IDENTIFICATION OF ROAD HORIZONTAL ALIGNMENT INCONSISTENCIES – A PILOT STUDY FROM THE CZECH REPUBLIC

Jiří Ambros[1]✉, Veronika Valentová[2]

CDV – Transport Research Centre, Líšeňská 33a, 636 00 Brno, Czech Republic
E-mails: [1]jiri.ambros@cdv.cz; [2]veronika.valentova@cdv.cz

Abstract. There is a problem with inappropriate speed consequences related to horizontal alignment of Czech rural roads. Evaluation of alignment consistency, i.e. the degree to which a road is designed and constructed to avoid critical driving manoeuvres, has been known as one of promising tools in this regard. The objectives of presented pilot study were (1) to prove the practical application on historical rural road, lacking design data, using low-cost technology, (2) to investigate the relation of obtained alignment consistency measures to actual safety, and (3) to propose further steps for practical implementation, e.g. for the needs of road agency. Given these objectives and literature review findings, GPS technology was chosen for data collection, with the aim of using alignment consistency levels. Pilot rural road section was approximately 2.5 km long and consisted of 3 straight segments and 3 curves. Data processing included determination of central trajectory, determination of horizontal alignment elements and segmentation, calculation of consistency measures, and identification of inconsistencies. The results are given in terms of the consistency level of individual curves, followed by validation by the results of accident data analysis. In the end, several practical applications are listed and described.

Keywords: rural road, horizontal alignment, consistency, speed, accident, safety.

1. Introduction and problem statement

Road horizontal alignment is one of general features which have a significant impact on driving and safety. It consists of straight segments (tangents) connected by horizontal curves (and other transition elements). Specifically curves are places of special interest because of the higher risk of a traffic accident due to additional centripetal forces exerted on a vehicle, driver expectations, and other factors (Hummer *et al.* 2010). According to PIARC *Road*

Safety Manual (2003) from 25% to 30% of all fatal accidents occur in 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 horizontal curve accidents. In order to structure these numbers disaggregated Police data were used for Fig. 1. It provides division of Czech road fatalities by road settings (rural or urban roads), road network elements (sections or intersections) and their categories (motorways, national or regional roads).

Grey blocks in Fig. 1 show the most critical settings according to the number of road fatalities in 2013: these are rural segments of national or regional roads. In both categories between 40% and 50% fatalities are related to curve accidents. Within these accidents on regional roads inappropriate speed was attributed as main cause of 66% fatalities. Czech act No. 361/2000 Coll. defines inappropriate speed as a result of not accommodating driving speed to road conditions (e.g. snow or ice) and situations (e.g. curve, intersection or grade) or sight conditions (e.g. in fog, rain or at night).

To sum up, this critical situation is to a significant extent related to inappropriate speed consequences related to horizontal alignment of Czech rural roads. According
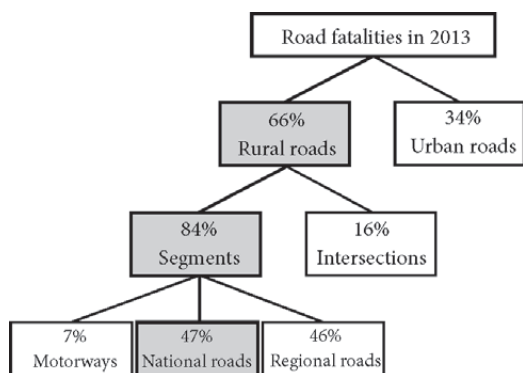

Fig. 1. Division of Czech road fatalities by road settings according to 2013 police data

to Hassan (2004), alignment consistency has been defined as the degree to which a road is designed and constructed to avoid critical driving manoeuvres – consistent road design thus refers to one that ensures that successive geometric elements are coordinated in a manner to produce harmonious driver performance without surprising events. Alignment consistency evaluation is therefore one of several promising tools that may be employed to improve roadway safety performance (Hassan 2004).

It is to be noted that the alignment parameters, such as distinction between straight and curve segments, may be unknown, since not often updated and precise design plans are available, especially in the case of historical alignments of rural roads.

Authors of the paper were inspired by alignment consistency approach and were interested in testing the practical feasibility in the Czech conditions. Therefore the objectives of presented pilot study were as follows:
- to prove the practical application on historical rural road, lacking design data, using low-cost technology;
- to investigate the relation of obtained alignment consistency measures to actual safety;
- to propose further steps for practical implementation, e.g. for the needs of road agency.

