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Coordination of horizontal and sag vertical curves on two-lane rural roads: Driving simulator study

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ABSTRACT

The highway geometric design guidelines for several countries provide suggestions for the coordination of horizontal curves overlapping with sag vertical curves (sag combinations) to avoid combined configurations that produce undesirable optical effects and reduced safety. Such suggestions are derived from studies based on the drawing of the perspective of the road. This drawing method is severely limited with respect to the simulation of the perspective view of the highway to the driver during the dynamic task of driving. Interactive driving simulation methods are deemed to be more efficient for these objectives.

This paper reports the results of a study carried out using an interactive driving simulator to evaluate the effects on the driver's speed behavior of different configurations of sag combinations and non-combined curves on a flat grade with the same features as the horizontal curves of the sag combinations (reference curves). The speed behaviors of drivers along the tangent–curve transitions of sag combinations and reference curves were recorded. The speed on the approach tangent, the speed at the midpoint of the horizontal curve and the maximum speed reduction (MSR), the difference between the maximum speed on the last 200 m of the approach tangent and the minimum speed on the first half of the horizontal curve, were analyzed. One-way repeated MANOVA was performed to determine if the driver's speed behavior on the horizontal curves was influenced by different configurations of sag combinations and reference curves.

The primary 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 high values of maximum speed reduction along the tangent–curve transition, which pointed to the driver's reaction to an incorrect perception of the road alignment. Therefore, this result confirmed the effectiveness of the road design guidelines for the coordination of horizontal curves and sag vertical curves.

1. Introduction

Curves are the geometric element of the road alignment characterized by a greater risk of accidents. According to the Fatality Analysis Reporting System (FARS), since 2005, approximately 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 [1]. Such statistics are attributed to the erroneous perceptions of the alignment features that induce drivers to assume a behavior inadequate to the geometric design of the curved section [2].

Several research studies have noted that the occurrence of erroneous perception increases as the complexity of the alignment increases and that erroneous perception could be a significant factor in the conditions of horizontal curves overlapping with sag vertical curves or with crest vertical curves [3–6].

In particular, Smith and Lamm [3] hypothesized that an overlapping crest curve may cause the horizontal curve to look sharper than it actually is, while a sag curve may cause the horizontal curve to look flatter than it actually is (called the driver perception hypothesis). In response, the driver may adopt a lower or higher speed, respectively, than if the radius was on a flat grade. Therefore, the erroneous perception of the horizontal curve may be particularly hazardous for the horizontal curve overlapping with a sag vertical curve (called a combined curve or sag combination) where the drivers may perceive a sharp curve as a flat one. Taking into account these findings, research has been undertaken to quantify the safety effects of combinations of horizontal curves and vertical curves for two-lane rural roads [7].

The road design guidelines of several countries (e.g., Italy, Spain, USA) [8–10], as a priority, encourage avoiding the overlapping of

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horizontal and sag vertical curves and, if not possible, affirm the need to overlap the vertices and to design vertical and horizontal curves with lengths of the same order of magnitude (referred to as a suggested sag combination in this study). In addition, the guidelines suggest avoiding a sag combination formed by a horizontal curve just after the end of the sag vertical curve because this configuration (referred to as a critical sag combination in this study) causes important undesirable optical effects. These suggestions come from studies based on drawings of the perspective of the road. This drawing method is considered to be heavily limited because it does not simulate the perspective view of the road to the driver during the dynamic task of driving. Therefore, in the last decade, numerous studies on the visual perception of the road used the most advanced computer animation techniques [6,11–14]. However, such visualization techniques are non-interactive and do not evaluate the driver's reaction to his perception of the road scenario.

The driving simulation is considered to be the most accurate method to study the driver's perception [e.g., 15,16]. Driving simulators offer several advantages, such as low costs to conduct experiments, easy data collection, safety for test drivers, and the ability to conduct experiments in controlled conditions. In addition to these 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 record the effects of the road configurations on driver behavior in terms of speeds, trajectory, braking, etc. Such features are the reasons for the growing use of driving simulators for modeling driver visual demand on three-dimensional highway alignments [17,18], for testing the effectiveness of road treatments on rural roads with crest vertical curves [19–21], for analyzing the influence of sag vertical curves on car-following behavior [22], and for evaluating the effect of the interaction between overlapping horizontal and vertical alignments [23–25].

