THE BALTIC JOURNAL
OF ROAD AND BRIDGE ENGINEERING

ISSN 1822-427X / eISSN 1822-4288
2016 Volume 11(2): 127–135

EVALUATION OF DESIGN CONSISTENCY ON HORIZONTAL CURVES FOR TWO-LANE STATE ROADS IN TERMS OF VEHICLE PATH RADIUS AND SPEED

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Abstract. Experimental investigation was conducted on a 24 km long segment of the two-lane state road to collect the driver behavior data. The research involved 20 drivers driving their own cars equipped with the GPS device. Considering the impact of path radius and speed on the side friction demand, the design consistency on horizontal curves was evaluated by determining the margins of safety. The analysis showed that the vehicle path radii were mainly smaller than curve radius, on average for 12%. Regression analysis indicated that the percentage difference between the curve radius and vehicle path radius is not affected by the speed, speed differential and geometric characteristics of the curve and surrounding elements. Two different margins of safety were analyzed. One is the difference between maximum permissible side friction (based on design speed) and side friction demand, while another is the difference between side friction supply (based on operating speed) and side friction demand. Generally, demands exceeded supply side friction factors on curves with radii smaller than 150 m, whereas "poor" conditions (in terms of Lamm's consistency levels) were noted for curves under approximately 220 m. Both values are very close to the critical radius below which higher accident rates were observed according to several accident studies. Based on the results of the research, it is proposed to use a 12% smaller curve radius for the evaluation of margin of safety and that curves with radii smaller than 200 m should be avoided on two-lane state roads outside the built-up area.

Keywords: critical vehicle path radius, demand side friction factor, design consistency, global positioning system (GPS), horizontal curve, operating speed.

1. Introduction

Motorized road transport is one of the important characteristics of modern civilization which, with all the benefits that provides, also has a human cost. According to World Health Organization (2013), road traffic injuries are the eight leading cause of death globally. Approximately 1.24 million people die each year on the world's roads and another 20 to 50 million sustain nonfatal injuries as a result of road traffic crashes (World Health Organization 2013). Factors, mainly affecting road safety, are the driver, the vehicle and the road. Accident black spots indicate that, in addition to drivers' errors, road alignment characteristics also affect accident occurrence. Based on statistics from different countries, Lamm *et al.* (1995) have found that more than 50% of the fatalities can be attributed to accidents that occur on rural two-lane roads and at least half of them are related to curve road sections. In general, from 25% to 30% of all fatalities occur in curves (Lamm *et al.* 1999). A large percentage of fatalities are related to horizontal curves in Croatia. According to Road Safety Bulletin (2013), approximately 35% of total accidents with fatalities in 2013 in Croatia occurred along horizontal curves.

More detailed researches show that the accident rates are significantly higher in sharp curves and the number of road accidents tends to increase when the radii of horizontal curves decrease. Road safety problems are more frequent in curves with radii less than 200 m (Raff 1953), but there are several other critical radii suggested, such as 400 to 500 m (Krebs, Kloeckner 1977). According to different studies from various countries, a general form of the relationship between the horizontal curve radius and number of accidents per million vehicle kilometers was developed, as presented in Fig. 1 (PIARC 2003).

Horizontal curves are high-accident locations with most severe consequences. According to Final Report of the ERA-NET programme 2012 (ERA-NET ROAD 2012), 10% of the total accidents are single-vehicle or run-off-road accidents and this rate increases to even 45% when considering only fatal accidents. According to NCHRP Report

doi:10.3846/bjrbe.2016.15

500 (Torbic *et al.* 2004), run-off-road and head-on crashes account for 87% of fatal crashes at horizontal curves for U.S. highway system in 2002, of which even 76% were single-vehicle crashes in which the vehicle left the road and hit a fixed object or overturned, while 11% were head-on crashes. Single-vehicle accidents on horizontal curves usually occur due to loss of vehicle control or stability as a result of exceeding the limiting values of side friction because the driver is traveling too fast to safely negotiate the curve.

Certainly, one of the most commonly used and most effective strategies to improve road safety is road design consistency. It is defined as the condition in which roadway geometry does not violate driver expectations (Castro *et al.* 2013). A consistent road design implies logically arranged successive elements that produce consistent speeds and do not require abrupt actions which increase the accident occurrence. Road characteristics should conform to driver expectancy and provide safe and comfortable ride. Inconsistent road design can produce unexpected changes in dynamic and speed conditions, which may impose high workloads that can surprise the driver and lead to speed or path errors (Cafiso, La Cava 2009). Previous design consistency studies can be categorized into several main groups: operating speed, vehicle stability, alignment indices and driver workload (Hassan *et al.* 2001). Also, various driving performance measures have been recently recognized as appropriate for the evaluation of design consistency (Cafiso, La Cava 2009).

The most frequently used design consistency criteria are based on operating speed because the changes in operating speed are obvious indicators of design alignment inconsistencies (Nicholson 1998; Castro *et al.* 2013). These measures include the design speed and operating speed consistency for a single geometric element and consistency of operating speeds within one road section (Lamm *et al.* 1995). Operating speed is usually defined as 85^{th} percentile speed and many operating speed models have been developed in different regions of the world (Castro *et al.* 2013; *Modeling Operating Speed: Synthesis Report* 2011).