After this introduction and following literature review, a pilot study is presented: firstly the data and method is introduced, followed by results, discussion and conclusions.

2. Literature review

There are several variables available for evaluating alignment consistency. Hassan (2004) mentions mostly predictors of horizontal curve radius, curvature change rate, degree of curve, and others. Subsequently Misaghi and Hassan (2005) introduced new factors based on the speed reductions of individual drivers such as 85MSR (85th percentile of the maximum speed reduction for individual drivers based on data from nine points on the curve and approach tangent) and $\Delta 85V$ (85th percentile speed reduction for individual drivers based on data from two points on the approach tangent and at the middle of curve). Zuriaga *et al.* (2010) studied speed variation on tangent-curve transitions, using $\Delta 85V$, $\Delta V85$, deceleration length, and deceleration length inside the curve. Cafiso *et al.* (2010) used following consistency measures in prediction modelling: relative area bounded by the speed profile, standard deviation of operating speed profile, average speed differential and speed differentials density. Dell'Acqua *et al.* (2013) used two consistency measures: the first was the relative area bounded by the speed profile and the average weighted speed; the second was the standard deviation of operating speeds in each design element.

Nevertheless two consistency measures have been used the most: 85th percentile speed (V_{85}) and curvature change rate of a segment (*CCR*) (Cafiso *et al.* 2010; Hassan 2004; Lamm *et al.* 2002). While V_{85} expresses operating speed, *CCR* serves as an indicator of alignment curvature of specific segment. Applying these two indicators for alignment classification is typically done using difference

threshold for several alignment quality classes. The most common operationalization criteria are introduced in Table 1. They include the cut-off points defining three classes of alignment consistency (good, fair, poor) according to seminal works of Lamm and his colleagues (Lamm *et al.* 1999, 2002, 2007).

Should these measures be used, both curvature (in horizontal alignment) and speed data have to be collected. To obtain alignment data GPS technology has been used recently to collect alignment data for these purposes and various authors have used different approaches for obtaining alignment parameters from GPS data (Ben-Arieh *et al.* 2004; Biagioni, Eriksson 2012; Castro *et al.* 2006). 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; a universal automated method of road alignment inference does not exist (Bogenreif *et al.* 2012; Findley *et al.* 2012; Rasdorf *et al.* 2012).

Regarding necessary data collection there have been various techniques of speed measurement: reviews of past studies mention the most stop watches, radars or lidar guns (Hassan 2004; TRB 2011), others used loop detectors (Brijs *et al.* 2006) or portable magnetic traffic sensors (Park *et al.* 2010). Nevertheless global positioning system (GPS) location has become a state-of-the-practice since 2000 (NCHRP 2002); what is more they may be purchased for a relatively low price at sufficient performance (Lee *et al.* 2012).

3. Data collection and analysis

Based on the problem statement and literature review and having the objective of using low-cost technology, GPS technology was chosen for the data collection, with the aim of using alignment consistency levels mentioned in Table 1.

Cheap off-the-shelf Holux M-1000C Bluetooth GPS Logger was used (Fig. 2). It has small size and light weight (62.5×41×17.1 mm, 53 g, according to the factory information). Its receiver searches up to 66 satellites simultaneously and updates position data each second and logs up to 100 000 coordinates. It is operated in L1 and C/A modes with accuracy <2.2 m in horizontal position and <5 m in vertical position for 95% of time. Collected data may be then uploaded to a computer through USB/Bluetooth connection and tracking history can be shared, for example in GoogleEarth.

Table 1. Classification of the consistency level by their impact on road safety (Lamm *et al.* 2002)

Level 1: good	Level 2: fair	Level 3: poor
$\Delta CCR \leq 180$	$180 < |\Delta CCR| \leq 360$	$|\Delta CCR| > 360$
$\Delta V_{85} \leq 10$	$10 < |\Delta V_{85}| \leq 20$	$|\Delta V_{85}| > 20$

Notes: $|\Delta CCR|$ – the absolute difference of curvature change rate of consecutive segments, gon·km^{-1}; $|\Delta V_{85}|$ – the absolute difference of operating (85th percentile) speed on consecutive segments, km·h^{-1}

Given the focus on historical rural roads, a road section Jinačovice – Kuřim on road III/3846 near the city of Brno (Czech Republic) was selected for the data collection. It was chosen in flat rural area so that driving is not influenced by urban areas or vertical alignment. Its length is about 2.5 km. The road is two-lane, undivided, paved, without shoulders, approximately 6 m wide. It is a part of historical secondary road network, with approximate daily traffic volume of 6000 vehicles and speed limit 90 km/h.

