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# A Study on Driving Performance Along Horizontal Curves of Rural Roads

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*Several studies have indicated that road crashes are more likely to occur on horizontal curves than on straight roadway segments for a good number of reasons, the most important of which is associated with the driver's behavior along the curve depending on his or her perception of the road geometry. However, the evaluation of the effects of curve features on driving performance still remains a critical issue for road safety and design. The main objective of this study is to investigate driver's behavior and his perception of road curves, which is directly related to road safety. Specifically, the effects of some curve features (radius, transition curve, visibility, cross-section) on driving performance are investigated through a multifactorial experiment based on driving simulation. The driving speeds and trajectories of a sample of 34 drivers were statistically processed over 72 different curves distributed along three test scenarios. The main and interaction effects of the independent variables are described and discussed in the Results section providing a significant improvement of the actual knowledge in this field of research. In general, the results confirm that driving simulation can disclose the relationships between road design features and driver behavioral aspects that are crucial issues in creating a safer road infrastructure.*

**Keywords** Q1

## 1. Introduction

The evaluation of the effects of curve features on driving performance still remains a critical issue for road safety and design. Several studies (Brenac et al., 1996; National Highway Traffic Safety Administration [NHTSA], 2008; Safetynet, 2009) have indicated that crashes are more likely to occur on horizontal curves than on tangent sections of roadway because of the increased demands placed on the driver and the vehicle that could lead to a wrong choice of speed and trajectory (Charlton, 2007; Hummer et al., 2010). Traffic crash statistics (NHTSA, 2008) have consistently demonstrated that the average crash rate on horizontal curves is significantly higher than that on tangent sections. In 2008, the crash rate in the United States for horizontal curves was about 3 times higher than that of other types of highway segments and, about three- fourths of curve-related fatal crashes involved single vehicles leaving the roadway and striking trees, utility poles, rocks, or other fixed objects, or Q2

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overturning. Other studies (Safetynet, 2009; Srinivasa et al., 2009) have basically confirmed these findings on other countries:

- the crash rates on curves varied from 1.5 to 4 times higher than on tangent sections
- 25% to 30% of fatal crashes occurred on horizontal curves
- single vehicle run-off-the-road accidents yielded approximately 60% to 70% of all fatal crashes on curves.

Among the curve features that mostly affect road safety by means of increasing the crash rates, one can name low curve radii, narrow lanes, and cross-sections (which include shoulders and lanes) that are frequently found as the most significant factors. Several negative relationships between curve radius and crash rate have been established in the literature, especially for run-off-the-road crashes recorded along curves (Choueiri et al., 1994; Takeshi & Nozomu, 2005). Moreover, some correlations between individual curve geometric characteristics and safety performance were established (American Association of State Highway Transportation Officials [AASHTO], 2010; Strathman et al., 2001; Zegeer et al., 1992). Other researchers (Findley et al., 2012; Hummer et al., 2010) attributed the high crash rates often recorded on curves to the centripetal force exerted on a vehicle while passing through a curve. It could cause an additional driving task to be more difficult to manage by the driver that, consequently, may more easily cause a mistake and/or an accident.

To handle these problems, especially those related to speeding and vehicle control along a curve, and improve road safety, several in-vehicle systems and road treatments have been developed over the years, most commonly categorised as enforcement, education, or engineering interventions (McGee & Hanscom, 2006; Srinivasa et al., 2009). Nonetheless, several crashes are still being recorded along curves, mainly caused by the driver behavior that, according to the most shared and consolidated current approach to road safety issues (Carsten, 2002), is strongly affected by road geometries, the traffic, and the environment.

For this reason many researchers have concentrated their efforts to study the drivers' behavior on horizontal curves (Benedetto et al., 2009; Charlton, 2007; Martens et al., 1997; Zakowska, 2010).