Ensuring the vehicle stability is also important as insufficient side friction at horizontal curves may result in vehicle skidding or rollover. Therefore, identification of locations that do not provide a sufficient level of vehicle stability can be used for the evaluation of geometric design consistency. Lamm *et al.* (1995) have recommended a design consistency measures based on the margin of safety

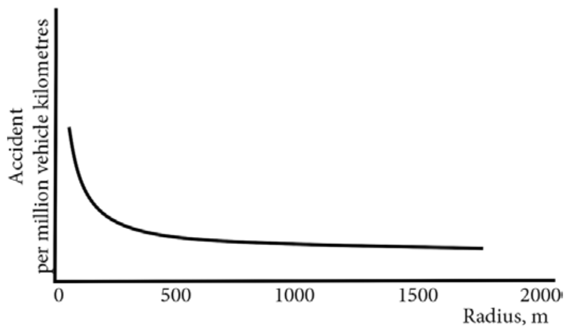

Fig. 1. Effect of horizontal curve radius on accident risk (PIARC 2003)

which is defined as the difference between maximum permissible side friction (f_{Rperm}) and side friction demand (f_{RD}). Side friction demand can be determined from the basic equation of vehicle stability on horizontal curves knowing the operating speed, while maximum permissible side friction is determined on the basis of the skid resistance analyses.

A simple method to evaluate design consistency is to check quantitative measures of the general character of a road segment alignment, collectively called alignment indices. These measures are based on the assumption that the changes in the general character of an alignment between road sections result in geometric inconsistencies (Hassan *et al.* 2001). Some examples of the alignment indices are average radius per roadway section, ratio of maximum radius to minimum radius, average vertical curvature and curvature change rate (the ratio of an individual curve radius to the average radius of the whole road section) (Cafiso, La Cava 2009). Due to their simplicity of use, some of these quantitative measures are included in standard road design procedures.

Design consistency can also be evaluated by using the driver workload criteria. Driver workload increases with the increase in the complexity of the driving situation and increases with the decrease of the time available for information processing and decision making (Nicholson 1998). This consistency criterion is least used because the driver workload is difficult to quantify. However, there are some measures that can be used for the driver workload quantification, such as sight distance and visual demand (Hassan *et al.* 2001).

Driving performance measurements comprise of vehicle trajectory, speed profile, longitudinal deceleration and lateral acceleration (Cafiso, La Cava 2009). They are direct consistency indicators since they point to the deviations between the driver behavior and real highway's geometric and operational features. Previous driving performance studies were using instrumented vehicles, equipped with GPS, video camera and some other devices (Cafiso, La Cava 2009; Said *et al.* 2009).

Most of previous design consistency and road safety studies were based on operating speed whereas only a few researchers were studying the impact of real vehicle path radii on vehicle stability. For this reason, the improved vehicle stability measure was chosen for the examination of design consistency on horizontal curves. As the vehicle stability measure is based on checking the margin of safety (the difference between the limiting value of side friction and demand side friction), the improvement of the consistency measure relates with the inclusion of the real vehicle path radius when calculating the side friction demand. Therefore, the purpose of this paper is to analyze the relationship between horizontal curve radius and real vehicle path radius. Except the analysis of the vehicle path radii, the combined effect of measured speeds and vehicle path radii on the margin of safety for horizontal curves were investigated. Since the existing vehicle stability procedures for evaluating design consistency are based on the assumption that the driver's path radii are equal to the curve radius and that the vehicle moves with constant speed, it is logical to check the safety margins based on actual path radii and speeds. In order to analyze the conformance of the road geometry with the driver behavior, a real-world experiment was conducted. The investigation was carried out on a 24 km long segment of the two-lane state road in which the direct measurements of driving behavior were collected by using a 10 Hz GPS device.

Concerning the driving performance, the objective is to determine the impact of speed and geometric features of the road to the minimum vehicle path radius on horizontal curves. In previous studies, which were relatively limited in radius-estimating techniques, there were only a few attempts to identify possible relationship between the vehicle path and curve radius (Glennon, Weaver 1972; Said *et al.* 2009). Previous researchers have identified great differences in vehicle path and geometric design but only Said *et al.* (2009) gave a clear relationship between curve radii and differences in curvature between the vehicle path and the alignment. They observed higher differences in curvature on sharper curves which are less safe than flatter curves what further raises even more safety concerns. Glennon and Weaver (1972) found that significant number of drivers deviate from the roadway curvature, adopting a path radius sharper than that of the roadway. They indicated that most of vehicle paths exceed the degree of roadway curve at some point of the curve and that this tendency is independent of speed.