GPS logger was placed on dashboard of personal vehicle whose driver was daily commuting on this route. The route was covered fifteen times by the same driver during April and May 2012. The position and time was recorded in the interval of 1 second.

The collected position and time data were used for subsequent calculations. As mentioned there is no available design documentation for historical rural roads; what is more they were built before application of design standards, therefore often without transition curves. Therefore a method of determination of design parameters had to be developed, in order to obtain data for calculation of consistency measures. Important step of this process is segmentation into straight segments and curves – as indicated in literature review, there is no universal automated method

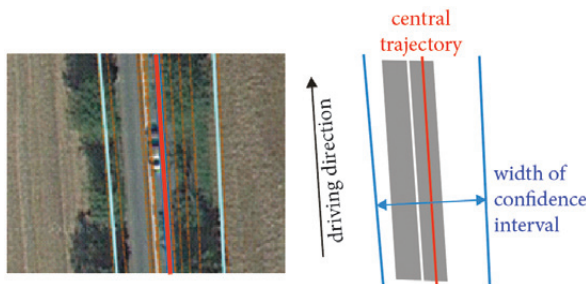**Fig. 2.** Holux M-1000C Bluetooth GPS Logger which was used in the pilot study

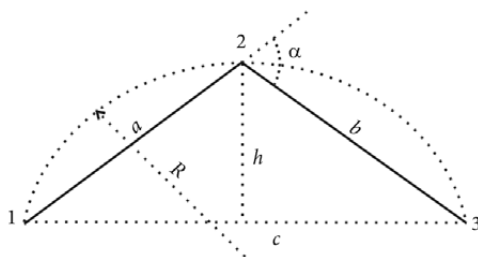**Fig. 3.** Visualization of central trajectory and confidence interval

Fig. 4. Scheme of elements used in the calculation of radius

in this regards. Therefore authors proposed their own approach which will be described in the further text. Following steps of data processing included: (1) determination of central trajectory; (2) determination of horizontal alignment elements and segmentation and (3) calculation of consistency measures (operating speed and curvature change rate) for these segments. These steps are described in turn in the following paragraphs.

3.1. Central trajectory

In order to be able to calculate and visualize data points in Czech conditions, their coordinates had to be converted from WGS 84 to Czech planar coordinate system JTSK, which is conformal, i.e. it preserves angles. Each of 15 runs provided individual trajectory (sequence of points); intersections of perpendicular lines to each trajectory segment (pair of points) created the central trajectory in one direction. Standard deviation, obtained during the calculation, was used to calculate the limits of 95% confidence interval:

$$mean \pm 1.96 \cdot SD, \tag{1}$$

where *mean* – coordinate on central trajectory, m; *SD* – standard deviation of individual trajectories coordinates, m.

The width of confidence interval varied between 5 m and 10 m (Fig. 3). This accuracy is comparable to other studies (Graettinger *et al.* 2001; Ogle *et al.* 2002) and thus considered acceptable.

3.2. Horizontal alignment

Central trajectory was used for following calculations. Firstly, coordinates of central trajectory points were used for the calculation of respective lengths *a*, *b*, *c* and angle α between each three of them, as well as sagitta *h*, using law of cosines (Fig. 4). Given these values, radius *R* was calculated as follows:

$$R = \frac{c^2 + 4h^2}{8h}, \tag{2}$$

where *R* – radius, m; *c* – length, m; *h* – sagitta, m.

Radii were not determined with a single value for whole curves, but always only for each three consecutive points. The "window" of three points was moving with overlaps, i.e. the first window contains points 1 to 3, the second window contains points 2 to 4, etc. Based on the driving speed and GPS sampling frequency, the distance was on average 20 to 30 m between a pair of points. Therefore for each moving interval of this length potential transition curves were approximated by circular curves.

In the next step, angles $α_i$ were summed up to calculate the so called cumulative angle ω (Fig. 5), which was then used as a criterion to distinct between points laying in straight segment and points laying in curve. Based on several trials of different number of points, the cumulative angle of five consecutive points proved as the best descriptor. Based on visual assessment, a limit value was estimated

under which the central point of these five points lay in the curve. Its value is 8 gon (7.2 degrees).

