Safety Ranking of Rural Curves Based on Design Consistency Measures

Jiří Ambros*

Centrum dopravního výzkumu, v.v.i.

Líšeňská 33a, 636 00 Brno, Czech Republic

Tel: +420 541 641 362; Fax: +420 541 641 711; Email: jiri.ambros@cdv.cz

Veronika Valentová

Centrum dopravního výzkumu, v.v.i.

Líšeňská 33a, 636 00 Brno, Czech Republic

Tel: +420 541 641 355; Fax: +420 541 641 711; Email: veronika.valentova@cdv.cz

Peter Oríšek

Centrum dopravního výzkumu, v.v.i.

Líšeňská 33a, 636 00 Brno, Czech Republic

Tel: +420 541 641 355; Fax: +420 541 641 711; Email: peter.orisek@cdv.cz

* Corresponding Author

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ABSTRACT

Speeding as a consequence of improper horizontal alignment of rural roads is one of current traffic safety issues on Czech roads. The evaluation of design consistency, i.e. a degree to which a road is designed and constructed to avoid critical driving manoeuvers, has been known as one of the promising tools in this regards. The objective of the presented study is to prove a practical application of this concept on a sample of Czech national road network without its design data. A data collection vehicle was used to obtain position data on selected roads. The data processing included a determination of horizontal alignment elements and segmentation and a calculation of consistency measures. The calculated speed consistency level allowed safety ranking of curves. These results are subsequently validated with the ranking based on crash frequency. At the end, several practical applications are outlined.

Keywords: alignment, curve, speed, design consistency, safety ranking

1 INTRODUCTION

Road horizontal alignment is one of general features which have a significant impact on driving and safety. It consists of tangents (straight sections) connected by horizontal curves and other transition elements. Curves are places of special interest for their higher crash risk due to additional centripetal forces exerted on a vehicle, driver expectations, and other factors (*1*). According to PIARC's Road Safety Manual (*2*), 25 to 30% of all fatal crashes world-wide occur on curves. This amount is even higher in the Czech Republic. According to the statistical year-books of Czech Traffic Police, more than one third of total road fatalities are related to curve crashes. In order to structure these numbers, disaggregated Police data were used for Figure 1. It provides a division of Czech road fatalities counts by road settings (rural or urban roads), road network elements (sections or intersections) and their categories: motorways, national roads (1^{st} class roads) or regional roads (2^{nd} and 3^{rd} class roads).

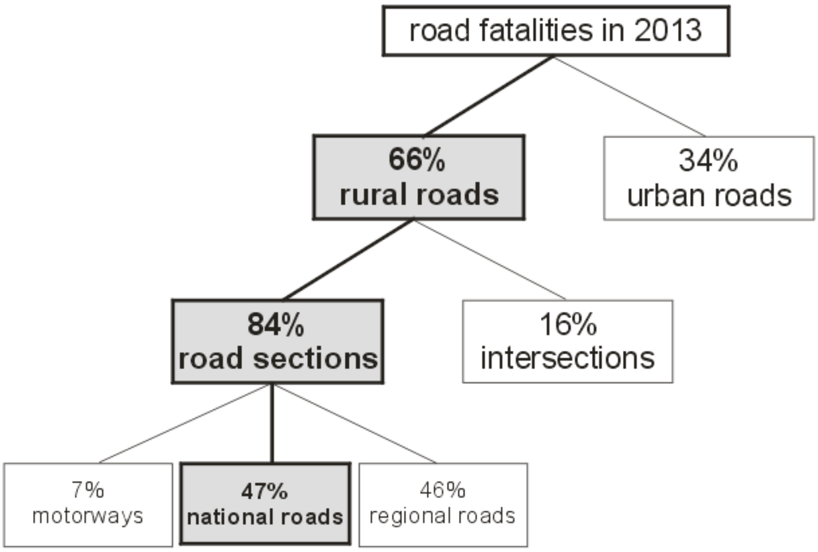

FIGURE 1 Division of Czech road fatalities counts by road settings according to 2013 police data.

Each level of graph provides several blocks describes in terms of percentages of road fatalities in 2013. The blocks with higher percentage in each level present more critical settings. For example, the first level documents that 66% of road fatalities occurred on rural roads, while remaining 34% occurred on urban roads; therefore, rural roads are more critical. Bold lines and grey blocks in Figure 1 illustrate the most critical settings through the whole graph: they are rural sections of national roads. 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.

