate (CCR), curve radius, length, vertical grade, visibility of segment end)
- Cross-section (climbing lane, road width, shoulder width, cross slope, overtaking possibility)
- Road equipment and roadside (road signing, guardrails, delineator posts, vegetation)

Some variables were extracted from databases of national road agency, some were manually identified in Google Maps; cross slope was measured by an instrumented vehicle. An effort was made to filter out the segments with non-standard parameters, such as multiple lanes, medians, intersections, bus stops, pedestrian crossings, tunnels, and railroad level crossings. The goal was to obtain a sample of two-lane undivided rural segments (potentially with climbing lanes), where speed should only be influenced by the listed attributes. In total 296 segments (168 tangents and 128 curves) were obtained.

Before modeling, frequencies of categorical variables were studied. In cases where some category was present in fewer than 10% of segments, the variable was discarded – this was the case of delineator posts and road signing. In addition, inter-correlations of explanatory variables were checked. In case they were high (with Pearson correlation coefficient above 0.5), e.g. between road width and shoulder width, it was assured that only one of such variables entered the model. Descriptive characteristics of explanatory variables which were used for modeling are presented in Table 1, separately for tangents and curves.

TABLE 1 Descriptive Characteristics of Explanatory Variables

Tangents				Curves			
Continuous variable	Min.	Max.	Mean	Continuous variable	Min.	Max.	Mean
Traffic volume [veh/day]	2268.5	8846.5	5037.5	Traffic volume [veh/day]	2268.5	8846.5	5063.0
Length [m]	201.3	3193.2	642.0	Length [m]	204.5	1477.3	408.9
CCR [gon/km]	0.3	53.6	11.9	CCR [gon/km]	21.0	454.8	75.0
Cross slope [%]	-1.7	3.5	1.3	Cross slope [%]	0.3	4.4	1.5
				Radius [m]	106.7	2068.6	975.7

		Proportions [%]	
Categorical variable	Category	Tangents	Curves
Road width	≤ 9.5 m	22.6	**10.9**
	9.6 – 11.5 m	40.5	49.2
	> 11.5 m	36.9	39.8
Shoulder width	≤ 0.75 m	25.0	17.2
	0.76 – 1.5 m	32.7	33.6
	> 1.5 m	42.3	49.2
Vegetation	none / bushes	20.2	25.0
	single trees	36.3	37.5
	trees / forest	43.5	37.5
Overtaking possibility	no / yes	34.5 / 65.5	47.7 / 52.3
Guardrails	no / yes	63.1 / 36.9	60.2 / 39.8
Vertical grade	no / yes	53.6 / 46.4	38.3 / 61.7
Visibility of segment end	no / yes	23.8 / 76.2	82.0 / 18.0
Climbing lane	no / yes	92.3 / 7.7	88.3 / 11.7

Common model form was adopted (*20*):

$$V_{85} = b_0 + \sum_{i=1}^{n} b_i x_i \qquad (1)$$

where V_{85} is the 85th speed percentile, x_i are explanatory variables (in Table 1), b_i are regression coefficients to be estimated.

Models were calibrated separately for tangents and curves. Multivariate regression modeling in IBM SPSS was used, in backward-stepwise manner, keeping the variables with significance level below 0.05 (5%).

Inspired by previous studies (*20, 30, 31*), the following steps were taken:

1. Developing a model for tangent speeds (with the above mentioned potential explanatory variables) in order to obtain predictions V_t.
2. Developing a model for curve speeds (with the above mentioned potential explanatory variables, including predictions V_t) in order to obtain predictions V_c.

The modeling results are shown in Table 2. Column B presents a vector of unstandardized regression coefficients, i.e. the values of intercept (b_0) and coefficients b_i from equation 1; the next columns include standard errors (SE), standardized regression coefficients (β) and achieved levels of statistical significance (Sig.).

TABLE 2 Estimated Regression Coefficients of Speed Prediction Models

Tangents	B	SE	Sig.	**Curves**	B	SE	Sig.
(Intercept)	92.119	3.376	0.000	(Intercept)	50.704	15.316	0.001
Traffic volume	-0.001	0.000	0.023	V_t	0.559	0.158	0.001
Length	0.004	0.001	0.001	CCR	-0.070	0.011	0.000
Cross slope	-2.169	0.838	0.011	Shoulder width	-1.660	0.794	0.039
Road width	1.611	0.741	0.031	Climbing lane	4.399	1.904	0.023
Overtaking	3.962	1.200	0.001				
Visibility of segment end	3.026	1.283	0.020				
Climbing lane	10.347	2.232	0.000				

Note: B = unstandardized regression coefficients; SE = standard errors; Sig. = achieved levels of statistical significance; V_t = predicted speed in preceding tangent.