According to Charlton (2007) drivers' mistakes related to horizontal curves could be caused by the interaction of three main driver's behavioral problems: the inability to meet increased attentional demands, the misperceptions of speed and curvature, and the incapacity to maintain a correct lane position. Several human factors studies based on the analysis of the relationship between the driver performance and road design (Brenac, 1996; Said et al., 2009) have associated such behavioral problems to the geometric features of curves, to the extra effort required in lane keeping, and to the reduction in the visibility distances along the road axis often associated with curves. The width of shoulders and lanes combined with the radius of curve have been found to be significant factors that affect sight distances and vehicle operations (Choueiri et al., 1994). The effects of using spiral curves (clothoids) in tangent-curve transition have been widely investigated (Craus & Polus, 1977) to determine the desirable length of spiral curves based on data collected over driver steering behavior (Said et al., 2009) or driving path (Perco, 2006) to incorporate the actual driving performance on road design. The reduced visibility along curves limits the driver's ability to anticipate the course of the road ahead and, consequently, increases the uncertainty and leads to driving mistakes (Martens et al., 1997) especially in terms of using inappropriate speed and trajectory to negotiate a curve. In a pilot study Zhao et al. (2013) investigated how curve information could affect driver performance using a cognition model. The authors found that the process of the drivers' behavior on curves could be explained by the cognition theory (Anderson et al., 1997), according to which the driving performance consists of three phases: information perception (i.e., the basis for the cognition), driving decision, and operation execution. The more exact the transformed information is, the easier the driver can make appropriate decisions and correct operations. Zhao et al. concluded that, to avoid any driving mistakes along a curve, it is essential to give the appropriate warning information well in advance.

Nowadays, one of the main instruments that is recognized as the most effective tool for studying driving behavior, evaluating the interactions between driver, vehicle and road environment by means of an interdisciplinary approach, is the driving simulator (Bella, 2009). The driving simulator allows the study of variability of the driver's behavior under different conditions (e.g., geometries and traffic flows) and offers a very promising perspective for road safety design and management, thus overcoming the problems (e.g., safety, cost, experimental control) of field studies. Moreover, the driving simulator allows the researcher to collect and process continuous speed and trajectory profiles instead of only spot data, thus avoiding the deficiencies encountered in spot data collection (Bella et al., 2014a, 2014b; Bella & Calvi, 2013; Calvi, Benedetto, & De Blasiis, 2012; Calvi & D'Amico, 2013; Calvi & De Blasiis, 2011; Pérez Zuriaga et al., 2010). In simulated settings it is also possible to develop experiments in a controlled environment and under pre-established conditions that are applicable to all participants, collect driving performance data, and investigate the interactions between drivers and road features, especially the geometric characteristics of the road alignment. By all means, the main reason behind an increasing interest in driving simulator is that several studies have demonstrated that this tool provides the driver with enough visual information to allow him or her to correctly perceive speeds and distances (Bella, 2009; Kemeny & Panerai, 2003; Törnos, 1998; Yan et al., 2008). The research that compares drivers' behavior in virtual reality and in the real world is called "driving simulator validation studies." Specifically, Blaauw (1982) defined the absolute validity of simulators as the numerical correspondence between behavior in the driving simulator and that in the real situation, and the relative validity as the correspondence between effects of different variations in the driving situation. According to Törnos (1998), the relative validity is necessary for a simulator, though the absolute validity is not essential, because research questions usually deal with matters that are related to the effects of independent variables, with experiments that investigate the difference between a control scenario and other experimental scenarios. Such validity could be verified even if the driver behavior in simulated settings is not totally analogous to the behavior in the real world, due essentially to the lack of motivational and emotional context (Engström & Aust, 2011).

Q3

Using a driving simulator, Van Winsum and Gosthelp (1996) studied the effect of road design on driving performance. Their findings indicated that stricter curve radii increase the demands on vehicle control with the consequence of the driver's need to correct more and more the trajectory of the vehicle. On the contrary, when the speed was lowered, vehicle control improved. In another driving simulator study, Comte and Jamson (2000) demonstrated that a high percentage of curve crashes are caused by a driver speeding along a curve that subsequently results in him or her losing control of the vehicle or being forced into a skid.

The research presented in this article is the continuation of two previous pilot studies (Benedetto et al., 2009; Zakowska, 2010) aimed at investigating the driver's perception of road curves and behavior in relation to curve characteristics. These pilot studies validated the sample of drivers and the simulation tests and provided preliminary results on a smaller number of geometric conditions. Their findings demonstrated that advanced techniques of visualization and simulation of road space can disclose the relationships between design road parameters and behavioral aspects important to create safer road infrastructures.

In this article the effects of several geometric characteristics of curves on driving performance are investigated and statistically analyzed, taking into account the main and interaction effects of several factors related to curves such as the radius, the clothoids, and visibility, evaluated for different roadway configurations. A full comprehensive study is presented that compared all the effects of several independent variables that include roadways and curves characteristics on selected dependent measures of driving performance.