It is important to emphasize that in the previous studies, based on continuous GPS data, all the participants were driving the same instrumented test vehicle. That could certainly affect the driver's behavior and it is, therefore, possible that the data may differ significantly during the test and at common driving conditions. However, there is a data collection methodology proposed by Pérez-Zuriaga *et al.* (2013) which involves drivers with their own cars. The data collection process consists of placing GPS devices on passenger's cars. At the entering to the selected road segment, drivers are asked to participate in the research, so the GPS device is placed on the vehicle and the vehicle is released at the exit checkpoint. This methodology ensures collecting a large amount of data which is appropriate for developing different models based on speed. Similar data collection methodology was performed in this study with a detailed description presented below.

2. Data collection and equipment used

An experimental investigation was designed and conducted to collect the driver behavior data on a segment of the two-lane state road D1 in the Central Dalmatia (Croatia). The investigation included 20 drivers (13 males and 7 females) with ages ranging from 25 to 60 years and with different driving experiences (from 2 to more than 30 year). Each driver performed driving test on the selected road segment in both directions, with their own personal car equipped with a GPS device. The rides were recorded between October 2012 and April 2013, during a daylight hours on a dry pavement. The data were collected on a 24 km long road segment outside the built-up area, with a wide range of geometric characteristics. The road segment consists of 97 horizontal curves with radii varying from 80 to 1000 m and 92 tangents with lengths up to 700 m. In most of the cases, there is no spiral transition between the tangent and circular curve or there is a short one (mostly lengths from 20 to 30 m). The roadway is marked and paved with a constant lane width of 3.5 m. The longitudinal grades range from 0% to 6% and the posted speed limit for the greater length of the segment is 60 km/h with four shorter 80 km/h sections.

It is a road segment with relatively low traffic volume and with no main intersections what makes it suitable for collecting the data in free-flow conditions, related only to the geometry of the alignment and driving style of each driver. All the data with any external disturbance were excluded from the database and only the free-flowing vehicles (having at least 5 seconds headway) were taken into consideration. During the driving test, an assistant, seated in the rear seat of the car, was marking the non-free flow sections, using a specific option of the GPS device. This option allows the user to record any event during the drive very easily, just by pressing the button on the GPS device which is later evident in the speed profile when reading the data. In order to reduce the number of non-free flow sections, the driver would have been pulled off the road and included again when the road was empty.

The test drives were carried out by using a high performance GPS device which measures speed, position, acceleration and heading ten times a second. The data, relevant to this study, include speeds, speed differentials, path radii and geometric characteristics of the road (curve radii, super elevations, grades, deflection angles and lengths of horizontal alignment elements). The operating speeds (V_{85}), 85th percentile speed differentials ($\Delta_{85}V$) and critical 15th percentile path radii (R_{15}) were determined from the test rides. The operating speed is usually represented by the 85th percentile of the distribution of observed free-flowing speeds at a particular road segment, i.e. the speed at or below which 85% of drivers actually drive. The greatest speed differential between the preceding element (tangent or curve) and horizontal curve was calculated for each individual vehicle, and the 85th percentile value of these differentials was then determined. The 85th percentile of speed differential represents the differential speed not exceeded by 85% of drivers traveling under free-flow conditions. The 85th percentile speed differential ($\Delta_{85}V$) was chosen rather than the differential of the operating speeds (ΔV_{85}), because the ΔV_{85} is not representative indicator of speed differential (Pérez-Zuriaga *et al.* 2013). Namely, speed distributions at the curved and tangent sections are not the same, so the simple subtraction of the operating speeds is not valid. Also, the 85th percentile speeds at these two locations are probably made by different drivers. As recommended by some authors (Nicholson 1998; Said *et al.* 2009), the 15th percentile path radius was selected for the critical curve path radius. The 15th percentile radius represents the critical value, because the path radii of only 15% of drivers are smaller than R_{15}. Besides the test rides data, the actual curve radii, super elevations, grades, deflection angles and lengths of different alignment elements were determined from the road survey, which was made in 2006 by Croatian Roads Ltd (company for managing, constructing and maintaining of state roads in Croatia).

The path radius of the horizontal curve can be calculated from a measured length of the curve and change in heading, using the formula:

$$R = \frac{57.3L}{D_C}, \qquad (1)$$

where R – curve radius, m; L – length of curve, m; D_C – the change in heading, degrees.

Based on precisely recorded positions and headings (accuracy is 0.2°), GPS device automatically calculates radii of turn. Carlson *et al.* (2005) have identified and tested eight techniques to obtain horizontal curve radii and have concluded that the GPS method provides the most accurate results. GPS method showed the smallest maximum relative error in measured and real curve radii, less than 3% for radii in the range of 60 to 330 m. It was also shown that the precision of radius estimating methods increases as the curve radius decreases.

The recorded test drives data were determined using appropriate software. As relevant for each curve and each test drive, the minimum constant radius was chosen as an achieved vehicle path radius. To avoid variations in the path radii values, caused by any possible noise in data due to lower satellite signals reception, the selected minimum path radius was determined on the curve section with minimum 0.5 seconds of travel and with no significant deviations in curvature (up to 5%).