Internal validity of the presented models may be illustrated by the signs of regression coefficients:

- Increasing length, road width, visibility and enabled overtaking and climbing (which have positive signs of coefficients) are associated with an increase of speed; the same positive relationship holds for the influence of the preceding tangent speed on speed in the following curve.
- On the other hand, an increase in traffic volume, cross slope or curvature change rate (CCR) with negative coefficient signs is associated with a decrease in speed.

These associations are generally logical and consistent with literature (*20*): increasing segment length, road width as well as a possibility of overtaking, using a climbing lane, or visibility through the segment, allow higher driving speed. The increased tangent speed is then translated into the following curve; on the other hand, higher curvature, cross slope or traffic volume leads to speed decrease.

The coefficients of determination (R^2) of the presented models were 0.271 for tangents and 0.398 for curves. To make sure that they are sufficient and model predictions make sense, an external validity test was conducted. Validation against crash indicators as "objective safety" was chosen, following numerous previous applications of this approach (e.g. *30*, *32*, *33*). The presented validation was based on a comparison of speed differences (calculated from predicted speeds) against "objective safety", expressed in terms of empirical Bayes estimate of expected crash frequency (EB) (for details see *34*). EB estimates the presented long-term average as a combination of:

1. expected crash frequency according to crash prediction model (safety performance function)

$$N = b_0 \cdot I^{b_1} \cdot L^{b_2} \qquad (2)$$

   where N is crash frequency, I traffic volume, L length, b_i estimated regression coefficients, and
2. recorded crash frequency based on Police data.

Consistently with other studies (*35*, *36*), only single vehicle crashes were used for the validation, since they are more clearly linked to road geometry and speed. Crash frequencies were summed over a 6-year period (2009 – 2014) and for all severity levels (property-damage-only, light injuries, serious injuries, fatalities) for each curve. The model was calibrated with the use of generalized linear modeling with negative binomial error structure in IBM SPSS.

Validation results, in terms of absolute values of speed difference (consistency), are displayed in Figure 1. Categories were chosen so that each bin contains at least 10 values. Values of EB averages form a clear rising trend, with the last bin (ΔV > 6 km/h) being by more than 50% higher than the first bin ($\Delta V < 2$ km/h). This also confirms that self-explaining roads (with minimal speed differences, i.e. maximal speed consistency) are the safest.

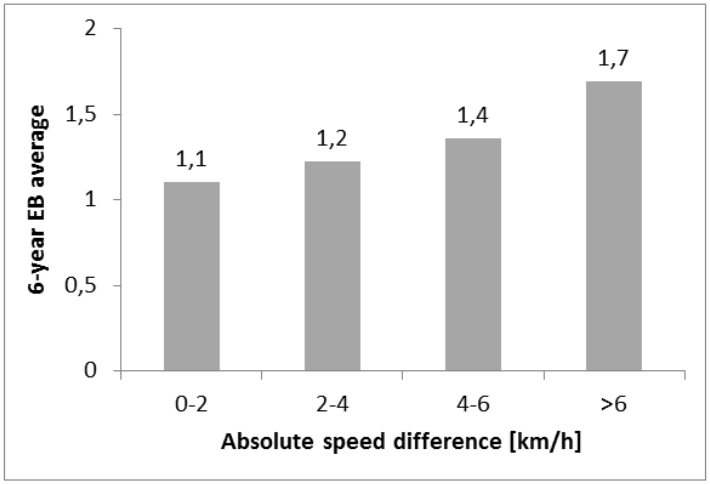


FIGURE 1 Results of validation of absolute speed difference against empirical Bayes (EB) estimate of expected crash frequency.

Step 4: Network-wide determination of speed consistency

As described in Step 3, the regression models were based on a reduced sample, and thus the model results (predictions) do not cover the complete network. A model "extension" was conducted in the following steps:

1. Selection by length of tangents ≥ 200 m (as already used in Step 3) and curves ≥ 50 m (as opposed to previously used 200 m).
2. Filtering out non-standard segments (multi-lane, bus stops, etc.), similarly to Step 3.