Using this threshold straight segments and curves were classified. In order to obtain segments with logical positions and lengths, minimum number of consecutive points was set to 4. However there may be inaccuracies in GPS localization which causes some points to be assigned incorrectly; points were thus visually checked and corrected. Fig. 6 shows two example cases of these corrections.

3.3. Curvature change rate

Above mentioned values of lengths and radii were used for the calculation of curvature change rate for individual segments (i.e. circular curves) according to the following formula (Lamm *et al.* 2002):

$$CCR_i = \frac{\dfrac{L_i}{R_i} \cdot \dfrac{200}{\pi} \cdot 10^3}{L_i} \cong \frac{\dfrac{L_i}{R_i} \cdot 63700}{L_i}, \qquad (3)$$

where CCR_i – curvature change rate, gon·km^{-1}; L_i – length, m; R_i – radius, m; i – segment number.

Based on curvature change rates a distinction was made between straight segments and curves: segments were considered straight where the discovered curvature change rate ranged between 0 gon/km and 50 gon/km. This threshold was determined based on visual checks of resulting alignment and served as an adjustment of previous segmentation based on cumulative angle, as described in paragraph 3.2. This way the section was divided into six segments, as shown in Fig. 7: straight segments are formed by white dots, curves are in red dots. The section contains three straight segments (No. 1, 3, 5) and three curves (segments No. 2, 4, 6).

Table 2. Calculated values of curvature change rates and speed in segments

Segment number	Curvature change rate, gon·km^{-1}	Speed V_{85}, km·h^{-1}	$|\Delta V_{85}|$, km·h^{-1}	Consistency classification based on $|\Delta V_{85}|$ and Table 1
1	36	91		
			2	good
2	99	93		
			2	good
3	25	95		
			15	fair
4	252	80		
			2	good
5	43	78		
			6	good
6	257	72		

3.4. Operating speed

Within the study 85th percentile of measured speeds on individual segments was used as the operating speed. The following Table 2 and the graph in Fig. 8 presents the calculated curvature change rates and speeds for individual segments. Segments are numbered according to Fig. 7.

4. Results

The results are given in terms of the consistency level of individual curves. An illustrative speed model equation is also introduced. In order to verify the safety performance assessment, accident data analysis results are also mentioned.
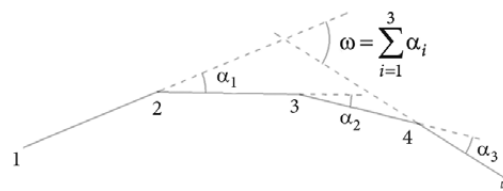

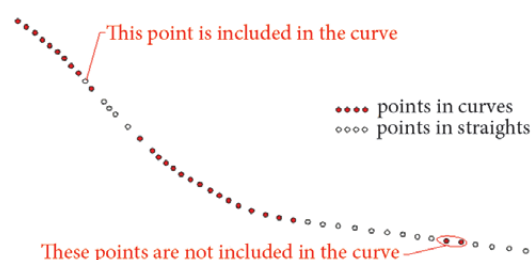**Fig. 5.** Scheme of the principle of five-point cumulative angle calculation

Fig. 6. Two example cases of corrections of segmentation into curves and straight segments
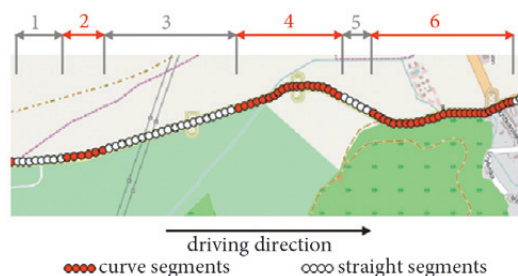

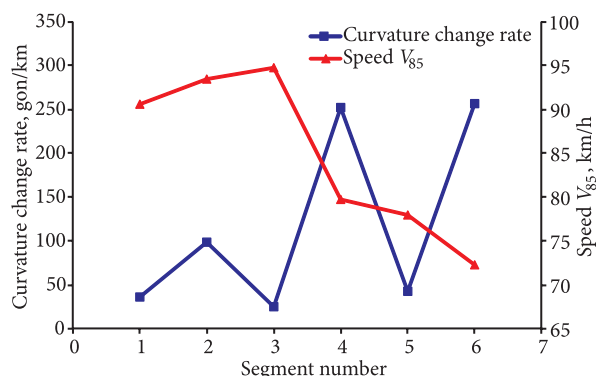**Fig. 7.** Result of segmentation into curves and straight segments

Fig. 8. The course of curvature change rate and speed on studied road segments

4.1. Consistency level

The graph in Fig. 8 shows an obvious reduction of speeds in the curve of a curvature change rate exceeding 250 gon/km. According to Table 2, the curve was considered "fair". The following Fig. 9 shows the evaluation of curves consistency.