The values of minimum path radii and appropriate speeds were determined from the 40 drives (20 drives in each direction). Only the sharper curves were analyzed, because the safety is significantly lower in sharper curves with radii up to 400 or 500 m (Krebs, Kloeckner 1977). Additionally, the precision of radius estimating is decreasing with the increase in curve radius. Therefore, only 49 curves with radii varying from 80 to 315 m were selected for analysis. The geometric characteristics of analyzed curve sections are summarized in Table 1.

3. Data analysis

Based on actual continuous data, collected in an investigation on two-lane state road segment, driving performance and vehicle stability were selected for the examination of design consistency on horizontal curves. The objective is to investigate the consistency on horizontal curves by comparing curve radii and critical 15th percentile vehicle path radii and by analyzing the margins of safety. Differences between radii were observed and it was attempted to find the causes of these deviations. It was analyzed whether the speed, speed differential and geometric characteristics of the road affect the driver's choice of path radius. In addition to actual vehicle path radii, the side friction factors were determined, based on vehicle path radii and speeds under real world conditions. The results of the analysis are presented below.

3.1. Analysis of vehicle path radii

Characteristics of the road alignment should be consistent with driver's expectations. The most logical method of checking the road design consistency is comparing the driver's behavior parameters with the actual geometric alignment and detecting their differences. The collected data were used to compare curve radii and critical 15th percentile vehicle path radii and to investigate whether the vehicle speed, speed differential and geometric characteristics of the road affect the driver's choice of vehicle path. The analysis was performed using the multiple linear regressions. In order to investigate horizontal curves with different curvatures, the percentage difference between the actual curve radius and critical 15th percentile vehicle path radius was chosen as dependent variable:

$$\Delta R = \frac{R - R_{15}}{R} 100. \qquad (2)$$

The selected independent variables are 85th percentile curve speed V_{85}, km/h, 85th percentile speed differential $\Delta_{85}V$, km/h, curve radius R, m, grade s, %, superelevation e, %, curve length L, m, previous tangent length L_{pt}, m, following tangent length L_{ft}, m, previous spiral length L_{ps}, m, and following spiral length L_{fs}, m. Besides the geometric characteristics of surrounding elements, speed differential was also chosen as an explanatory variable in the regression analysis in order to include the driver behavior

Table 1. Geometric features of the analyzed curves

Element	Geometric characteristics	Minimum	Maximum	Mean	Standard deviation
Horizontal curve	Radius, m	80	315	161	64
	Length, m	30	320	125	71
	Deflection angle, °	19	142	54	29
	Super elevation, %	2	7	4	1
	Grade, %	0	6	2	2
Adjacent elements	Previous / following tangent length, m	0	337	78	72
	Previous / following spiral length, m	0	60	17	19

in the transition between successive elements. In most of the cases (93%), drivers were decreasing the speed from preceding element to the curve, so only speed reductions were taken into consideration.

At first, the analysis with the data from the test drives of each direction was performed showing that there were no dependence between ΔR and characteristics of surrounding elements as well as speed differential. Therefore, further analysis was conducted with the data from 40 test drives, considering only speed and geometric characteristics of curves. Before the multiple linear regression procedure, the effects of each variable were examined by their individual scatter plots and individual regressions, as shown in Fig. 2. From this preliminary analysis, it was found that the selected independent variables cannot explain much of the ΔR variability. The curve length has the most significant impact on ΔR, while the influences of some independent variables are negligible. The diagrams for curve radius, curve length, deflection angle, operating speed and speed differential (for one direction) are shown in Fig. 2.

Although the selected variables do not explain much of the ΔR variability, some regularities about drivers' behavior could be concluded. Generally, drivers tend to adopt a path radius sharper than that of the road alignment. On average, the critical vehicle path radius is 12% smaller than curve radius. The similar was found by Glennon and Weaver (1972). According them, the radius of the highway curve was from 1.1 to 1.5 times larger than the critical path radius. The highest range of vehicle path radii was found on sharper curves, as shown in Fig. 2a. On sharp and short curves with small deflection angles, many drivers cut the curve performing path radius greater than centerline curve radius (Figs 2a–2c), in order to make the ride more comfortable. At the same time, sharper curves (radii less than about 150 m) are also related to the highest positive ΔR values of even 25%. Since these are small radii curves, they correspond to lower operating speeds but do not depend on curve length and deflection angle. Such behavior could be explained with steering corrections. In order to comfortably negotiate sharp curves, drivers often underestimate the curvature of the alignment. Somewhere along the curve the mistake is realized and it is usually corrected by more or less abrupt turn of the steering wheel which results in path radius smaller than that of the curve. Smaller path radius causes an increase of centripetal acceleration and thus an increased demand of side friction. In poor driving conditions and for speeds not adapted to the curve geometry, such steering corrections may result in vehicle instability and they may potentially cause a single-vehicle accident. The radii inconsistencies were observed in curves sharper than about 150 m indicating an increased risk of skidding which may be related to the fact that sharp curves are associated with increased accident rates, as shown in Fig. 1. Differences in radii basically do not depend on the vehicle speed as shown in Fig. 2d. Also, no statistically significant relationship between ΔR and $\Delta_{85}V$ was found, as it is shown in Fig. 2e.

