Effects of combined curves on driver’s speed behavior: driving simulator study

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Abstract

The probability to occur in drive perception errors increases as the complexity of the road alignment increases. In particular perceptions errors could be significantly relevant in the conditions of horizontal curves overlapped with sag vertical curves (sag combinations or combined curves). The highway geometric design guidelines of several Countries provide suggestions for the coordination of the sag combinations in order to avoid combined configurations which can bring to undesirable optical effects and a reduced safety. Such suggestions come from studies based on the drawing of the perspective of the road. This drawing method is heavily limited with regards to the simulation of the perspective view of the highway to the driver during the dynamic task of the driving. Interactive driving simulation methods are deemed to be more efficient for these aims.

This paper reports the results of a study carried out using an interactive driving simulator and aimed at evaluating the effects on the driver’s speed behavior of different configurations of sag combinations and non-combined curves on flat grade with the same features as the horizontal curves of the sag combinations (reference curves).

The main result was that on suggested sag combinations the driver’s speed behavior did not differ in any statistically significant way from that on the reference curves. Whereas the critical sag combinations (configurations that should be avoided) caused a high reduction in speed along the tangent–curve transition, which pointed the driver’s reaction to the wrong perception of the road alignment. This result, therefore, confirmed the effectiveness of the road design guidelines for the coordination of horizontal curves and sag vertical curves.

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1. Introduction

Curves are the geometric element of the road alignment characterised by the greater risk of accidents. According to the Fatality Analysis Reporting System (FARS), since 2005, about 5000 fatalities each year have resulted from single-vehicle run-off-road crashes on the horizontal curve sections of 2-lane rural roads in the United States (National Highway Traffic Safety Administration, 2011). Such statistics are deemed to be due to the erroneous perception of the features of the alignment that induces drivers to assume an inadequate behavior compared to the geometric design of the curved section (Cartes, 2002). Several researches have pointed out that the occurrence of erroneous perception increases as the complexity of the alignment increases and that erroneous perception could be significantly relevant in the conditions of horizontal curves overlapping with sag vertical curves or with crest vertical curves (Smith and Lamm, 1994; Mori et al., 1995; Wooldridge et al., 2000; Bidulka et al., 2002). In particular Smith and Lamm (1994) hypothesized that an overlapping crest curve may cause the horizontal curve to look sharper while a sag curve may cause the horizontal curve to look flatter than it actually is (called driver perception hypothesis). Then the driver may adopt a lower or higher speed, respectively, than if the radius were on a flat grade. Therefore the erroneous perception of the horizontal curve may be particularly hazardous for the horizontal curve overlapping with sag vertical curve (called combined curve or sag combination) where the drivers may perceive a sharp curve as a flat one.

The road design guidelines of several Countries (e.g. Italy, Spain, USA) (Ministry of Infrastructures and Transports, 2001; Ministerio de Fomento, 2001; AASHTO, 2011), as a priority, invite to avoid the overlapping of horizontal and sag vertical curves and, if not possible, they affirm the need to overlap the vertices and to design vertical and horizontal curves with lengths of the same order of magnitude (here called suggested sag combination). In addition, the guidelines suggest to avoid sag combination formed by horizontal curve just after the end of the sag vertical curve, because this configuration (here called critical sag combination) causes important undesirable optical effects. These suggestions come from studies based on the drawing of the perspective of the road. This drawing method is deemed to be heavily limited, because it does not allow to simulate the perspective view of the road to the driver during the dynamic task of the driving. Therefore, in the last decade, numerous studies on the visual perception of the road were carried out by mean of the most advanced computer animation techniques (Bidulka et al., 2002; Hassan and Sayed, 2002; Hassan et al., 2002; Hassan and Easa, 2003; Hassan, 2004). However, such visualization techniques are non-interactive and do not allow to evaluate the driver’s reaction to its perception of the road scenario.