After filtering, the result represented 992 tangent–curve pairs, i.e. approx. a quarter of the original road network (609 km, i.e. roughly 380 mi). Values of explanatory variables (in Table 2) were assigned to the segments. Using the model equations, predictions were obtained and used for calculating the speed differences in all tangent–curve pairs:

$$\Delta V = V_c - V_t \qquad (3)$$

where ΔV is speed consistency, V_c is predicted speed in curve and V_t is predicted speed in preceding tangent.

Step 5: Categorization and optimization

The ranked list of curves was developed using a combination of the following criteria:

1. ascendant ranking of speed differences $\Delta V < -4$ km/h
2. ascendant ranking of curve radii < 400 m (critical value based on *37*)
3. descendant ranking of CCR differences > 180 gon/km (threshold value based on *11*)

As a result, 117 curves were identified as substandard (inconsistent), i.e. requiring subsequent optimization. This may be done either through consistent placement of traffic control devices or re-designing and reconstruction (e.g. curve flattening). Decisions on these strategies should ideally be based on some form of risk hierarchy; some examples are as follows:

- US *Manual on Uniform Traffic Control Devices* (*38*) selects the type of signs based on a difference between speed limit and advisory speed. Advisory speed may be selected based on accelerometer measurement, design speed equation, or using ball-bank indicator.
- In Queensland, Australia (*39*) curves are considered substandard if advisory speed is at least by 15 km/h lower than 85th speed percentile on the preceding tangent. A four-step hierarchy is formed based on approach (tangent) speed and advisory speed (measured by ball-bank indicator).
- In European research project SAFESTAR (*40*), a five-step hierarchy was proposed using 85th percentile of tangent speed (predicted by a regression model) and curve design speed. The approach was adopted in several European countries (Denmark, Netherlands, Poland), as well as in Texas *Horizontal Curve Signing Handbook* (*41*), where 85th percentiles of curve and tangent speeds are used; the former needs to be measured, the latter may be predicted by software.
- Portuguese research (*30*) employed prediction models for both tangent and curve speeds; based on differences between these speeds, consistency classes of signing were proposed.

The original intention was to use the SAFESTAR approach in the presented project. However, the determination of curve design speeds was found difficult since in the Czech Republic they are unavailable network-wide and their calculation was unreliable due to non-existing or inaccurate information on superelevation and friction. Therefore, it was decided to develop an approach inspired by the Portuguese example, i.e. using speed consistency calculated from predictions of both curve and tangent speeds (as described in Step 3).

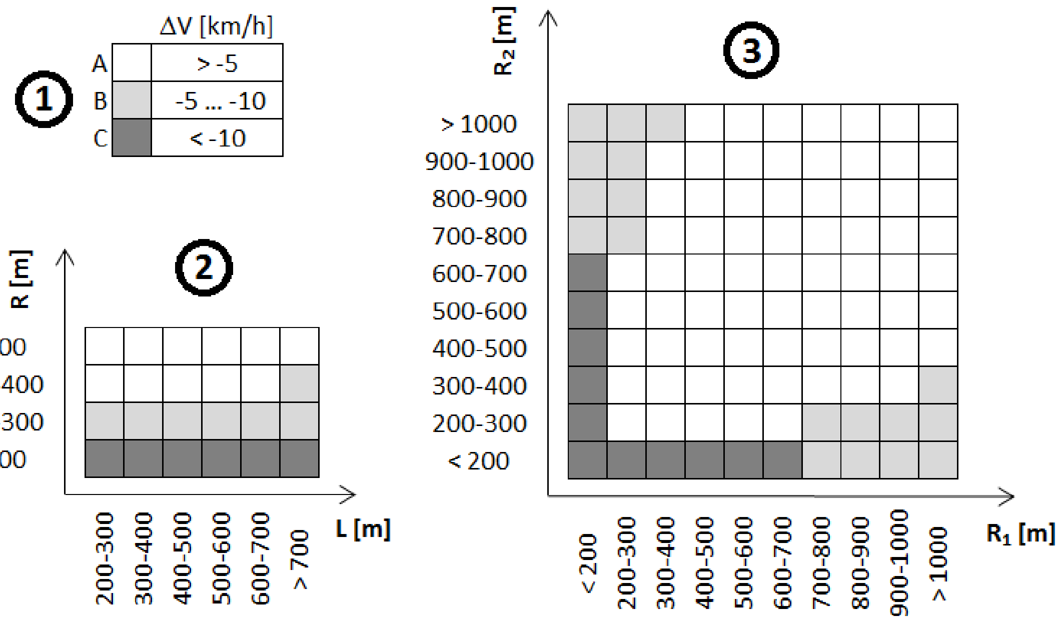
It is worth noting that the proposed approach not only considers the assessment of speed consistency, but also the assessment of relation design. Relation design means that sequences of design elements (i.e. tangents and curves) are formed in such way that the elements following one another are subject to specific relations (*11*). In many guidelines these relations are more or less qualitative or rather broadly defined; for example AASHTO *Green Book* (*42*) suggests a generally accepted ratio of two successive curves radii below 1.5 and avoidance of sharp curves at the ends of long tangents. In contrast German design guidelines (*43*) 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 proposed assessment approach consists of the following four steps:

1. “Single element” assessment based on empirically set thresholds of speed consistency (Number 1 in Figure 2).
2. “Relation design” assessment based on speed consistency adapted according to the above mentioned graphs from German guidelines (Numbers 2 and 3 in Figure 2).
3. Field inspection of assessed curves in order to investigate other influences, such as sight conditions, vertical alignment, vegetation, road surface, etc. Historical crash record may also be considered.
4. 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.

Two examples are given in Table 3:

- Curve 1 is assessed as A class in terms of speed consistency. The relation design assessment applies to the relationship of tangent length L and following curve radius R (A class); there is no another following curve (within 300 m), so the consecutive curve radii assessment ($R_1 + R_2$) does not apply. Crash history contains 1 crash in 6 years, which is below average in the analyzed sample (2 crashes in 6 years). However, a field inspection revealed a presence of a visual trap due to a combination of horizontal and vertical alignment. In summary, final assessment was downgraded from A to B.
- Curve 2 is assessed as C class in terms of speed consistency. The relation design is applied in both ways ($L + R$ and $R_1 + R_2$), since another curve follows within 300 m after the current curve – result is C class. During a field inspection negative cross slope was identified as well as excessive crash history (4 crashes in 6 years, which is double the average). The final assessment was thus downgraded from C to D.



		ΔV [km/h]
A	□	> -5
B	▒	-5 … -10
C	■	< -10

R [m]	200-300	300-400	400-500	500-600	600-700	> 700
> 400	□	□	□	□	□	□
300-400	□	□	□	□	□	▒
200-300	▒	▒	▒	▒	▒	▒
< 200	■	■	■	■	■	■

R₂ [m]	< 200	200-300	300-400	400-500	500-600	600-700	700-800	800-900	900-1000	> 1000
> 1000	▒	▒	▒	□	□	□	□	□	□	□
900-1000	▒	▒	□	□	□	□	□	□	□	□
800-900	▒	▒	□	□	□	□	□	□	□	□
700-800	▒	▒	□	□	□	□	□	□	□	□
600-700	■	□	□	□	□	□	□	□	□	□
500-600	■	□	□	□	□	□	□	□	□	□
400-500	■	□	□	□	□	□	□	□	□	□
300-400	■	□	□	□	□	□	□	□	□	▒
200-300	■	□	□	□	□	□	▒	▒	▒	▒
< 200	■	■	■	■	■	■	▒	▒	▒	▒

FIGURE 2 Three assessment steps: based on (1) speed consistency, (2) tangent length and following curve radius, and (3) radii of two consecutive curves (in case that intermediate tangent length does not exceed 300 m).

TABLE 3 Two Examples of Assessment

	Curve 1	Curve 2
		
1. Speed consistency	$\Delta V = -2$ km/h … **A**	$\Delta V = -19$ km/h … **C**
2. Relation design	$\left.\begin{array}{r}L = 471\text{ m}\\ R = 392\text{ m}\end{array}\right\}$ **A**	$\left.\begin{array}{r}L = 295\text{ m}\\ R = 138\text{ m}\end{array}\right\}$ **C**
	–	$\left.\begin{array}{r}R_1 = 138\text{ m}\\ R_2 = 325\text{ m}\end{array}\right\}$ **C**
3. Field inspection	– combination with vertical curve – 1 crash in 6 years (below average)	– negative cross slope – 4 crashes in 6 years (above average)
4. Combined assessment	**A** downgraded to **B**	**C** downgraded to **D**

For A to C classes, consistent application of traffic control devices (signing and marking) is proposed (see Table 4); for D class, a reconstruction is recommended.

TABLE 4 Proposal of Traffic Control Devices for Each Consistency Class

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

Note: Default traffic control devices (not listed in the table) consist of delineator posts and solid edge line.

Additionally, advisory speeds on warning signs and spacing of delineator posts and chevrons were recommended based on the curve radius. The details are listed in newly developed guidelines (*44*).

