EFFECT OF GEOMETRIC ROAD CHARACTERISTICS ON DECELERATION RATE IN TRANSITION FROM TANGENT TO HORIZONTAL CURVE FOR TWO-LANE RURAL ROADS

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Abstract

Evaluation of geometric design consistency presents an important safety aspect in road design. The most commonly used consistency criteria are based on defining operating speed variations along the road segment, usually by depicting operating speed profiles. Many models have been developed worldwide to predict operating speed on curves and tangents. However, it is not possible to create a continuous operating speed profile if transition acceleration and deceleration rates are not defined. Under this scope, this paper presents a study of the deceleration phenomenon based on speeds continuously measured on a segment of a two-lane state road by using a GPS device. Dependence of driver behaviour in tangent to curve transition on geometric characteristics of the road was analysed. The regression analyses show that the deceleration rate is only affected by the curve radius. More specifically, higher deceleration rates generally correspond to transitions between independent tangents to sharper curves that represent inconsistent road alignment.

Keywords: deceleration rate, horizontal curve, two-lane rural road, regression analysis, Global positioning system

1 Introduction

The construction of an operating speed profile is one of the basic steps in the process of designing safe and consistent roads. Consistent road design enables that successive geometric elements act in a coordinated way so that they produce harmonized driver performance without surprising events [1]. Road alignment elements that require large and sudden speed reductions are considered inconsistent and unsafe. Specifically, as confirmed by numerous studies [2-4], such inconsistent alignments represent high-risk locations. With the application of the operating speed profile, alignment elements consistency can be easily checked by simply identifying undesirably large speed changes in transition between adjacent elements. Thereby, design consistency measures based on operating speed profiles are one of the most commonly used tools for evaluating road geometry safety because of their advantages of fast processing, high efficiency, and good user convenience [5].
To construct the operating speed profile it is necessary to develop operating speed models and models for predicting acceleration/deceleration rates. The operating speed V_{85} is normally defined as the 85th percentile of the distribution of speeds selected by drivers in free-flow conditions on individual element of the road alignment [6]. Operating speed studies are widely studied and many models for predicting operating speed have been developed [6–8]. Previous models were mainly developed using linear regression, considering different geometric characteristics of the road.

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Furthermore, most existing operating speed models are based on spot speed data and certain assumptions about drivers' behaviour. Specifically, speeds were usually recorded at specific locations of a roadway, mostly at the middle point of horizontal curves and tangents, manually using radar or lidar guns. In the methodology of spot speed data collection, locations of speed recording are predefined and therefore information about the starting and ending point of the speed change is missing. As a result, the phenomenon of speed change between adjacent alignment elements is poorly investigated and only a few attempts to establish a relationship between geometric characteristics of the road and acceleration/deceleration rate have been registered so far [6, 7, 9, 10]. The methodology of continuous speed recording greatly simplifies this task. Table 1 presents a review of some previous deceleration studies for two-lane rural roads.

Table 1 Previous deceleration models for two-lane rural roads

Country and author	**Deceleration rate**		**Data collection methodology**
ITALY			
Marchionna and Perco [9]	$d = 1.757 - 0.222 \cdot \ln(R)$	$R^2 = 0.74$	Spot speed
CANADA			
Said et al. [10]	$d_{85} = 0.636 + 237.573 \cdot I_T/R - 0.602 \cdot I_T$	$\overline{R}^2 = 0.95$	Continuous speed
USA			
Lamm et al. [11]	0.85 m/s^2		Spot speed
Fitzpatrick et al. [7]	1.0 m/s^2 $d = 0.6794 - 295.14/R$ $R^2 = 0.48$ 0.0 m/s^2	$R < 175$ m 175 m $\le R <$ 436 m $R \ge 436$ m	Spot speed
Figueroa and Tarko [12]	0.69 m/s^2		Spot speed
SPAIN			
Pérez-Zuriaga et al. [6]	$d_{85} = 0.447 + 90.472/R$	$R^2 = 0.70$	Continuous speed

Note: d = deceleration rate (m/s^2); d_{85} = 85th percentile deceleration rate (m/s^2); R = curve radius (m); I_T = dummy variable (I_T = 1 for independent tangent preceding the curve, I_T = 0 for nonindependent tangent).