The driving simulation is deemed to be the most accurate method in order to study the drivers perception (e.g. Lamm et al., 1999; Bella, 2009). Driving simulators offer several advantages such as low costs entailed in carrying out experiments, easy data collection, the utmost safety for test drivers, the possibility of carrying out experiments in controlled conditions. Besides such important benefits, driving simulators are interactive. They allow the test driver to manipulate the pedals and steering wheel of the vehicle during the task of driving and allow the recording of the effects of the road configurations on driver behavior in terms of speeds, trajectory, braking, and the like. Such features are the reason for the growing use of driving simulators for modeling driver visual demand on three-dimensional highway alignments (Easa and Ganguly, 2005; Easa and He, 2006), for testing the effectiveness of road treatments on rural roads with crest vertical curves (Rosey et al., 2008; Auberlet et al., 2010; Auberlet et al., 2012) as well as for evaluating the effect of the interaction between overlapping horizontal and vertical alignments (Garcia et al., 2011; Hassan and Sarhan, 2012; Bella, 2014).

The experimental study at the driving simulator reported here was carried out in order to provide an additional and even more reliable validation of the guideline indications for the coordination of horizontal curves overlapping with sag vertical curves. More specifically the aim of the study was to asses if such suggestions are able to determine:

- on the suggested sag combinations, a driver’s speed behaviour that is not significantly different from that on the non-combined curves on flat grade with the same features as the horizontal curves of the sag combinations (called reference curve);
- on the critical sag combinations, a driver’s speed behaviour that is significantly different (more critical for the road safety) from that on the suggested sag combinations.
For this purpose, the driver’s speed behaviour of each driver along the tangent-curve transition was recorded. More specifically, the difference in speed between the point on the approach tangent located 200 m from the beginning of the horizontal curve and the midpoint of the curve was analyzed. This because, according to the literature (e.g. Lamm et al. 1998; Misaghi and Hassan, 2005; Bella, 2007; Bella 2008a), the speed reduction between successive locations of the road alignment increases as the driver detects undesirable optical effects or unclear and non-timely information provided by the road.

2. Method

A within-subjects design was carried out using the fixed-base driving simulator of the Inter-University Research Centre for Road Safety (CRISS). On the basis of the speed data collected on the tangent-curve transitions of reference curves and sag combinations, one-way repeated MANOVA was performed to evaluate if the driver’s speed behaviour on the horizontal curves was influenced by the type of curve (i.e. different configurations of sag combinations and reference curves).

It should be noted that driving simulators do have one important limit. Drivers do not perceive any risk in a driving simulator. The driver’s awareness of being immersed in a simulated environment might give rise to a behavior which is different than that on a real road. However, several simulator validation studies have afforded us sufficient guarantees as regards the relative validity, which refers to the correspondence between effects of different variations in the driving situation. Absolute validity, which refers to the numerical correspondence between behavior in the driving simulator and in the real world, is not essential, whenever the research is dealing with matters relating to the effects of independent variables (Tornos, 1998). For the purpose of the present study, only relative validity is required and the CRISS driving simulator has been previously validated as a useful tool for studying driver’s speed behavior on two-lane rural roads (Bella, 2008b). This evidence has also allowed us to successfully use the CRISS driving simulator for studying the driver behavior induced by road configurations as well as for providing insights that may help to guide road design of two-lane rural roads (e.g. Bella, 2011; Bella, 2013; Bella, 2014b; Bella, 2014c; Bella and D’Agostini, 2010; Bella and Russo, 2011; Bella and Calvi, 2013).

2.1. Road scenarios, sag combinations and reference curves

Two two-lane rural roads, about 15 km long, were designed. The cross-section was 10.50m wide, formed by two 3.75m wide lanes and two 1.50m wide shoulders. The values of the circular curves’ radius ranged from 118m to 800m. The length of tangents ranged from 150m to 2200m, while the deflection angle of horizontal curves ranged from 30° to 80°. The longitudinal grades were not over 6%. Italian guidelines assume for these roads a design speed ranged between 60 km/h (on curve with radius equal to 118m) and 100 km/h (on tangent). The posted speed limit is 90 km/h. These roads had the following types of sag combinations (fig. 1):

- suggested sag combination: the sag vertical curve is overlapped to horizontal curve so the vertices of the two curves coincided and their length was the same order of magnitude, as required by design guidelines for the coordination of horizontal alignment and profile (Ministry of Infrastructures and Transports, 2001);
- critical sag combination: the horizontal curve begins just after the end of the sag vertical curve. The their length was the same order of magnitude. The guidelines (Ministry of Infrastructures and Transports, 2001) suggest to avoid this configuration because it causes anomalies of the perspective of the road alignment.