4.2. Operating speed model

Based on the measurements, the relationship between curvature change rate and operating speed, the so-called speed model, was derived (Fig. 10). Linear regression was used, both intercept and slope were significant at level $p < 0.0001$.
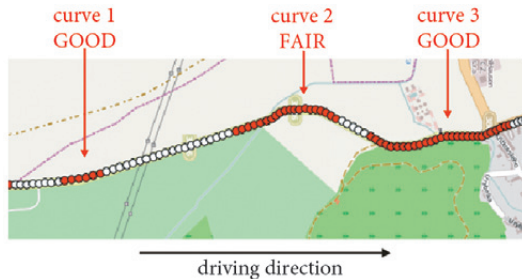

Fig. 9. Assessment of alignment consistency of the three curves

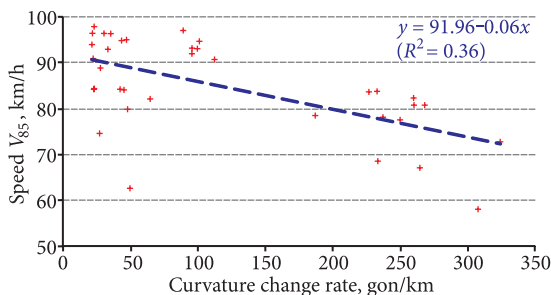**Fig. 10.** Illustrative speed model derived from data on the pilot road segment

Table 3. Equations of relatively similar speed models

Model derived from Czech pilot study	$V_{85} = 91.96 - 0.061 CCR$
Model derived in Lebanon	$V_{85} = 91.03 - 0.056 CCR$

where V_{85} – 85th speed percentile, km·h^{-1}; CCR – curvature change rate of segment, gon·km^{-1}.

Due to the small amount of data from single road, a model may only be considered as illustrative. In addition, a number of sources recommend using other variables and other function forms (TRB 2011). For example Dell'Acqua and Russo (2011) recognize following variables influencing actual driver speed behaviour:

- functional factors (pavement distress, intersections, driveways);
- geometric factors (radius, curvature change rate, width of lane and shoulder);
- speed factors (speed on the preceding curve).

Nevertheless in spite of its illustrative character, the model is relatively similar to some speed models used in the world, mentioned in Lamm *et al.* (2007) – see example in Table 3.

The equations of Czech and Lebanese speed model, as specified in Table 4, are relatively similar. One of reasons could be that, according to Lamm *et al.* (1999) and (2007), speed limit for Lebanese rural roads sample was 80 km/h, which is close to 90 km/h in the Czech case.

The decreasing trend of speed is confirmed by the expected relation to the curvature change rate of the road segments in question, as confirmed in the literature. This confirms the suitability of applying the criteria of speed and curvature change rate for the assessment of the level of consistency shown in Table 2. In addition, an accident analysis was performed in order to test this classification.

4.3. Accident analysis

The accident analysis in the curves in question utilized the Police data on road accidents. More than 50 accidents were identified in this road section in 1998–2013. This number was further narrowed down by excluding the accidents in the opposite direction and by the exclusion of accidents in straight road segments. The result amounted to 8 accidents which occurred – according to the Police classification – in the curve or in its vicinity. Table 4 provides an overview of these accidents with their characteristics. However it has to be noted that accident types and main factors are defined according to the police practices and not fully descriptive; for example "inappropriate way

Table 4. Information on accidents which occurred on the three studied curves and in their vicinity

Curve number	Year	Location	Accident type	Main factor	Number of injured persons (up to 24 hours)		
					fatal	severe	slight
1	2006	after curve	run-off-road	counterflow driving	0	0	1
	2008	curve	rear-end	insufficient gap	0	0	0
2	2000	curve	head-on	speed not accommodated to curve	0	0	1
	2003	after curve	run-off-road	inappropriate way of driving	1	0	0
	2003	curve	angle	inattention	0	0	0
	2007	curve	head-on	speed not accommodated to curve	0	0	0
	2008	curve	side	speed not accommodated to pavement condition	0	0	1
3	2002	after curve	run-off-road	speed not accommodated to pavement condition	1	0	0

of driving" or "inattention" may include several different and unexplained risk factors.

