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
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 85th percentile of the maximum speed reduction for individual drivers based on data from nine points on the curve and approach tangent) and Δ85V (85th percentile speed reduction for individual drivers based on data from two points on the approach tangent and at the middle of curve). Zuria-ga et al. (2010) studied speed variation on tangent-curve transitions, using Δ85V, ΔV85, deceleration length, and deceleration length inside the curve. Cafiso et al. (2010) used following consistency measures in prediction modeling: 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 (V85) and curvature change rate of a segment (CCR) (Cafiso et al. 2010; Hassan 2004; Lamm et al. 2002). While V85 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 |
| ΔCCR ≤ 180 | 180 < |ΔCCR| ≤ 360 | |ACC| > 360 |
| ΔV85 ≤ 10 | 10 < |ΔV85| ≤ 20 | |ΔV85| > 20 |

Notes: [ΔCCR] – the absolute difference of curvature change rate of consecutive segments, gon·km⁻¹; [ΔV85] – 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 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:

\[
\text{mean} \pm 1.96 \cdot \text{SD},
\]

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 \(\alpha\) 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:

\[
R = \frac{c^2 + 4h^2}{8h},
\]

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 \(\alpha\) were summed up to calculate the so called cumulative angle \(\omega\) (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):

\[
CCR_i = \left( \frac{L_i}{R_i} \right) \frac{100}{\pi} \times 0.63700 \frac{L_i}{I_i},
\]

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).

| 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             |                | good                                             |
| 2              | 99                              | 93             | 2              | good                                             |
| 3              | 25                              | 95             | 2              | good                                             |
| 4              | 252                             | 80             | 15             | fair                                             |
| 5              | 43                              | 78             | 2              | good                                             |
| 6              | 257                             | 72             | 6              | good                                             |

3.4. Operating speed

Within the study 85\(^{th}\) 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.
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 $p < 0.0001$. 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
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 \( AADT \); accident density \( AD \) was derived from the number of accidents and the length of road segments.

\[
AR = \frac{N}{365 \cdot AADT \cdot L \cdot t} \cdot 10^6, \quad (4)
\]

\[
AD = \frac{N}{L \cdot t}, \quad (5)
\]

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

<table>
<thead>
<tr>
<th>Census year</th>
<th>( AADT ), veh(^{-1})·day(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>2626</td>
</tr>
<tr>
<td>2005</td>
<td>4307</td>
</tr>
<tr>
<td>2010</td>
<td>5890</td>
</tr>
</tbody>
</table>

### Table 6. Safety indicators for the studied curves

<table>
<thead>
<tr>
<th>Curve number</th>
<th>Accident frequency in 14 years</th>
<th>Approximate curve length, m</th>
<th>Accident density, m(^{-1})·year(^{-1})</th>
<th>Average accident rate, veh(^{-1})·day(^{-1})·m(^{-1})·year(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>300</td>
<td>0.4</td>
<td>3.7</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>300</td>
<td>1.1</td>
<td>12.1</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>200</td>
<td>0.3</td>
<td>4.2</td>
</tr>
</tbody>
</table>
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 $\Delta V_{85}$.

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