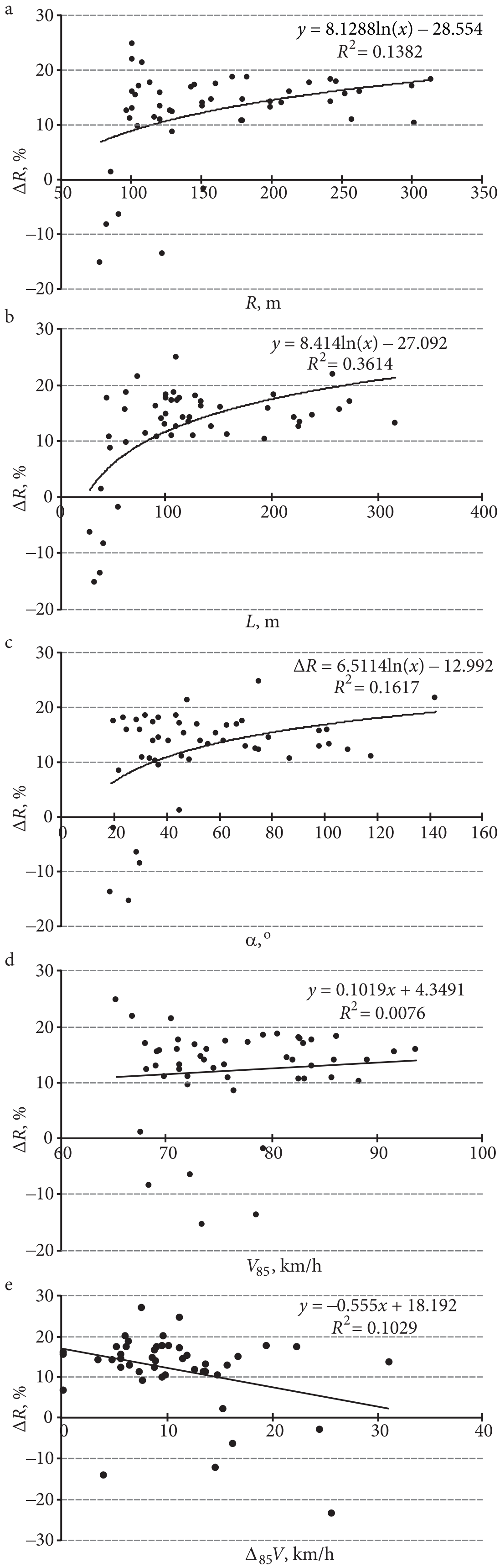

Fig. 2. Individual regression plots of percentage difference between radii versus: a – curve radius; b – curve length; c – deflection angle; d – operating speed; e – speed differential (for one direction)

The negative impact on the driver's choice of path radius might have had the absence of spirals or the application of very short spiral transitions, because the driver failed to adjust both, speed and path radius. So, it would be interesting to analyze the driver's behavior on sections with transition curves of sufficient length, traditional spiral transitions or even some new solutions, for example, general transition curves introduced by Kobryń (2014).

In order to further investigate the influence of the curve radius on radii differences, standard deviations of percentage difference between curve radii and critical path radii of each drive were calculated. The relationship between these standard deviations and curve radii is presented in Fig. 3. It could be noticed that the curve radius does not affect the difference between the curve and each driver's critical path radius. The average standard deviation of percentage radii difference is about 9% with slightly greater standard deviations on sharper curves.

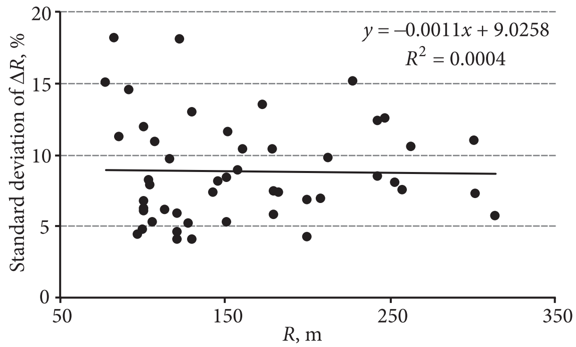

Fig. 3. The relationship between standard deviations of the percentage radii differences and curve radii

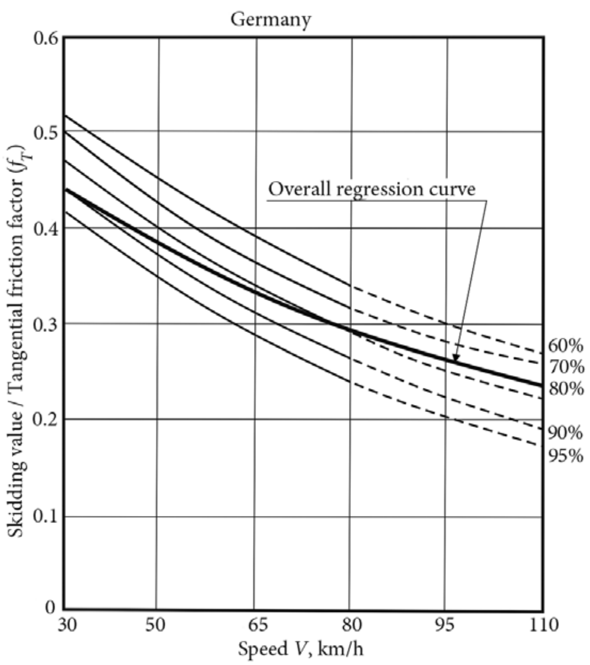

Fig. 4. The overall regression curve compared to tangential friction factors for Germany (Lamm *et al.* 1995)