Such sag combinations and reference curves (non-combined curves on flat grade with the same features as the horizontal curves of the sag combinations) were the curves of interest. Half of these curves were on the first road and the other half was on the second alignment. This in order to:

- limit the order effect induced by the same sequence of presentation of the curves to the driver (the two road scenarios were driven by drivers in a counterbalanced order);
- limit the duration of tests in the driving simulator and consequently limit the potential effects of fatigue on the driver (see also the next section Procedure and participants).
The geometric parameters of the curves are shown in table 1, while figure 1 shows the configurations of the two types of sag combination.

Table 1. The Geometric features of the references curves and sag combinations

<table>
<thead>
<tr>
<th></th>
<th>Horizontal curve</th>
<th>Vertical curve</th>
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<tbody>
<tr>
<td></td>
<td>R</td>
<td>Lc</td>
</tr>
<tr>
<td>Reference curves</td>
<td>252</td>
<td>480</td>
</tr>
<tr>
<td>Suggested sag</td>
<td>252</td>
<td>480</td>
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<tr>
<td>combinations</td>
<td>437</td>
<td>660</td>
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<tr>
<td>Critical sag</td>
<td>437</td>
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<td>480</td>
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<td></td>
<td>437</td>
<td>660</td>
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</table>

R = radius of horizontal curve
Lc = length of horizontal curve in m
(Lcl+Lcirc+Lcl)
Lcl = length of clothoids in m
Lcirc = length of circular curve in m
L_a.t. = length of approach tangent in m
L_d.t. = length of departure tangent in m

γ = deflection angle
Rv = radius of vertical curve in m
Lr = length of vertical curve in m
ia = approach grade in percent
id = departure grade in percent
Δi = |iap-ipv|
2.2. Apparatus

The CRISS simulation system is an interactive fixed-base driving simulator. The system allows to represent the infrastructure scenario, traffic conditions, configurations of horizontal and vertical alignments, cross section features, and to simulate the friction between tires and road surface and the vehicle’s physical and mechanical characteristics. The hardware interfaces (wheel, pedals and gear lever) are installed on a real vehicle. The driving scene is projected onto three screens; one in front of the vehicle and two on each side.

The usual field of view is 135°. The scenario is updated dynamically according to the travelling conditions of the vehicle, depending on the actions of the driver on the pedals and the steering wheel. The resolution of the visual scene is 1024x768 pixel and the update rate is 30-60 Hz depending on scene complexity. The system is also equipped with a sound system that reproduces the sounds of the engine. This setup provides a realistic view of the road and surrounding environment.

The system allows the intensity of driver actions on the brake, accelerator pedal, and steering wheel to be recorded and provides many parameters to describe travel conditions (e.g., vehicle barycenter, relative position in relation to the road axis, local speed and acceleration, steering wheel rotation angle, pitching angle, rolling angle). All the data can be recorded at time or space intervals of a fraction of a second or a fraction of a meter.

Figure 2 shows an example of the road scenario as seen by the driver during the driving simulation.

2.3. Procedure and participants

The experiment was carried out using dry pavement conditions in good state of maintenance and with the free vehicle on its own driving lane. Whereas, on the driving lane a modest traffic was distributed randomly for the sole purpose of inducing the driver not to invade it. The vehicles in the opposite lane were always present in those sections set away from the curves of interest. The simulated vehicle was a standard medium class car, both for dimension and for mechanical performance, with an automatic gear. The data recording system acquired all the parameters at spatial intervals of 5 m.