To sum up, this critical situation is to a great extent related to speeding consequences related to rural road curves. One of the reasons may be the lack of design consistency: drivers are likely to make fewer errors in the vicinity of geometric features that conform to their expectations than they do in the vicinity of features that violate their expectations (*3*). Consistent design should ensure that successive geometric elements are coordinated in a manner that minimizes variability in vehicle speeds, prevents critical driving maneuvers and reduces crash risk (*4, 5*). Design consistency evaluation and improvement is therefore one of several promising tools that may be employed to improve roadway safety performance (*6*).

The objective of the presented study is to prove practical application of this concept on rural sections of the selected Czech national roads, without their design data. A data collection vehicle was used to obtain position data on the selected road network. The data processing included a determination of horizontal alignment elements and segmentation and calculation of design consistency measures. The calculated speed consistency level allowed safety ranking of curves. These results were subsequently validated with actual safety performance using the potential for safety improvement calculated with a crash prediction model and empirical Bayes method.

After this introduction and the following literature review the study is presented: firstly the data collection and analysis method is introduced, followed by results, and finished with discussion and conclusions.

2 LITERATURE REVIEW

Since one of the symptoms of a geometric feature that violates driver's expectation is inconsistent operating speed in the vicinity of this feature, consistent operating speeds are thought to be a product of consistent design (*3*). Therefore, variables for evaluating design consistency are usually defined in terms of operating speed (*7*).

McFadden and Elefteriadou (*4*) used 85^{th} percentile of maximum speed reduction calculated from data in nine points on the curve and the approaching tangent; subsequently, Misaghi and Hassan (*8*) introduced 85^{th} percentile speed reduction for individual drivers based on data from two points on the approaching tangent and at the middle of the curve. Cafiso et al. (*9*) used the following consistency measures in prediction modelling: a relative area bounded by the speed profile, a standard deviation of operating speed profile, average speed differential and speed differentials density. Camacho-Torregrosa et al. (*10*) developed an index based on speed differential and average speed reduction.

Nevertheless, one consistency measure has been used the most (*6, 7, 9*): based on the key works of Lamm and colleagues, design consistency is evaluated in terms of the magnitude of speed reduction between successive design elements. Design is regarded as 'good' if the magnitude of the difference in 85^{th} percentile is lower than 10 km/h; the design is 'fair' if the difference is between 10 km/h and 20 km/h; and the design is 'poor' if the difference is higher than 20 km/h (*11, 12, 13*).

Should these measures be used, position and curvature data (horizontal alignment) have to be obtained. They may certainly be retrieved from map sources or project documentations. However, there may also be cases when the alignment parameters are unknown. GPS positioning has recently been used in this regards, followed by different approaches to segmentation and calculation of required measures (*14 – 17*).

In order to prove validity of safety ranking based on design consistency measures, a comparison with crash situation is typically conducted. However, there are different approaches to quantification of safety based on crash occurrences: while earlies studies used crash rates (e.g. *11, 18*), other methods were recommended later, in order to take into account statistical characteristics of crash data (e.g. *3, 19*). Further differences are in the selection process of target group of crashes believed to be related to road alignment: e.g. Anderson et al. (*3*) used both single- and multi-vehicle crashes but excluded, among others, crashes with animals; on the other hand, Lamm et al. (*12*) report that German comparison studies rely on run-off-the-road crashes and deer crashes. Weller (*20*) saw 'driving' crashes (i.e. single vehicle crashes) as the only reasonable category, while Turner et al. (*21*) combined loss-of-control and head-on crashes. Most authors do not detail these considerations and use all the crashes together.

3 DATA COLLECTION AND ANALYSIS

The study was conducted in one of the Czech regions (Kraj Vysočina) with rolling terrain. There are 5 national roads in this region; the ones with the highest traffic volumes and risk were selected for the study (roads No. 19 and 34). Figure 2 shows where the region and the selected roads are located. Both roads have an overlapping part which was considered as a part of road 34, as indicated by colors in Fig. 2.