## 2. Method

A multifactorial experiment was conducted using the advanced driving simulator of the Inter-Universities Research Centre for Road Safety (CRISS) at Roma Tre University. The overall aim was to evaluate the effects of different curve features on driving speed and lateral positions (trajectories) along a curve.

### *2.1. Participants*

The sample of participants that took part in the study included 34 volunteers (20 men and 14 women with a mean age of 26 years, and an age range of 22 – 35 years), recruited from students and staff of the Department of Engineering at Roma Tre University. Participants had to respect the following requirements: no experience with the driving simulator, at least 4 years of driving experience, and an average annual driven distance on rural roads of at least 3000 km.

Three participants, having completed the driving, experienced a degree of discomfort as revealed from the questionnaire that each volunteer had to fill out at the end of the tests and, consequently, and were excluded from the postprocessing of data. Among the sample of drivers, consideration was also given to outliers; that is, drivers whose average speed values along the alignment were higher than three standard deviations (SDs) from the sample's average speed. Under such condition, one driver was excluded from the analysis. Thus, the sample used for the analysis consisted of 30 licensed drivers (18 men and 12 women) with an average age of 26.2 years (SD = 4.9 years), and an age range of 23 to 35 years. Their average driving experience was 8.6 years. In terms of driving exposure, 13.5% of the participants drove between 4,000 and 8,000 km/year, 43.7% drove between 8,000 and 12,000 km/year, 33.5% drove between 12,000 and 20,000 km/year, and 9.3% indicated that they drove for more than 20,000 km/year.

### *2.2. Apparatus*

The experiment was conducted in the simulation laboratory of the CRISS at Roma Tre University, using an interactive fixed-based driving simulator that includes a complete vehicle dynamics model, specifically designed for research on road safety. Figure 1 shows the CRISS driving simulator.

The simulator consists of a real car with a force-feedback steering wheel, brake pedal, and accelerator. The driving simulator is positioned in front of three angled projection surfaces that produced a 135° (horizontal) × 60° (vertical) forward view of the simulated scenario from the driver's position inside the car. The resolution of the visual scene is

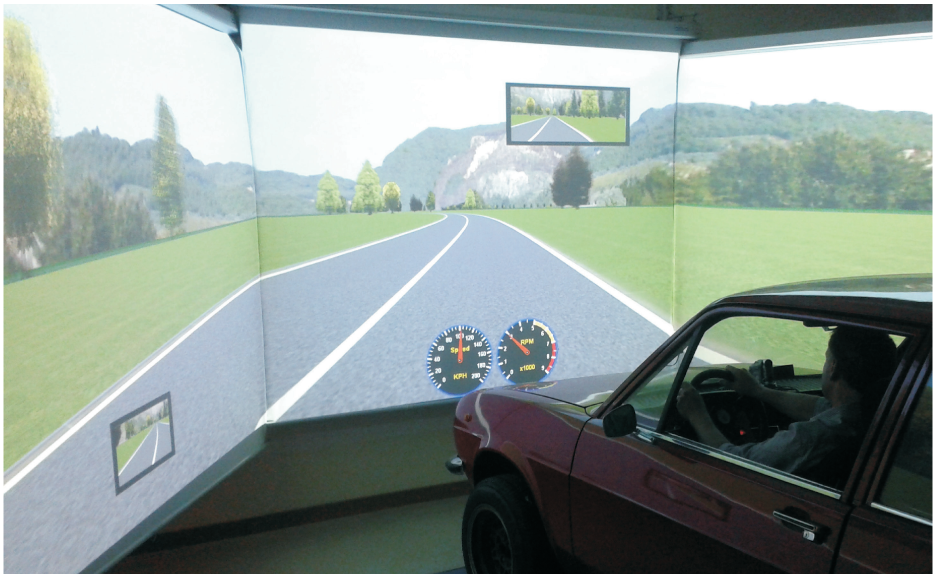

**Figure 1.** Inter-Universities Research Centre for Road Safety driving simulator.

1024 × 768 pixels with a refresh rate of 30 to 60 Hz depending on scene complexity and traveling conditions of the vehicle.

The driving simulator provides haptic feedback from the steering wheel. The audio system of the car is linked with the simulator software so that it can accurately simulate surround environment sounds for engine noise, external road noise, and sounds for other traffic interactions and thus further enhancing the realism of the driving experience.