The accident performance in the three monitored curves (Fig. 9) was further assessed with the use of the accident indicators. Since the segments had different lengths, simple accident frequency could not be used. Instead two common indicators derived from accident frequency were used – these were accident density and accident rate. Accident rate *AR* was derived from the number of accidents, length of road segments, and their *AADT*s; accident density *AD* was derived from the number of accidents and the length of road segments.

$$AR = \frac{N}{365 \cdot AADT \cdot L \cdot t} \cdot 10^6, \qquad (4)$$

$$AD = \frac{N}{L \cdot t}, \qquad (5)$$

where *AR* – accident rate, $veh^{-1} \cdot day^{-1} \cdot m^{-1} \cdot year^{-1}$; *N* – annual accident frequency; *AADT* – annual average daily traffic volume, $veh^{-1} \cdot day^{-1}$; *L* – segment length, m; *t* – observed time period, year; *AD* – accident density, $m^{-1} \cdot year^{-1}$.

AADT value was used from the national traffic census – since the route does not involve any volume changes at intersections, *AADT* value is uniform for all studied segments. The census takes place every 5 years, i.e. it was conducted in 2000, 2005 and 2010 within studied period (Table 5). Since *AADT* is gradually increasing in time, the calculations in individual years, when the accidents occurred, used the values which were linearly interpolated between the values from the national traffic census.

Furthermore, the average of these individual accident rates was used. The results are shown in Table 6.

The mentioned values of both indicators of accident performance make it obvious that the second curve (classified as "fair") is significantly less safe than the other two, which were classified as "good". The ratio between accident rate for "good" and "fair" consistency is about 1:3, which corresponds with the findings of similar foreign analyses synthesised in Lamm *et al.* (1999).

5. Summary, discussion and conclusions

Original objectives were (1) to prove the practical application, (2) to investigate the relation of alignment consistency measures to actual safety, and (3) to propose further steps for practical implementation, for example for road agency. These objectives were reached as described in the previous text. Effective use of low-cost off-the-shelf GPS module, placed in personal vehicle, proved as a sufficient

way to collect acceptable data. Data were processed and used to evaluate alignment consistency levels and identify the inconsistencies. This assessment was confirmed by accident occurrence in terms of both accident density and accident rate. It was shown that utilized classification objectively identifies differences in safety of individual road segments.

Alignment consistency level may be therefore used as an indirect road safety indicator. This indirect indicator may be used proactively, i.e. without waiting for an accident, e.g. within a road safety audit of a project documentation. This way it is possible to come closer to the so-called self-explaining roads. Such roads have homogeneous categories whose alignment and equipment correspond with expectations of their users. Since the expectations of drivers correspond with the real situation, the traffic flow on self-explaining roads should be smooth and safe.

It has to be noted that the process used in the pilot study may have several potential inaccuracies, such as GPS module position quality, sample size, segmentation thresholds or consistency classification limits. Regarding operating speed models, TRB (2011) review *Modeling Operating Speed* listed among others following limitations and deficiencies:

– the great majority of existing models predict speeds for passenger cars only;
– most models predict speeds on horizontal curves while relatively few models predict speeds on tangents;
– relatively few models consider combinations of horizontal and vertical alignment;
– linear regression was used for most models;
– relatively few models include acceleration-deceleration models for speeds approaching and exiting curves;
– a majority of models assume a constant speed throughout the horizontal curve.

Although authors made effort to ensure against significant biases, these may still play some role in the study. Some limitations were present already due to the given

Table 5. Values of *AADT* on studied route from national traffic census

Census year	*AADT*, $veh^{-1} \cdot day^{-1}$
2000	2626
2005	4307
2010	5890

Table 6. Safety indicators for the studied curves

Curve number	Accident frequency in 14 years	Approximate curve length, m	Accident density, $m^{-1} \cdot year^{-1}$	Average accident rate, $veh^{-1} \cdot day^{-1} \cdot m^{-1} \cdot year^{-1}$
1	2	300	0.4	3.7
2	5	300	1.1	12.1
3	1	200	0.3	4.2

conditions of cost- and time-effectiveness. Nevertheless authors consider this study as a pilot only and are planning to extend the study, ideally using more vehicles and larger road network for modelling speed on both curves and straight segments. The calculation procedure will also be algorithmized in order to automate the process, which may also lead to its modifications and/or improvements.