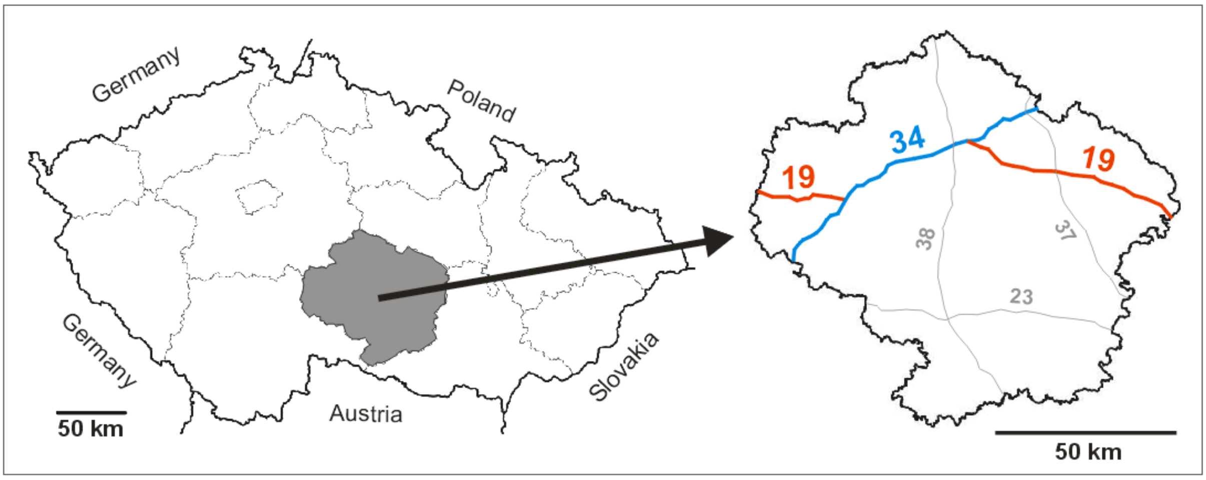

FIGURE 2 Geographical location of selected national roads within the region and the Czech Republic (http://commons.wikimedia.org/).

The roads are paved, two-lane, undivided, approximately 7 meters wide. Approximate average annual daily traffic volume is between 5,000 and 10,000 vehicles, general speed limit is 90 km/h. Figure 3 provides two illustrative photographs of selected roads. After excluding the road sections in built-up areas (through-roads), their total length was approximately 100 km.

FIGURE 3 Illustration of road environment on selected roads (https://maps.google.cz/).

3.1 Alignment data

The roads in question were driven through on two weekdays in November 2013, in one direction, as close as possible to free-flow speed. The inspection vehicle of Centrum dopravního výzkumu, v.v.i. (Transport Research Centre) was used for this purpose. It is a customized Volkswagen Transporter T5 vehicle 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 (10 records per second). At the typical speed of 90 km/h the speed synchronization period equals to 2.5 m of driven distance. All data were stored on a solid-state drive (SSD) in XML format.

It is difficult in the Czech Republic 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 (*17*); for this study it was programmed into an internal web module in order to ensure its wider application. It was developed using a PHP programming language and MySQL database system. The employed calculation procedure consisted of several steps:

– Transformation of 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 tests, its value was set at 80 gon/km.

Details may be found in the paper describing the pilot study (*17*). The results of segmentation were visualized with HTML and JavaScript environment using MapQuest free online web mapping service. Figure 4 presents one example (grey dots form tangents, red dots are curves).

FIGURE 4 Illustration of segmentation results (tangents in grey, curves in red).

In terms of design consistency, each segment may be characterized by its values of CCR and speed. These measures change continuously within a segment, as illustrated in Figure 5, which shows the values related to the example section from Figure 4.