The system was widely validated in previous studies (Bella, 2005, 2008) and used for evaluating driving performance in terms of speed, acceleration, and trajectory under different driving conditions and road environments (Bella & Calvi, 2013; Calvi, Benedetto, & D' Amico, 2012; Calvi, Benedetto, & De Blasiis, 2012; Calvi, Benedetto, & Messina, 2012; Calvi & D'Amico, 2013; Calvi & De Blasiis, 2011; Calvi, De Blasiis, & Guattari, 2012; Guattari et al., 2010).

The data recording system acquires all the parameters of driving performance like position, speed, acceleration, and braking at rates up to 20 Hz. All the features of the simulator are designed to enhance the verisimilitude of participants' virtual driving experience in the study to ensure the effectiveness and reliability of results.

The experiments were developed excluding other vehicles along the driving direction of participants, with light traffic in the opposite lane to induce the driver to avoid occupying temporarily the opposite lane, limiting curve cutting, or any similar behavior (especially for the two road configurations that represent two-lane rural roads). The characteristics of the simulated vehicle were of a standard medium class car with automatic transmission. The driver could see the speed on the speedometer projected on the front screen.

### *2.3. Tests Alignment*

Three different scenarios were designed and implemented in virtual reality environment (Figure 2), each one representing a typical Italian road configuration characterized by

**Figure 2.** Simulation frames of road configurations.

different cross-section: a two-lane rural road with no shoulder, a two-lane rural road with wider lanes and shoulders, and a highway with divided carriageways (two lanes for each driving direction). Each scenario (corresponding to a test and to one of the three road configurations) is composed of 24 horizontal curves manipulated with three different radii (sharp, medium, and shallow), both directions for each curve (left and right), two conditions of visibility (unrestricted and restricted, using steep side slopes along the road at the inner edge of curves), and two conditions of the transition curve (with or without clothoid). The characteristics of the curves were the same for each one of the three test scenarios. Moreover the order in which the curves appeared to the participants was the same for each test scenario, whereas the sequence of the three scenarios was counterbalanced across participants. The simulated roads were designed so that two horizontal curve sections were separated by one straight section. The length of the straight section was between 300 and 500 meters. The overall aim of implementing these straight sections between curves consisted in preventing, or at least limiting, that driver performance (speed and trajectory) along a curve could be biased by the previous curve of the road alignment.

Although in all the scenarios low traffic was present in the opposite lane, the drivers were not constrained by vehicles ahead. No vertical signs were displayed to allow the drivers to choose the speed they desired, without any other constraints than what the road environment could suggest them.

The length of each experimental scenario was 14.3 km and the vertical alignment was flat. Also, the terrain surrounding all the roads was flat and uniform with no houses, trees, or other landscape elements, except for those curves whose visibility was restricted by a cut slope at the inner edge of the curve.

### *2.4. Independent Measures*

Four independent measures were manipulated in this study: road configuration, geometric element, visibility condition and transition curve, for a total of 72 horizontal curves investigated in terms of driver's speeds and trajectories.

*2.4.1. Road Configuration.* Three levels of road configuration, whose characteristics are common to most of the Italian existing road network, were reproduced in the driving simulator. These three road categories were associated with the speed limit, the function of the road, and the cross-section geometry as follows:

- Road A: two-lane rural road, characterized by a cross-section of 6.00 meters, consisted of two lanes of 3.00 meters wide and gravel shoulders, central line painted, no edge lines painted. The Italian speed limit on this road is typically 60 km/h;
- Road B: two-lane rural road, characterized by a cross-section of 10.00 meters, consisted of two lanes of 3.50 meters wide and two paved shoulders of 1.50 meters wide, central, and edge lines painted. The Italian speed limit on this road is usually 80 km/h;
- Road C: highway, composed of a dual carriageway with two lanes for each driving direction (each lane was 3.50 meters wide). The shoulders were 2.00 meters wide and the median was 2.00 m. The Italian speed limit on this road is usually 110 km/h.

*2.4.2. Geometric Element.* Three levels of curve radius were investigated for each road configuration: 200 m radius (referred to in this experiment as sharp curve), 500 m radius (referred to as medium curve), and 1000 m (referred to as shallow curve). All the radii were investigated for left and right curves. Therefore, the roadway geometry manipulation included six options: right sharp curve, left sharp curve, right medium curve, left medium curve, right shallow curve, and left shallow curve.