To sum up, although the study was only pilot and may have some drawbacks, the result proved that the collected data, used indicators and calculated data, may be used for the classification of consistency of the road horizontal alignment. The method may have several practical applications in the future, which will be shortly outlined in the following points:

– *Identification of critical curves for efficient local reconstructions*. In Czech standards a process of road design is dictated mostly by design speed, which is set according to road category. These standards govern not only 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 often lower design speed is set in the whole road section, while the critical curve inconsistency itself remains untreated. The method proposed in the paper would be beneficial in identifying 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 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 as well as comprehensible road signing which would inform of this unsatisfactory curve. The consistent road signing would provide drivers with clear information which situation 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 traffic sign "advisory speed limit". It is a useful way to inform drivers who do not drive through this route daily, while not limiting the drivers who are familiar with this route.

– *Determination of the "ideal" operating speed*. This speed could be determined using information on speed behaviour and safety performance of selected roads. The ideal operating speed should reflect both the real speed of vehicles V_{85}, as well as the safe speed, hypothetically representing the maximum speed limit. The speed limit itself should be based on operating speed (Fitzpatrick *et al.* 1997), while other factors may be taken into account as well: for example Dutch algorithm of setting "safe and credible speed limits" (SaCredSpeed) considers actual driving speed, but also considers road design and police enforcement (Aarts *et al.* 2010). Resulting "ideal" speed may be used already during the road designing stage; the aim is to minimize the difference between the design and real speed. The quality should then be evaluated in the same way as in Table 1, while using the difference between the design and real speed instead of ΔV_{85}.

References

Aarts, L.; van Nes, N.; Donkers, E.; van der Heijden, D. 2010. Towards Safe Speeds and Credible Speed Limits, in *The 4th International Symposium on Highway Geometric Design*, 1–5 June 2010, Valencia, Spain.

Ben-Arieh, D.; Chang, S.; Rys, M.; Zhang, G. 2004. Geometric Modeling of Highways Using Global Positioning System Data and B-Spline Approximation, *Journal of Transportation Engineering* 130(5): 632–636.
http://dx.doi.org/10.1061/(ASCE)0733-947X(2004)130:5(632)

Biagioni, J.; Eriksson, J. 2012. Inferring Road Maps from Global Positioning System Traces Survey and Comparative Evaluation, *Transportation Research Record* 2291: 61–71.
http://dx.doi.org/10.3141/2291-08

Bogenreif, C.; Souleyrette, R. R.; Hans, Z. 2012. Identifying and Measuring Horizontal Curves and Related Effects on Highway Safety, *Journal of Transportation Safety & Security* 4(3): 179–192. http://dx.doi.org/10.1080/19439962.2011.646001

Brijs, T.; Wets, G.; Krimpenfort, R.; Offermans, C. 2006. Impact of Hourly Measured Speed on Accident Risk in the Netherlands: Results from Exploratory Study Using Geographic Information Systems, *Transportation Research Record* 1972: 85–93. http://dx.doi.org/10.3141/1972-13

Cafiso, S.; Di Graziano, A.; Di Silvestro, G.; La Cava, G.; Persaud, B. 2010. Development of Comprehensive Accident Models for Two-Lane Rural Highways Using Exposure, Geometry, Consistency and Context Variables, *Accident Analysis and Prevention* 42(4): 1072–1079.
http://dx.doi.org/10.1016/j.aap.2009.12.015

Castro, M.; Iglesias, L.; Rodríguez-Solano, R.; Sánchez, J.A. 2006. Geometric Modelling of Highways Using Global Positioning System (GPS) Data and Spline Approximation, *Transportation Research Part C* 14: 233–243.
http://dx.doi.org/10.1016/j.trc.2006.06.004

Dell'Acqua, G.; Busiello, M.; Russo, F. 2013. Safety Data Analysis to Evaluate Highway Alignment Consistency, *Transportation Research Record* 2349: 121–128. http://dx.doi.org/10.3141/2349-14