The driving procedure was broken down into the following steps: (a) communicate to the driver about the duration of the driving and the use of the steering wheel, pedals, and automatic gear; (b) train as to how to use the driving simulator on a specific alignment for approximately 10 min to allow the driver to become familiar with the simulator’s control instruments; (c) execute the first test scenario; (d) have the driver vacate the car for about 5 min so as to reestablish a psychophysical state similar to the one at test start and to fill out a form with personal data (e.g., years of driving experience, average annual distance driven); (e) execute the second test scenario; and (f) have driver answer a questionnaire as to any discomfort perceived during the driving procedure, including the type (e.g. nausea, giddiness, daze, fatigue, other) and the intensity (e.g. null, light, medium, high). Participants were instructed to drive as they normally would in the real world.

Thirty-five drivers were selected to perform the driving in the simulator according to the following characteristics: no experience with the driving simulator, at least four years of driving experience and an average annual driven distance on rural roads of at least 2500 km.
The participants, male (63%) and female (37%), ranged from 23 to 60 years of age (average 26). From the analysis of the questionnaire filled in by the drivers at the end of the test, it emerged that no participants experienced any discomfort condition. No participant therefore was excluded from the sample. The sequence of the two scenarios was varied for each driver, so as to avoid any influences that might result from the repetition of the experimental conditions in the same order. The participants completed the procedure in less than 60 minutes.

2.4. Data collection

For each sag combination and reference curve, the speeds of the drivers were recorded along the section formed by the last 200 m of the approach tangent and the horizontal curve. More specifically, the following local speeds of each driver were collected (fig 3):

- speed \( (V_T) \) at the point (T) on the approach tangent located 200 m from the beginning of the horizontal curve;
- speed \( (V_C) \) at the midpoint (C) of the horizontal curve;
- the difference of speed \( (\Delta V_{T,C}) \) between \( V_T \) and \( V_C \).

\( V_T \) was analyzed in order to ascertain whether or not, driver’s speed at point T was unaffected by the type of the successive curve. It should be noted that the choice of this point is consistent with the results of Fitzpatrick et al. (2000) who found that the speed along the approach tangent does not begin to drop until at a point closer than 200 m to the point of curvature. Should it be confirmed, as expected, that \( V_T \) does not depend on the type of curve, the possible difference between the values of \( V_C \) and \( \Delta V_{T,C} \) on the different successive curves (sag combinations and reference curves) shall exclusively depend on the conditioning induced by the type of curve.

\( V_C \) and \( \Delta V_{T,C} \) were analyzed to ascertain if the drivers’ speed behavior on the section of tangent-curve transition was affected by the type of the curve.

3. Data analysis and results

In order to evaluate the effects on the driver’s speed behaviour induced by the 2 types of sag combination and reference curves, a repeated measures MANOVA was performed. More specifically, one-way repeated measures MANOVA was carried out in order to investigate the effects on the two dependent variables \( (V_T \) and \( \Delta V_{T,C} \)) due to the independent variable (or factor) type of curve (3 types: reference, and 2 types of sag combination: suggested and critical).

It should be noted that \( V_C \) was not used as dependent measure in MANOVA test in order to avoid redundancy in the dependent variables. Figure 4 shows the mean values of the dependent measures \( V_T \) and \( \Delta V_{T,C} \) and their 95% confidence intervals for every type of curve. The \( V_C \) values are also shown.

The MANOVA revealed a significant effect for type of curve \( (F_{(6,272)} = 14.616, P = 0.000) \). Univariate statistics (Mauchly’s test revealed that the assumption of sphericity was ascertained for \( V_T \), while for \( \Delta V_{T,C} \) a Greenhouse–Geisser correction was used) showed that the type of curve did not affect the dependent measure \( V_T \) \( (F_{(1.749, 120.710)} = 1.886, P = 0.161) \), while it significantly affected the dependent measure \( \Delta V_{T,C} \) \( (F_{(2, 138)} = 3.811, P= 0.024) \).

Fig. 3. Locations where speed data were collected
Hence, having ascertained that \( V_T \) is not affected by the driver’s perception of the type of curve, it is possible to affirm that the difference between the values of \( \Delta V_{T-C} \) depends entirely on the conditioning induced by the type of curve.