This study aims to develop a regression model for predicting deceleration rate in transition between tangent and curve for two-lane rural roads, including geometric characteristics of the road as explanatory variables. Since values of deceleration rates are generally higher than acceleration rates and deceleration is riskier action than acceleration, only the phenomenon of deceleration was analysed in this study. The data used in this study were recorded on a segment of the state road DC1 in Croatia using a GPS device. The survey included a representative sample of drivers performing test rides in free-flow conditions with their own personal cars. A more detailed description of the data collection methodology is presented below.

2 Data collection

An experimental investigation was conducted on a 24 km long road segment of the state road DC1 to collect the driver behaviour data. The high-performance GPS device was used to record test drives of 20 drivers (of different ages and with different driving experiences), performed with their own personal cars. Section of the analysed road segment DC1 and GPS data logger used are shown in Figure 1. The selected road segment is a two-lane rural road with relatively low traffic volume (the average annual traffic is about 1400 veh/day) and with no main intersections which allowed to collect the data in free-flow conditions. The selected road segment consists of alignment elements with a wide range of geometric characteristics: 97 horizontal curves with radii varying from 80 to 1100 m and 92 tangents with lengths up to 700 m. The analysed road section was designed several decades ago when, according to the former guidelines, the use of spirals was not obligatory. Therefore, in most of the curves, 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 survey was conducted under optimal weather conditions (daylight and dry pavement).

Deceleration rate analysis is performed for tangent to curve transitions but only for tangents longer than 120 m. The analysed road section consists of too many short tangents which are not allowed according to Croatian guidelines for road design [13]. Furthermore, individual speed profiles show that drivers generally do not notice short (dependent) tangents where speed cannot be fully developed and is usually adjusted according to adjacent curves. To ensure alignment elements consistency, Croatian guidelines for road design [13] define minimum tangent length (in m) as two times the design speed in km/h (2·Vd). Therefore, the minimum tangent length for the selected road segment would be 120 m. Accordingly, a total of 20 tangent to curve transitions in each direction were considered on the entire road segment (i.e., 40 sections in total).

The data relevant for this analysis relate to appropriate speeds, times of speed reductions, and geometric characteristics of the road (curve radii, longitudinal slopes, deflection angles, and lengths). The lowest speeds along horizontal curves and highest speeds along tangents are considered to be the desired drivers' speeds [6]. Except for the data from individual test rides, geometric characteristics of the road were determined from the road survey, which was made in 2006 by Croatian Roads Ltd (company for managing, constructing, and maintaining state roads in Croatia). Based on the data collected in the above field survey, operating speed prediction models for horizontal curves and tangents have already been developed by the authors [14].

3 Data collection

Considering previous deceleration rate models (Table 1), linear regression was used to establish a possible relationship between deceleration rate and geometric characteristics of the road. The independent variables considered in this study are curve radius R (m), deflection angle α (°), length of horizontal circular curve L_c (m), length of preceding and succeeding tangent, respectively L_{T1}, L_{T2} (m), and longitudinal slope s (%). The values of deceleration rates in tangent to curve transitions d_i (m/s^2) were calculated based on individual driver speed profiles, considering lowest speeds along horizontal curves V_c^i (km/h), highest speeds from tangents V_t^i (km/h), and time intervals of speed reduction Δt (s):

$$d_i = \frac{V_c^i - V_t^i}{3.6 \cdot \Delta t} \quad (1)$$

After individual deceleration rates have been calculated using equation (1), the value of the 85th percentile was determined for each configuration. The stepwise regression was used to determine the deceleration rate model, i.e., to investigate which geometric characteristics are correlated with d_{85}. Table 2 presents descriptive statistics for variables used in the development of the deceleration rate model.