*2.4.3. Visibility Condition.* According to the design speed assumed by the Italian guidelines (Ministry of the Infrastructures and Transports [MIT], 2001) for each curve on each road configuration, two levels of curve visibility restriction were analyzed manipulating the steep side slopes along the road at the inner edge of curves (good, unrestricted visibility, and poor, restricted visibility). As a consequence, the visibility was considered "unrestricted" when the driver could see in front of him or her a road segment longer than the stopping sight distance, calculated according to Italian guidelines (MIT, 2001), based on the design speed of the specific curve. The visibility was "restricted" when such distance was not perceivable, meaning that the available visibility was lower than the stopping sight distance. In this last case, the roadside elements (steep side slopes) were designed and implemented in such a way that the driver should adopt a speed of about 30% lower than the design speed of the curve to drive on under safe conditions (stopping sight distance $\leq$ available visibility).

*2.4.4. Transition Curve.* Two levels of transition curve over a tangent-curve configuration were considered: with and without clothoids. The clothoids were designed, according to Italian guidelines (MIT, 2001), differently for each curve.

### *2.5. Dependent Measures*

The dependent measures considered for evaluating the effects of the independent measures on driving performance were:

- Driving speed
- Pathologic discomfort (PD)
- Dispersion of trajectory (DT).

*2.5.1. Driving Speed.* The driving speeds were analyzed to obtain the average driver's speed evaluated from the beginning to the end point of each curve. Then, the average speed and SD of the sample of drivers was computed for each curve. Among the different speed-related parameters of literature, the average speed is considered a surrogate measure

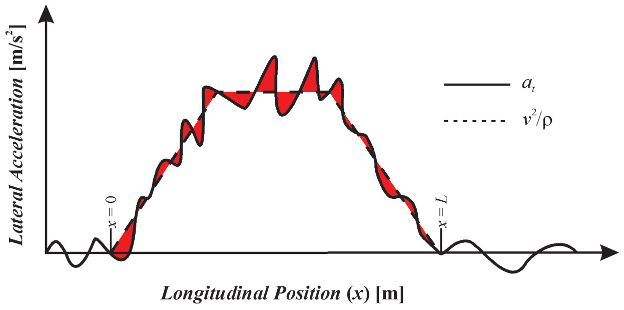

**Figure 3.** Pathologic discomfort (PD).

for safe driving (Moreno & García, 2013; Yan et al., 2008), able to indirectly assess road safety management where historical crash data are limited or unavailable.

*2.5.2. Pathologic Discomfort.* The PD is a surrogate measure of safety presented and discussed in previous articles, where its correlation with accident rate was established and validated under different driving conditions, in simulated (Calvi, 2010; Calvi & D'Amico, 2006, 2013) and real (Casolo et al., 2008) environments.

Pathologic discomfort takes into account the local variability of lateral acceleration, consequence of the driver's need for correcting his trajectory to follow the geometry of the road axis. In other words, PD is based on the self-explaining road concept: a participant who drives on a self-explaining road assumes a correct and safe trajectory, and the local lateral accelerations depend only on the curvature of the road geometry. If the driver corrects the vehicle's trajectory more than what the road curvature imposes, the road is not self-explaining and, consequently, it can be unsafe. If the local lateral accelerations do not only depend on the actual road curvature, they are biased by the driver's corrections of trajectory.

The repeated local oscillations of lateral acceleration represent a violation of driver expectancy. Pathologic discomfort was computed for each curve of the alignments using Equation (2):

$$PD = \int_{x=0}^{x=L} \left| a_t(x) - \frac{v^2(x)}{\rho(x)} \right| dx \tag{1}$$

where, $x$ is the instantaneous distance from the start position of the curve considering that the vehicle is traveling along the curve driven by the specific driver, $a_t$ is driver's lateral acceleration, $v$ is the average speed of the driver along the curve, $\rho$ and $L$ are the radius and the length of the curve respectively. Figure 3 shows a graphical representation of PD that corresponds to the colored area between the two curves of the driver's lateral acceleration and of the theoretical lateral acceleration, based on the average speed and the real curvature of the road.

Pathologic discomfort was then homogenized, divided by the length $L$ of the curve in order to allow a comparison among curves characterized by different lengths.