Post hoc tests using the Bonferroni correction revealed that the mean value of \( \Delta V_{T-C} \) (17.1 km/h) on reference curves was not significantly different than that (16.8 km/h) on suggested sag combinations (mean difference = 0.3 km/h; \( P = 1.000 \)). The mean value of \( \Delta V_{T-C} \) on reference curves (17.1 km/h) was less than the mean value (22.0 km/h) on critical sag combinations, however the difference was not statistically significant (mean difference = 4.9 km/h; \( P = 0.125 \)). The difference between the mean value of \( \Delta V_{T-C} \) on suggested sag combinations and that on critical sag combinations was statistically significant (mean difference = 5.2 km/h; \( P = 0.045 \)).

It should be noted that the high value of \( \Delta V_{T-C} \) for the critical sag combinations could be due to the longitudinal grade at midpoint of the curve (in this point the road is uphill). However the values of longitudinal grade are low (1.5% and 2.9%) and, in accordance with the literature (e.g. TRB, 2011), they do not lead to any appreciable conditioning of drivers’ speeds. This is also supported by the result that was obtained on \( V_T \): the mean value of \( V_T \) was not significantly different for the 3 longitudinal grades of the approach tangent (0%, 2% and 4%; see table 1). Hence, the reduction in speed on the critical sag combinations it is deemed to be due exclusively to the configuration of the combined curves.

4. Discussion and conclusions

The data analysis showed:

- the same driver’s speed behavior on reference curves and suggested sag combinations (\( V_T \) and \( \Delta V_{T-C} \) did not differ statistically significant for the 2 types of curve);
- a different driver’s speed behavior on critical sag combinations and on suggested sag combinations (\( V_T \) did not differ statistically significant and \( \Delta V_{T-C} \) on the critical sag combinations was significantly higher - + 5.2 km/h - than the value on suggested sag combinations). Similar result was obtained from the comparison of the driver’s speed behavior on critical sag combinations and reference curves. However in this case the difference of \( \Delta V_{T-C} \) was not statistically significant, although the value (+4.9 km/h) was practically the same of that recorded between the critical sag combinations and suggested sag combinations (+5.2 km/h).

The first result does not support the hypothesis according to which on the sag combinations, because the horizontal radius is deemed to be perceived as being greater than it actually is, the driver adopts a significantly less reduction of speed between the approach tangent and the curve than that on reference curves. The result is consistent with a previous study carried out at CRISS driving simulator (Bella, 2014) which did not confirm the perception hypothesis for the sag combinations, and it is in line with the findings of Hassan and Sarhan (2012), who found slight differences in drivers’ responses on sag combinations and on flat horizontal curves.
The obtained results confirm the effectiveness of the road design guidelines for the coordination of horizontal curves and sag vertical curves. The suggested sag combination do not determine an anomalous driver’s speed behavior, whereas the critical sag combination causes a high reduction in speed along the tangent-curve transition, which points the driver’s reaction to the wrong perception of the road alignment.

It should be noted that such suggestions come from studies based on the drawing of the perspective of the road and are not based on the analysis of the driver’s speed behavior induced by the driver’s perception of the road while driving. Consequently the findings of the present driving simulator study, that are based on the analysis of the driver’s speed behavior induced by the road configurations, provide an additional and even more reliable validation of the guideline indications for the coordination of the sag combinations.

Finally, it should be noted that the speeds on the reference curves and sag combinations, although being fully consistent with those obtained in previous studies on driver’s speed behaviour on combined curves carried out using driving simulators (Garcia et al. 2011; Hassan and Sarhan, 2012), are high in comparison with those that are usually recorded for free vehicles on real two-lane rural roads. However for the purposes of the study, absolute validity is not essential and it is necessary only to have the relative validity according to Tornos (1998), since the research is dealing with matters relating to the effects of independent variables and is not aimed at determining absolute numerical measurements of the driver behavior. It must also be noted that the relative validity of the CRISS driving simulator for speed research analysis on two-lane rural roads similar to those used in this research was previously proven (Bella, 2008b). For these reasons, sufficient guarantees are provided concerning the validity of the methodological approach used in the present study.

The findings of this study are valid only as regards the configurations of combined curves which have been studied. Further research should be aimed at enlarging the sample of curves in terms of longitudinal grade of the approach tangent and departure tangent as well as horizontal radius.

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