Finally, the stepwise regression was used for determination of the radii differences model. Fig. 2 shows that the approximation with logarithmic form is slightly better than the linear approximation for curve length, deflection angle and curve radius. Therefore, the logarithmic values of these variables were chosen in the multiple linear regression modelling. The modelling process resulted in a regression model with only the length of curve L as independent variable:

$$\Delta R = 8.41\ln(L) - 27.09. \quad (3)$$

Other proposed independent variables were excluded from the model as it was established they do not contribute much to the overall prediction. The model states that the percentage difference between the radius of road alignment and critical vehicle path radius increases in longer curves. Adjusted coefficient of determination of the model is 0.348 and it indicates that, although there is certain dependence between the percentage of the radii difference and curve length, it is very weak and unreliable.

3.2. Analysis of safety margins based on path radii and speeds under real world conditions

Vehicle stability is an important measure often used for evaluating design consistency on horizontal curves. The loss of vehicle stability on horizontal curves can be result of excessive centripetal force, i.e. it may be due to exceeding the limiting values of side friction. Therefore, this safety criterion is based on determining the margin of safety. Two types of safety margins were analyzed in this paper. The first is the difference between maximum permissible side friction and side friction demand, while the second represents the difference between side friction supply and side friction demand. Maximum permissible side friction factors are based on skid resistance researches and they are different in each country. However, skid resistance backgrounds do not exist for all countries, because these studies are quite complex and expensive. For example, the skid resistance background in Germany is based on an exhaustive study conducted on different types of pavements and in different driving conditions (Lamm *et al.* 1995). For the safety reasons, the 95th percentile distribution curve is used to determine the maximum tangential friction factors what means that only 5% of measured values are smaller. The model of Lamm *et al.* (1995) was used in this paper. Based on the maximum tangential friction factors of selected countries (Germany, France, Sweden, Switzerland and United States), they established an overall regression relationship between the maximum tangential friction factor f_T and design speed V_d, km/h:

$$f_T = 0.59 - 4.85 \cdot 10^{-3} V_d + 1.51 \cdot 10^{-5} V_d^2. \quad (4)$$

The developed overall curve (4) was compared with friction factors, measured on German highways, as shown in Fig. 4. It could be noticed that the overall regression curve covers between 80% and 90% of the measured values from the German skid resistance inventory.

The side friction supply $f_{Rsupply}$ is a fraction of tangential friction, reduced due to tire-specific influences, as described in Eq (5). Maximum permissible side friction factor can be determined according to side friction supply $f_{Rsupply}$ and utilization ratio n (6).

$$f_{Rsupply} = 0.925\, f_T, \tag{5}$$

$$f_{Rperm} = n\, f_{Rsupply}. \tag{6}$$

The utilization ratio n varies between 40% to 60% for rural roads, with respect to the topography and whether it is an existing road. This means that there will still be from 83% to 93% of friction available in the tangential direction for acceleration, deceleration or some evasive maneuvers when driving through curves (Lamm *et al.* 1995).

Side friction demand f_{RD} is calculated from the basic equation of vehicle stability on horizontal curves, based on operating speed V_{85}, km/h, radius of horizontal curve R, m, and super elevation rate e, %:

$$f_{RD} = \frac{V_{85}^2}{127R} - 0.01e. \tag{7}$$

This formula assumes that drivers follow a path with a radius equal to curve radius and with constant speed. As demonstrated on a real-world experiment, this assumption is not true, i.e. the vehicle path radii are usually smaller than designed radius. Thus, the margins of safety are much less than anticipated. In order to obtain more realistic margins of safety, side friction demand factors were determined for each individual vehicle using the Eq (7), considering vehicle path radii, appropriate curve speeds and actual super elevations on curves determined from the road survey. Based on individual side friction demands, the 85th percentile side friction demand f_{RD85} was determined for each horizontal curve. The 85th percentile side friction demand is the side friction demand that is not exceeded by 85% of drivers. The resulting side friction demands were compared with maximum permissible side friction factors, as shown in Fig. 5. Maximum permissible side friction factors are calculated from the Eq (6), considering the applicable design speed V_d = 60 km/h and utilization ratio for exiting roads n = 60%, as defined by Lamm *et al.* (1995). One design speed is selected for the whole analyzed road section, so the maximum permissible side friction factor f_{Rperm} = 0.196 is unique for all curves, regardless of speeds under real world conditions. Whereas the operating speeds are in excess of the design speed on all analyzed curves, the comparison between side friction demands and side friction supply, determined for operating speeds, is also done. This side friction supply, based on operating speed, represents maximum available side friction (in terms of the Lamm's overall regression curve) at pure cornering.