*2.5.3. Dispersion of Trajectory.* The dispersion of trajectory (DT) is an indicator related to the vehicle's position within the driving lane. It implicitly takes into account the average value of lateral position and *SD* that are frequently used for evaluating the lateral control

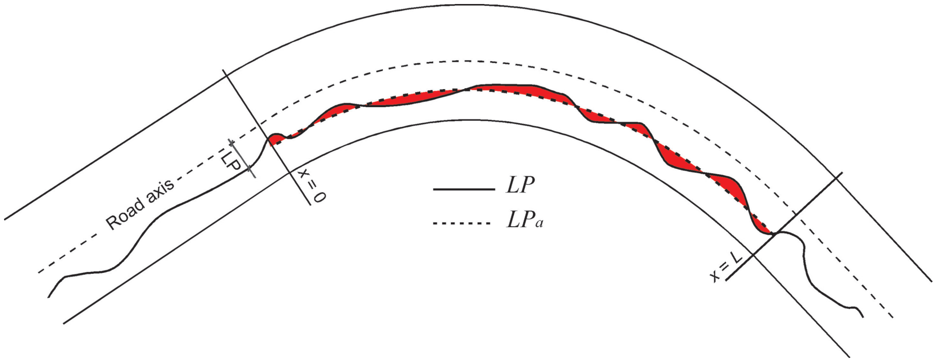

**Figure 4.** Dispersion of trajectory (DT).

of vehicles. Dispersion of trajectory can be considered as a surrogate measure of safety, as the lack of harmonized lane position is a primary cause of single-vehicle run-off the road crashes and head-on collisions, specifically on horizontal curves (Rosey et al., 2008; Yan et al., 2008). Moreover, according to McGehee et al. (2004), the lane position variability, that can be evaluated using DT, provides a measure of driving performance that describes the safety relevance of changes in driving behavior. DT corresponds to the dispersion of driver's trajectory along a curve, evaluated as the area between the curve that represents the driver's local trajectory (i.e., the vehicle lateral position [LP], or displacements along the road) and the line corresponding to the driver's average lateral position along the same curve (Figure 4). The higher the indicator is, the more difficulties the driver will experience in perceiving the road geometry. DT was computed for each curve of the alignments using Equation (1):

$$DT = \int_{x=0}^{x=L} |LP(x) - LP_a| dx \tag{2}$$

where, $x$ is the instantaneous distance from the start position of the curve considering that the vehicle is traveling along the curve driven by the specific driver, $LP$ is the local lateral position of the driver (distance of the centre of the vehicle from the road axis), $LP_a$ is the average driver's lateral position along the curve, and $L$ is the length of the curve. DT was then homogenized, divided by the length $L$ of the curve to allow a comparison among curves characterized by different lengths.

### *2.6. Procedure*

Upon arrival at the laboratory, each participant was firstly briefed on the experimental procedure. Some general instructions were communicated to the driver about the duration of the driving and the use of the steering wheel, pedals, and automatic gear. More specifically, drivers were instructed to drive as they normally would in the real world, maintain a comfortable, reasonable and safe speed according to road conditions, and remain in the right lane only.

Then the participants read and signed an informed consent form, besides a demographic questionnaire with personal data (e.g., gender, date of birth), years of driving experience, and average annual mileage driven.

Subsequently, the participants completed a practice drive on a training scenario for approximately 10 minutes to familiarize themselves with the simulator controls. During the practice drive, the participants were encouraged to adjust their seat position so as to be comfortable.

Following this, each participant drove all three routes, with a break of 20 minutes after each run to reestablish psychophysical conditions similar to those at the beginning of the test. Finally, the driver was asked to fill out a questionnaire about the discomfort encountered during driving, to eliminate from the sample those participants that experienced some kinds of discomfort (nausea, giddiness, fatigue, other) during the tests.

The sequence of the three scenarios was counterbalanced across participants to avoid any biases due to the repetition of the same order in the experimental conditions. Each full experiment lasted for about 1 hour.

## 3. Results and Discussion

Each dependent variable was analyzed using the repeated measures ANOVA $3 \times 6 \times 2 \times 2$ with the road configuration (two-lane rural road with 6 m of cross-section, two-lane rural road with 10 mof cross-section, highway), the geometric element (three curve radii and two directions), the visibility (unrestricted and restricted), and the transition curve (with and without clothoid) as within-subject factors. Before performing the analyses of variance, all data were subjected to the Kolmogorov-Smirnov test to determine whether they were normally distributed (i.e., one of the main assumptions needed to correctly apply the ANOVA test). As well, the evaluation of sphericity assumption was needed too for verifying the multivariate normal assumption (Lewis, 1993). When the sphericity assumption was violated (in this study, when the Mauchly test was significant) adjustments were made to the results of the ANOVA using the Geisser-Greenhouse epsilon that provides an *F* test using a much more stringent criterion (Geisser & Greenhouse, 1958). Therefore, where the within-subject variables violated the sphericity assumption, the Geisser-Greenhouse probabilities were reported. Additional post-hoc tests performed on each dependent measure allowed investigation of interaction and main effects on the driver performance due to the independent measures. A significance level of 0.05 was adopted for all the significance tests.