Dell'Acqua, G.; Russo, F. 2011. Road Performance Evaluation Using Geometric Consistency and Pavement Distress Data, *Transportation Research Record* 2203: 194–202. http://dx.doi.org/10.3141/2203-24

Findley, D. J.; Zegeer, C. V.; Sundstrom, C. A.; Hummer, J. E.; Rasdorf, W.; Fowler, T. J. 2012. Finding and Measuring Horizontal Curves in a Large Highway Network: a GIS Approach, *Public Works Management & Policy* 17(2): 189–211. http://dx.doi.org/10.1177/1087724X11419307

Fitzpatrick, K. C.; Shamburger, B.; Krammes, R. A.; Fambro, D. B. 1997. Operating Speed on Suburban Arterial Curves, *Transportation Research Record* 1579: 89–96. http://dx.doi.org/10.3141/1579-11

Graettinger, A. J.; Rushing, T. W.; McFadden, J. 2001. Evaluation of Inexpensive Global Positioning System Units to Improve Crash Location Data, *Transportation Research Record* 1746: 94–101. http://dx.doi.org/10.3141/1746-13

Hassan, Y. 2004. Highway Design Consistency: Refining the State of Knowledge and Practice, *Transportation Research Record* 1881: 63–71. http://dx.doi.org/10.3141/1881-08

Hummer, J. E.; Rasdorf, W.; Findley, D. J.; Zegeer, C. V.; Sundstrom, C. A. 2010. Curve Crashes: Road and Collision Characteristics and Countermeasures, *Journal of Transportation Safety & Security* 2(3): 203–220. http://dx.doi.org/10.1080/19439961003734880

Lamm, R.; Beck, A.; Ruscher, T. 2007. *How to Make Two-Lane Rural Roads Safer: Scientific Background and Guide for Practical Application*. WIT Press. 144 p.

Lamm, R.; Psarianos, B.; Cafiso, S. 2002. Safety Evaluation Process for Two-Lane Rural Roads: a 10-Year Review, *Transportation Research Record* 1796: 51–59. http://dx.doi.org/10.3141/1796-06

Lamm, R.; Psarianos, B.; Mailaender, T. 1999. *Highway Design and Traffic Safety Engineering Handbook*. McGraw-Hill. 1088 p.

Lee, J.-S.; Yun, D.-G.; Sung, J. 2012. Test of Global Positioning System-Inertial Measurement Unit Performance for Surveying Road Alignment, *Transportation Research Record* 2282: 3–13. http://dx.doi.org/10.3141/2282-01

Misaghi, P.; Hassan, Y. 2005. Modeling Operating Speed and Speed Differential on Two-Lane Rural Roads, *Journal of Transportation Engineering* 131(6): 408–417. http://dx.doi.org/10.1061/(ASCE)0733-947X(2005)131:6(408)

NCHRP 2002. *Collecting, Processing, and Integrating GPS Data into GIS: A Synthesis of Highway Practice*. NCHRP Synthesis 301. Washington: National Academy Press. 65 p.

Ogle, J.; Guensler, R.; Bachman, W.; Koutsak, M.; Wolf, J. 2002. Accuracy of Global Positioning System for Determining Driver Performance Parameters, *Transportation Research Record* 1818: 12–24. http://dx.doi.org/10.3141/1818-03

Park, P. Y.; Miranda-Moreno, L. F.; Saccomanno, F. F. 2010. Estimation of Speed Differentials on Rural Highways Using Hierarchical Linear Regression Models, *Canadian Journal of Civil Engineering* 37(4): 624–637. http://dx.doi.org/10.1139/L10-002

Rasdorf, W.; Findley, D. J.; Zegeer, C. V.; Sundstrom, C. A., Hummer, J. E. 2012. Evaluation of GIS Applications for Horizontal Curve Data Collection, *Journal of Computing in Civil Engineering* 26(2): 191–203. http://dx.doi.org/10.1061/(ASCE)CP.1943-5487.0000127

TRB 2011. *Modeling Operating Speed: Synthesis Report*. Transportation Research Circular E-C151. Washington: Transportation Research Board. 126 p.

Zuriaga, A.; García, A.; Torregrosa, F.; D'Attoma, P. 2010. Modeling Operating Speed and Deceleration on Two-Lane Rural Roads with Global Positioning System Data, *Transportation Research Record* 2171: 11–20. http://dx.doi.org/10.3141/2171-02