3 DISCUSSION

In the previous text, a methodology for the identification of substandard curves and their optimization towards improving the self-explaining performance was described. Nevertheless, each of the five presented steps is open to discussion and potential improvement in the future; some issues will be mentioned and commented on.

Issue 1: Disregarding transition curves

Transition elements provide a smooth connection between tangents and curves and are thus commonly used in road design. Some authors concluded that transition curves did not significantly influence speed (*45*), while others found that their presence ensures greater speed consistency in terms of more limited speed variations between design elements (*46*). Nevertheless, the presented study disregarded transition curves during segmentation procedures, as is common in most studies (*15*).

Issue 2: Choice of consistency speed indicator

Several studies recommended not to rely on a simple indicator of the difference of 85th percentiles of speeds, aggregated per segment, as was used in the presented study, since it may underestimate the real speed reduction (*4*). Other indicators, such as the 85th percentile of maximum speed reduction (85MSR) may circumvent the issue (*47*). Speed profiles could also be used, taking into account more locations within segment.

Issue 3: Excess of FCD-speed over radar-speed

There may be various reasons for the reported difference between speeds based on FCD and radar measurements:

- *Different driver samples.* Company drivers (captured in FCD-speed) are usually professionals, who may tend to drive faster than common drivers (radar-speed).
- *Free-flow speed definition.* Free-flow speeds from FCD and radar data have different definitions. In addition, when using radar, various headway thresholds may lead to different results (*48*).

Excess of FCD-speeds was also found in a Belgian study (*23*), where it reached almost 10 km/h. In this perspective, a difference of 2 km/h in the presented study should not have severely biased the analyses.

Issue 4: Explanatory power of speed models

Coefficients of determination (R^2) of developed speed regression models are relatively low. However, their magnitudes are similar to the ones obtained in other studies, based on FCD (*31, 49*). This finding may be explained by the characteristics of FCD: traditional studies are based on samples collected in more or less controlled conditions (daytime, season, weather, etc.) and may thus yield homogeneous results with high R^2 values; on the other hand, FCD studies use an "anonymous" sample collected in various days, seasons and weather conditions, leading to heterogeneous results with low R^2 values. TRB synthesis (*20*) lists other potential reasons of insufficient models, such as a limited sample size and number of observations, consideration of passenger cars only, or flawed assumption of data independence. The low explanatory power may lead to insufficient reliability in cases when models are applied in different time and space from the original conditions. Therefore, the models could benefit from the improvement: e.g. adding potential additional explanatory variables, and considering vehicle and driver characteristics using random effect models (*29*).

Issue 5: Size of speed differences

Thresholds of speed differences (5 and 10 km/h), which were obtained and used for assessment and categorization in Step 5, may appear low – for example compared to French (*50*) or Spanish (*51*) guidelines, which use threshold values 40 or 45 km/h. However, when relative proportions of curves and specific speed difference ranges are compared, the values are relatively close: for example (*52*) differences up to 16 km/h were reported for 85% of curves in the French review, which is comparable to 83% in the presented Czech sample.

In addition, there may also be a difference attributed to the fact that the network analyzed in this study consisted of national roads, which are of relatively high standard, as opposed to secondary roads, which are often a target of similar foreign studies (a local road sample in a Polish study (*31*) had average curvature change rate of approx. 3.5 times higher than the national road sample in the presented Czech study). This stresses the fact that it will be also valuable to adapt the described methodology to lower road categories, which have more challenging horizontal alignment with higher speed differences (as shown in the pilot study *53*).

4 CONCLUSIONS

Improving the road network according to principles of self-explaining roads is a promising way of increasing level of safety; however, there are no clear guidelines on how to measure and improve the self-explaining performance of the existing roads. In order to apply this approach on Czech national roads, the presented study was conducted. The paper describes all the conducted steps, from data collection and processing to the final categorization and optimization proposal. Although several checks were done in the process (including validation of predicted speed consistency), the procedure is far from perfect – there is a number of open questions which were previously summarized, calling for further improvement of the methodology.

The methodology was certified for practical use and will be applied by the Czech national road agency. After the real-life application, a follow-up study may focus on an evaluation of effectiveness of the proposed placement of traffic control devices. Further practical extension could also consider wider applications of the concept of self-explaining and forgiving roads, such as setting a functional hierarchy of the road network, optimized speed limits or innovative cross-section configurations, e.g. 2+1 roads.

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