Table 2 Descriptive statistics for geometric road characteristics and 85th percentile deceleration rate

Variable	N	Mean	Standard Dev.	Standard Error	Min.	Max.
d_{85} [m/s²]	40	-0.477	0.153	0.024	-0,960	-0,235
R [m]	40	410.125	239.362	37.846	100	1100
α [°]	40	37.625	24.467	3.869	8	102
L_c [m]	40	210.025	129.223	20.432	45	539
L_{T1} [m]	40	236.425	136.439	21.573	123	683
L_{T2} [m]	40	126.500	128.625	20.337	21	683
s [%]	40	-0.04	2.555	0.404	-5.5	4.5

The initial step in the linear regression procedure with several independent variables is to examine the effect of each variable by their individual scatter plots. Among the considered independent variables, only individual scatter plots for R, $L_{T,1}$ and L_{T2} are presented in Figure 1 because of the greatest established correlations with the dependent variable.
The stepwise regression resulted in a model with only the curve radius as an independent variable:

$$d_{85} = -0.340 \frac{40.063}{R} \tag{2}$$

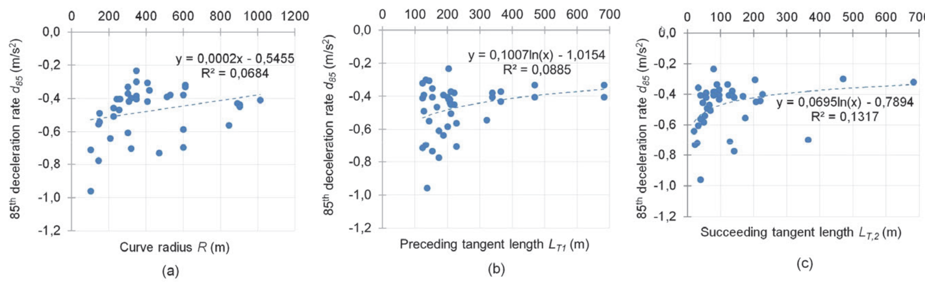

Figure 1 Individual scatter plots of the 85th percentile deceleration rate versus: a) curve radius; b) preceding tangent length; c) succeeding tangent length

Other considered independent variables that are not statistically significant were excluded from the model. According to the model presented with equation (2), intensive deceleration rates correspond to transitions from independent tangents to curves with smaller radii. Although the length of the preceding tangent is excluded from the model, individual speed profiles show that these rates are generally higher for longer tangents. Considering the relatively low adjusted coefficient of determination ($\bar{R}^2 = 0.297$), model (2) cannot be considered statistically significant. Even though there is certain dependence between the 85th percentile deceleration rate and inverse of curve radius, it is very weak and unreliable.
Although the regression analysis did not result in a statistically significant model, the form of the developed model is consistent with previous deceleration rate models [6, 7, 10]. Speed data used for model development were recorded on a road section with horizontal curves mostly without spiral transitions or with very short ones which might have had an impact on drivers' behaviour. So, it would be interesting to analyse the driver's behaviour on sections with spiral transitions of sufficient lengths. Therefore, it can be concluded that a larger sample of data (more drivers and road sections with spiral transitions of sufficient lengths) would result in a statistically more significant model.

Furthermore, an additional regression analysis was performed to investigate the deceleration phenomenon in more detail, considering 50th percentile deceleration rates. The regression analysis resulted in a model with reverse curve radius as an independent variable that showed even 65.6 % higher adjusted coefficient of determination than the model for predicting 85th percentile deceleration rate (Eqn (2)).
Although the additional regression analysis for d_{50} resulted in a slightly better model, it still cannot be considered a representative indicator of drivers' behaviour for most drivers. Nevertheless, additional regression analysis for d_{50} confirmed that the curve radius is the most important explanatory variable and indicated the need for a more detailed analysis, with a larger and more representative sample of data.