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

- on the suggested sag combinations, whether a driver's speed behavior is significantly different from that on the non-combined curves on a flat grade with the same features as the horizontal curves of the sag combinations (called the reference curve);
- on the critical sag combinations, whether a driver's speed behavior is significantly different (which is more critical for road safety) from that on the suggested sag combinations.

For this purpose, the speed behavior of each driver along the tangent–curve transition was recorded. More specifically, the maximum speed reduction (MSR), which is the difference between the maximum speed on the last 200 m of the approach tangent and the minimum speed on the first half of the horizontal curve, was analyzed.

According to the literature [e.g., 26–28,25], the maximum speed reduction along the tangent–curve transition is believed to be an efficient parameter for revealing undesirable optical effects or unclear and non-timely information provided by the road to the driver (MSR increases as the driver detects surprising events).

It should be noted that MSR (more specifically, the 85th percentile of the Maximum Speed Reduction) was proposed by McFadden and Elefteriadou [26] to study the speed differential in the tangent–curve transition. However, nothing prevents it from being used to study the speed differential between tangent and combined curves. This approach is used by Hassan and Sarhan [25]. These researchers carried out a driving simulation experiment to examine the operational effects of drivers' misperceptions of the horizontal curvature when overlapped with crest and sag vertical curves. For this effort, the maximum speed reduction from the tangent to the horizontal curve was used as the measure of drivers' speed behaviors. Such a parameter was believed to capture the full extent of the driver's response to the perceived curvature. The authors found that the maximum speed reduction between the tangent and the curve was consistent with the perception hypothesis (the mean maximum speed reduction was higher for crest combinations and was lower for sag combinations). However, the differences between the flat horizontal curves and sag combinations were slight, indicating small differences among driver responses.

Described in Section 2 below are the road scenarios and the geometric configurations of the curves that were studied, the features of the driving simulator and the procedures that were used, the participants who were involved in the experiment and the measures used for statistical analysis. Section 3 presents the outcomes of the statistical analysis. In the final section, the obtained results are discussed, and the conclusions are presented.

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). Using speed data collected on the tangent–curve transitions of reference curves and sag combinations, one-way repeated MANOVA was performed to evaluate whether the driver's speed behavior 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 limitation. Drivers do not perceive any risk in a driving simulator. The driver's awareness of being immersed in a simulated environment might cause a behavior which is different than that on a real road. However, several simulator validation studies have afforded us sufficient guarantees regarding relative validity, which refers to the correspondence between the effects of different variations in the driving situations. Absolute validity, which refers to the numerical correspondence between behavior in the driving simulator and in the real world, is not essential when the research deals with matters relating to the effects of independent variables [29]. For the purpose of the present study, only relative validity is required and the CRISS driving simulator was previously validated as a useful tool for studying the driver's speed behavior on two-lane rural roads [30]. More specifically, the validation study of the CRISS driving simulator [30] was carried out to compare the speeds recorded on several measurement sites with different alignment configurations on a real two-lane rural road and the speeds measured on the same road reconstructed in the driving simulator. The results of the comparative and statistical analyses established the relative validity because the comparison of the speed profiles obtained from the data recorded in field at the measurement sites showed a good correspondence to driver behavior in the simulator. The absolute validity was also obtained for all of the measurement sites, except for two less demanding configurations, including a very long tangent (1100 m) and a curve with a high radius (500 m) coming after a long descending tangent. For these configurations, the higher speeds recorded in the simulator appeared to originate from the different risk perceptions on the simulated road as opposed to that on the real road. This evidence allowed us to successfully use the CRISS driving simulator for studying driver behaviors induced by road configurations and for providing insights that may help to guide road design of two-lane rural roads [e.g., 31–37].

2.1. Road scenarios, sag combinations and reference curves

Two two-lane rural roads, each approximately 15 km long, were designed. The cross-section was 10.50 m wide, formed by two 3.75 m wide lanes and two 1.50 m wide shoulders. The values of the circular curves' radii ranged from 118 m to 800 m. The length of the tangents ranged from 150 m to 2200 m, while the deflection angles of the horizontal curves ranged from 30° to 80°. The longitudinal grades were not over 6%. Italian guidelines for these roads recommend a design speed ranged between 60 km/h (on a curve with radius equal