Therefore, in accordance with the side friction factors specified, two different margins of safety are defined. The first margin of safety represents the difference between maximum permissible side friction (based on design speed V_d) and side friction demand ($\Delta f_{R1} = f_{Rperm} - f_{RD85}$) (Lamm *et al.* 1995). The second margin of safety is the difference between side friction supply (based on operating speed V_{85}) and side friction demand ($\Delta f_{R2} = f_{Rsupply} - f_{RD85}$).

Based on vehicle stability, the design inconsistency was observed in a great number of curves. It could be noticed that the 85th percentile side friction demand factors were greater than permissible values in almost all curves and even in 43% of analyzed curves 85th percentile side friction demand exceeded side friction supply factors. The skidding of test vehicles did not happen, because the overall regression curve corresponds to friction values in the worst conditions (wet and dirty pavement, worn tires). However, these findings point to the danger of skidding when driving at higher percentile speed in poor driving conditions. The side friction demand factors, based on the speeds measured on dry pavement, can be compared with friction values that correspond to wet pavement conditions, as Lamm *et al.* (1990) indicated that the driver speed choice on two-lane rural highways is not affected by this condition.

Fig. 6 shows the margins of safety in relation to curve radii, with two sets of safety margins, Δf_{R1} and Δf_{R2}. Since the maximum permissible side friction factors are determined and based on design speed ($V_d < V_{85}$) and reduced by the utilization ratio n, in order to provide a level of skid resistance for safely accommodating the braking and

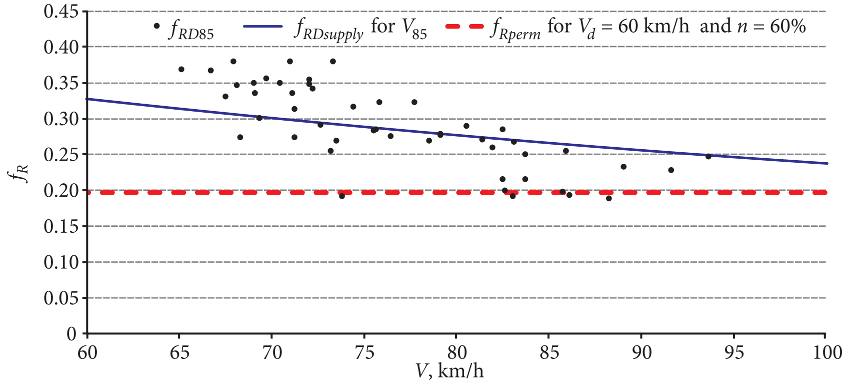

Fig. 5. The relationship between side friction demand, supply and maximum permissible side friction factors based on Lamm's overall regression curve (Lamm *et al.* 1995)

steering maneuvers, the first set of safety margins is lower than the second one and results in higher negative values. Generally, the greater negative margins of safety can be observed on sharper horizontal curves.

Based on accident statistics, Lamm *et al.* (1995) have defined three design consistency levels: "good design" for $R \geq 350$ m, "fair design" for 180 m $\leq R < 350$ m, and "poor design" for $R < 180$ m (Lamm *et al.* 1995). The limiting values of side friction differences for each consistency level were also specified: "good design" ($\Delta f_{R1} \geq 0.01$), "fair design" ($-0.04 \leq \Delta f_{R1} < 0.01$) and "poor design" ($\Delta f_{R1} < -0.04$). In accordance with Lamm's design consistency levels, it can be concluded that even 80% of analyzed horizontal curves can be classified as "poor design" while 20% represent "fair design". In order to establish the marginal radius for "poor" conditions, the trend line that minimizes the squared errors was found (Fig. 6). The limiting radius for "poor" conditions (in terms of $\Delta f_{R1} < -0.04$), approximately defined from the Fig. 6, is 220 m which is very close to the radius of about 180 m determined by Lamm *et al.* (1995).

Except the analysis of safety margins in terms of Δf_{R1}, considering the friction reserve for braking and steering maneuvers, the margins of safety for pure cornering, based on operating speeds (Δf_{R2}), were also analyzed. While the ranges for consistency levels, defined by Lamm *et al.* (1995), exist for Δf_{R1}, these consistency levels are not relevant for Δf_{R2}. In the case of Δf_{R2}, it is interesting to determine the marginal radius above which the curves are safe in terms of $\Delta f_{R2} = 0$. According to the trend line defined for Δf_{R2}, on curves with radii less than about 150 m, the 85th percentile side friction demands were greater than supplying, while the margins of safety in milder curves were almost always positive. These findings indicate increased risk of skidding for operating speeds on shaper curves with radii less than about 150 m in the case of pure cornering. So, the probability of skidding on curves with radii larger than about 150 m is negligible even in the worst pavement conditions, despite the fact that the operating speeds are greater, because the intensity of decreasing the side friction with the speed is lower for higher speeds.