4 Comparison of models

Figure 2 shows a graphical comparison of deceleration rates predicted with the model developed in this study (Eq (2)) and values from previous studies (from Table 1). As can be seen, the deceleration rate model proposed in this study gives results most similar to those of the Italian model developed by Marchionna and Perco [9], and with slightly larger differences in values, follows the form of the Spanish model [6].

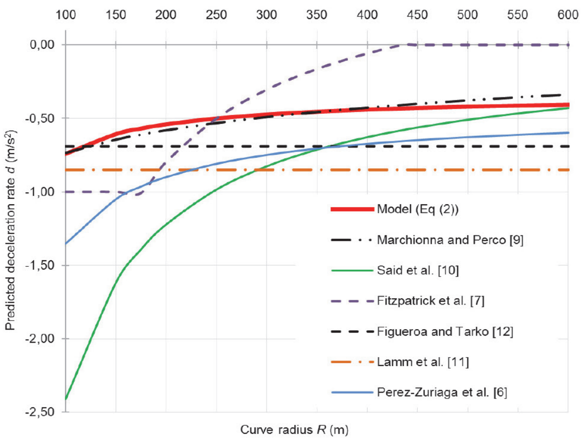

Figure 2 Comparison of deceleration rates predicted with the model developed in this study (Eq (2)) and those predicted with previous models

Differences in results between models can be explained by different data recording methods and by different terrain configurations. Dashed and dotted lines from Figure 2 represent models based on spot speed data [7, 9, 11, 12], while more recent models based on continuous data [6, 10] are presented with solid lines. Due to the limitations of the models based on spot speed data, first researches usually recommended constant values of deceleration rates. The most widely used value in the literature is -0.85 m/s², proposed by Lamm et al. [11]. However, even in some previous studies based on spot speed data [7, 9], models for predicting deceleration rate according to geometric characteristics have been established.
Among the models considered in Figure 2, the Canadian model [10] gives the results with the widest range of values. This can be explained by the fact that they recorded data not only on two-lane rural roads but also on ramps and freeways. Furthermore, Fitzpatrick et al. [7] recommended a step-function instead of a regression-type model, i.e., the regression model is applied only for curves of a certain range of radii (175 m < R < 436 m), while for radii outside this range it is recommended to use constant (average) values.

Differences in models due to terrain conditions can also be observed. Specifically, the terrain in North America is flatter than in Europe. It can be observed that the Northern American models give different results for milder curves (lower absolute values of deceleration rates) than European models. This can be explained by the fact that European models were developed based on data recorded on more curved sections (i.e., road sections with sharper curves), while Northern American models are based on data from flatter test sections.
Finally, such similarity of deceleration rate model from this study with previous European models ([6, 9]) can be explained with similar terrain conditions and maybe even similar road characteristics and similar traffic composition.

5 Conclusions

This paper presents the development of a regression model for predicting deceleration rate on a tangent to curve transitions for two-lane rural roads. An experimental field survey was conducted on a segment of a two-lane state road in a rural area to collect data required for model development. Data were continuously recorded using a high frequency GPS device. Considering different geometric characteristics of the road, the stepwise regression was used to examine their possible influence on the deceleration rate. The regression procedure resulted in a model with the only reverse of curve radius as an independent variable which is consistent with all previous deceleration models. The developed model has a very low adjusted coefficient of determination, and thus it cannot be considered statistically significant. Still, the results of regression analysis are logical, i.e., the model states that higher deceleration rates correspond to transitions from tangents to curves with smaller radii. Although this study showed a relatively small correlation between curve radius and deceleration rate, it can be concluded that more relevant results would be obtained with a larger sample of data. Furthermore, regarding the results of this study, it can be concluded that a constant deceleration rate (-0.85 m/s^2) most used so far does not represent real driver behaviour in tangent to horizontal curve transitions. The deceleration rate varies depending on the curve radius, and to obtain a model applicable in practice, the importance of collecting additional data for further research is highlighted.
Finally, with a reliable deceleration rate model combined with operating speed prediction models, the speed profile could be constructed and used for the evaluation of road design consistency.

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