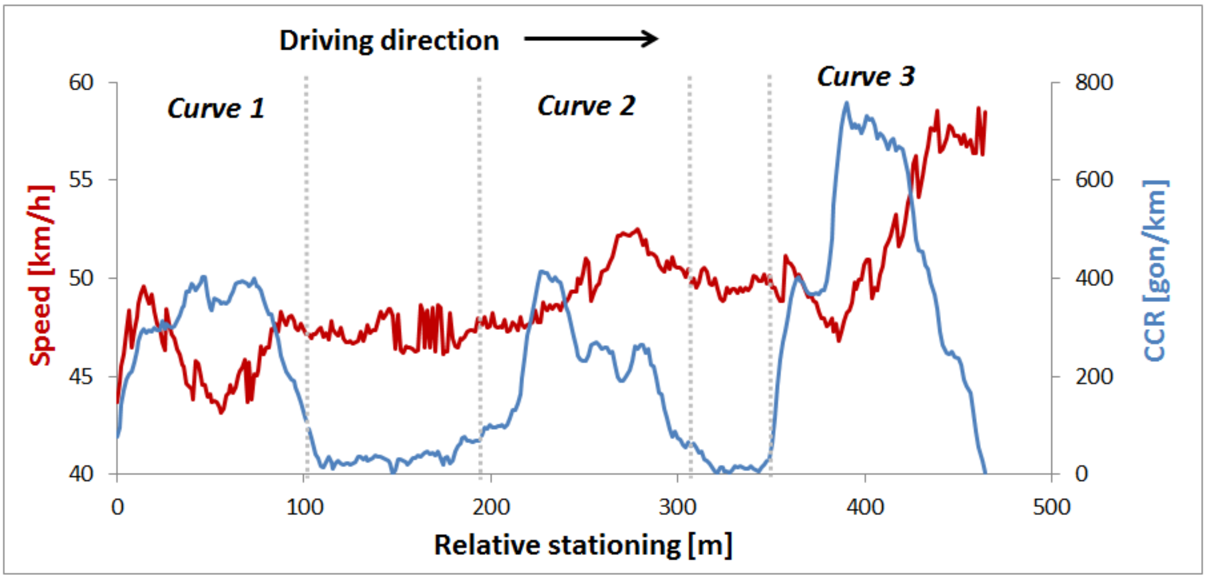

FIGURE 5 Speed and curvature change rate (CCR) within road section from Figure 4.

For each segment 85th percentile and average of CCR and speed were determined. The presented study evaluated only curves. The CCR and speed values were used in the following steps (crash modeling and validation).

3.2 Crash data

Crash locations are routinely georeferenced by Czech Traffic Police and described according to their methodology. This information was used in the study with the following characteristics:

– 5-year period (2009 – 2013)
– All severity levels (property damage only, slight/severe/fatal injury)
– Only single-vehicle crashes

Using this definition, crashes on selected roads were retrieved from the Police database and assigned as a crash frequency to each curve in QGIS software environment. As a risk exposure indicator, traffic volume data were retrieved from the National Traffic Census data of the Czech Road and Motorway Directorate.

In order to determine actual safety performance of each curve, an indicator of a potential for safety improvement (PSI, see e.g. *22*) was chosen. Its calculation required an estimation of expected crash frequency using a crash prediction model and adjustment according to empirical Bayes methodology. The crash prediction model was developed as a negative binomial regression model with explanatory variables of traffic volume, average curvature and curve length in the following form (for each curve i):

$$P_i = a \cdot AADT_i^b \cdot CCR_i^c \cdot \exp(d \cdot L_i) \tag{1}$$

where:

P_i … predicted (expected) crash frequency
$AADT_i$ … annual average daily traffic volume
CCR_i … average curvature change rate
L_i … length
a, b, c, d … regression coefficients to be estimated

SPSS procedure GENLIN was used for the modeling. Consistently with the literature (see e.g. *22*, *23*), further calculation steps for each curve i were as follows:

$$EB_i = w_i \cdot P_i + (1 - w_i) \cdot R_i \tag{2}$$
$$w_i = \frac{k_i}{k_i + P_i} \tag{3}$$
$$k_i = k \cdot L_i \tag{4}$$
$$PSI_i = EB_i - P_i \tag{5}$$

where:

EB_i … empirical Bayes estimate
w_i … weight
P_i … predicted crash frequency
R_i … recorded crash frequency
k_i … overdispersion parameter
L_i … curve length
PSI_i … potential for safety improvement

4 RESULTS

The objective of validation procedure was to compare the results of two rankings:

- potential for safety improvement (PSI) of curve i from the empirical Bayes method
- absolute difference of 85th percentile speeds ($|\Delta V_{85}|$) between curve i and tangent $i + 1$

Top ten curves ranked by descending PSI values (in units of crashes in 5 years) were used in the following graphs (Fig. 6), separately for roads No. 19 and 34.