In general, the analysis of safety margins showed that the sharper curves are more dangerous as higher vehicle dynamic inconsistencies were observed on smaller radius curves. It is also interesting to notice that the results from Fig. 6 are very similar to the conclusions of accident studies. Most of accident investigations from different parts of the world pointed out an important impact of the curve radius on road safety. Accident analyses showed that increasing curve radii cause lower accident frequency with different opinions concerning at which radius the impact decreases, starting with the value of about 200 m (Fig. 1). This accident frequency critical radius of 200 m lies somewhere between the marginal radius of 150 m and limiting radius for "poor" conditions of 220 m from the Fig. 6.

This leads to the conclusion that a road design with the use of radii larger than about 200 m would significantly increase the road safety. Milder curves are safer than sharper curves due to decreased probability of skidding as confirmed by accident rates. So, in order to improve the road safety, authors proposed that curves sharper than 200 m should be avoided on two-lane state roads outside the built-up area.

4. Conclusions

This paper presents the design consistency evaluation on horizontal curves, based on real-life driving data, in terms of the vehicle path radii and operating speeds. The research was carried out on a segment of the two-lane state road in Croatia using a GPS device. Specific characteristic of the research as well as the conclusions of the collected data analysis are presented below:

1. In most of the previous instrumented vehicles-based methods for obtaining driving behavior data, all drivers were using the same test vehicle. The data collection methodology used consists of different drivers driving their own cars equipped with a GPS device which certainly represents more realistic driver behavior data.

2. The differences between critical 15th percentile vehicle path and curve radii were observed. Generally, drivers tend to track vehicle path in sharper curvature than that of the road alignment with, on average, 12% lower critical path radius than that of the curve.

3. It was investigated whether the geometric design, speed and speed differential affect the percentage difference between the curve radii and critical 15th percentile vehicle

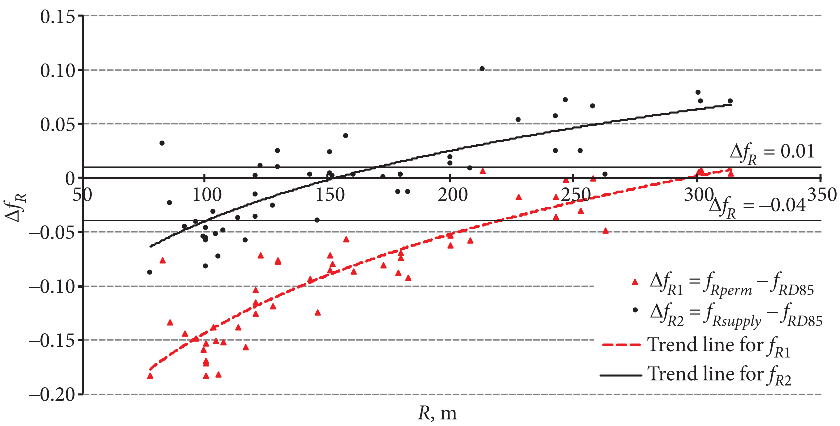

Fig. 6. The differences between supply and demand side friction factors in regard to the curve radius

path radii and no statistically significant correlation was found.

4. Vehicle path radii, lower than curve radii, are observed, which means that the current margins of safety are much less than anticipated. More realistic side friction demand factors (and thereby margins of safety) were determined based on the vehicle path radii, speeds under real world conditions and real super elevation rates. 85th percentile side friction demands were greater than permissible values (determined using the design speed V_d and utilization ratio $n = 60\%$) in almost all curves and in 43% of analyzed curves they exceeded supply side friction factors (determined based on Lamm's overall regression curve using the operating speed V_{85}).

5. The improvement of design consistency measure regarding to the vehicle stability is proposed in terms of lower curve radius. Since the critical vehicle path radius 12% lower than curve radius was observed, it is proposed to use this value when calculating the margin of safety. Smaller values of curve radii would result in lower margins of safety and thus inconsistencies would be easier detected and eliminated. Horizontal curves of the final road design would hence represent the satisfactory level of consistency even in real conditions for the majority of drivers. Designing horizontal curves that are in accordance with the driver behavior is a base to reaching a better design and safer roads.

6. Two types of safety margins were analyzed: Δf_{R1} and Δf_{R2}. Considering the difference between maximum permissible side friction and side friction demand (Δf_{R1}), the limiting radius for "poor" conditions (in terms of Lamm's consistency levels) was determined to about 220 m. Analyzing the difference between supply side friction and 85th percentile side friction demand (Δf_{R2}), negative margins of safety were observed on curves sharper than about 150 m while on milder curves they were almost always positive, despite the fact that the operating speeds are greater. Both radii are very close to accident frequency critical radius below which higher accident rates are observed.

7. Curves with radii less than 200 m should be avoided on two-lane state roads outside the built-up area due to increased risk of skidding for operating speeds.

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Received 12 January 2015; accepted 3 September 2015