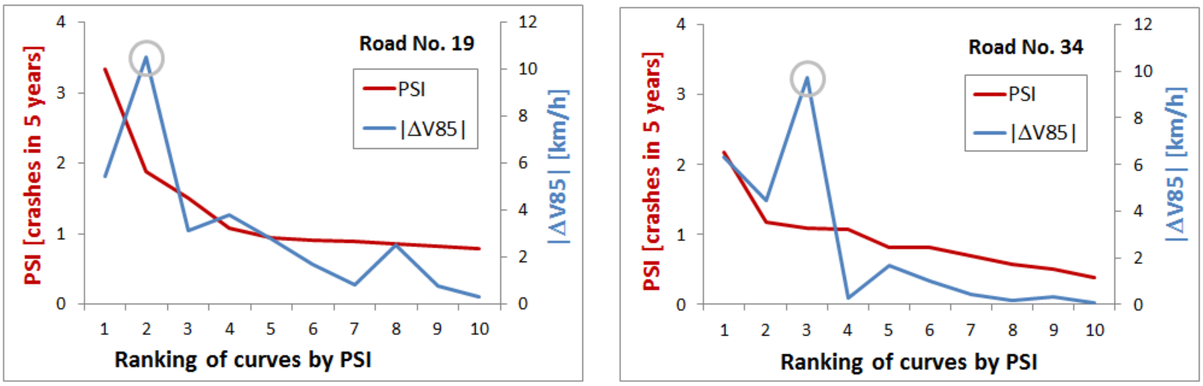

FIGURE 6 Comparison of results for top ten curves according to ranking by potential for safety improvement.

In general, there is an obvious relationship between trends of PSI and $|\Delta V_{85}|$. However, there is an outlying value of speed in both graphs (in grey circle). After checking specific locations it was found that these were the curves where the vehicle was driving uphill.

5 DISCUSSION AND CONCLUSIONS

The objective of the presented study was to prove the practical application of design consistency concept on rural sections of selected Czech national roads. The position data were collected by the inspection vehicle and processed in order to obtain CCR necessary to distinguish the alignment elements (tangents and curves). Speed consistency measure was calculated for each curve and compared with its potential for safety improvement based on the crash prediction model and empirical Bayes method. Both indicators were used in safety rankings of curves.

The results (Fig. 6) proved that there are relatively similar trends between both safety rankings. However, outlying values were also detected – specifically in the curves with vertical curvature which was not taken into account in the evaluation. There were also other limitations of the presented study:

– *Data collection*. Data were collected within a single ride only and in a single driving 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. In this regard, more drives, possibly with more drivers, could offer more representative 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 (*4*). Other measure, such as 85th percentile of maximum speed reduction, may circumvent the issue (*24*).

- *Crash sample*. The sample of modeled crashes was generally small: 199 crashes occurred in total in curves of roads No. 19 and 34, of which only part (117) were single-vehicle crashes, used for the modeling. Samples should generally be larger, for example Jonsson (*25*) recommends at least 200 crashes in order to construct sound models. There is also a 'low mean problem': in the studied sample there is approximately 0.8 crash per curve, or 0.5 single-vehicle crash per curve. This fact may produce unreliably estimated overdispersion parameter and therefore bias the following empirical Bayes estimate (*26*).
- *Other influences*. There is certainly a number of factors which influenced both crash frequency and speed and were not controlled for in the presented study, e.g. vertical curvature, but also cross section parameters such as the number of lanes, road width and local speed restrictions.

Notwithstanding these limitations, the results showed that speed consistency is related to actual safety (in terms of potential for safety improvement) and may thus serve as a surrogate measure. Further research will aim at improving the evaluation methodology and enlarging the sample so that the results may be more representative and valid.

Once improved the method may have several practical applications in the future, some of which are described:

- *Identification of critical curves for efficient local reconstructions*. In Czech standards the process of road design is mostly dictated by the design speed, which is set according to road category. These standards not only govern new road design, but also reconstructions of current roads. During reconstructions it is often impossible to adhere to requirements of curve radii according to the design speed. The frequent reasons are larger property demands and subsequent higher construction costs. Therefore, frequently set lower design speed is applied in the whole road section, while the critical curve inconsistency itself remains untreated. The ranking method proposed in the paper would be beneficial for the identification of these local inconsistencies and thus directing the reconstruction efficiently.
- *Proactive evaluation of selected roads*. Road agency may use the method to proactively evaluate selected roads, to compare or rank them, and to determine the importance of the application of road safety measures. A potential low-cost solution to improve road safety in the described locality and in some similar ones may then be immediately installed. The same holds for comprehensible road signing which would inform of the unsatisfactory curves. The consistent road signing would provide drivers with clear information about a situation they are to expect. This is important since Czech standards do not set a unified approach for installing suitable warning signs such as chevrons. These are often found at locations which are not as risky as others where such signs are missing. With the use of the mentioned method, the unsatisfactory curves could also be equipped with a road sign of advisory speed limit. It provides a useful way to inform drivers who do not drive through such route daily, while not limiting the drivers who are familiar with this route.

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