### *3.1. Descriptive Statistics*

Tables 1, 2, and 3 present summaries of driving speeds, PD, and DT (homogenized) in terms of their average values and *SD*s for every combination of the three manipulated factors (geometric element, visibility condition, transition curve) on roads A, B and C (the fourth factor considered was road configuration) respectively. In this section, the values of PD and DT refer to the homogenized values, meaning that the parameters were divided by the length of each corresponding curve to allow the comparison of the dependent measures amongst curves characterized by different lengths.

Finally, Table 4 summarizes the main and interaction effects of the independent variables on each dependent variable.

**Table 1**
Average and standard deviation of speed, PD, and DT for every combination of geometric element, visibility condition, and transition curve on Road A

| | | | | Speed (km/h) | | PD/L (m/s$^2$) | | DT/L (m) | |
|---|---|---|---|---|---|---|---|---|---|
| Road Configuration | Geometric Element | Visibility | Clothoid | Average | SD | Average | SD | Average | SD |
| Road A<br>Two-lane rural road<br>2 × 2.75m lanes<br>no shoulder | Sharp right curve | yes | yes | 85.20 | 14.81 | 0.198 | 0.088 | 0.080 | 0.032 |
| | | | no | 83.06 | 12.74 | 0.244 | 0.056 | 0.138 | 0.045 |
| | | no | yes | 85.79 | 12.05 | 0.144 | 0.074 | 0.097 | 0.046 |
| | | | no | 85.88 | 14.10 | 0.263 | 0.069 | 0.137 | 0.039 |
| | Sharp left curve | yes | yes | 88.86 | 12.94 | 0.144 | 0.056 | 0.066 | 0.030 |
| | | | no | 82.59 | 11.89 | 0.260 | 0.085 | 0.111 | 0.034 |
| | | no | yes | 87.27 | 14.92 | 0.140 | 0.061 | 0.079 | 0.041 |
| | | | no | 85.01 | 14.57 | 0.244 | 0.075 | 0.118 | 0.055 |
| | Medium right curve | yes | yes | 90.87 | 13.19 | 0.109 | 0.044 | 0.094 | 0.047 |
| | | | no | 95.22 | 11.40 | 0.233 | 0.070 | 0.134 | 0.044 |
| | | no | yes | 95.40 | 15.87 | 0.128 | 0.056 | 0.089 | 0.041 |
| | | | no | 90.02 | 16.10 | 0.182 | 0.061 | 0.159 | 0.055 |
| | Medium left curve | yes | yes | 88.37 | 14.38 | 0.129 | 0.058 | 0.084 | 0.037 |
| | | | no | 91.29 | 12.88 | 0.168 | 0.052 | 0.104 | 0.031 |
| | | no | yes | 93.57 | 15.46 | 0.114 | 0.061 | 0.070 | 0.032 |
| | | | no | 91.02 | 14.94 | 0.176 | 0.069 | 0.102 | 0.037 |
| | Shallow right curve | yes | yes | 99.99 | 14.51 | 0.143 | 0.051 | 0.140 | 0.030 |
| | | | no | 99.87 | 14.43 | 0.144 | 0.049 | 0.141 | 0.032 |
| | | no | yes | 97.81 | 15.70 | 0.131 | 0.053 | 0.133 | 0.042 |
| | | | no | 97.77 | 15.68 | 0.133 | 0.054 | 0.134 | 0.040 |
| | Shallow left curve | yes | yes | 99.87 | 14.12 | 0.133 | 0.041 | 0.118 | 0.031 |
| | | | no | 99.83 | 14.09 | 0.134 | 0.042 | 0.119 | 0.030 |
| | | no | yes | 95.90 | 16.08 | 0.101 | 0.035 | 0.103 | 0.033 |
| | | | no | 95.89 | 16.10 | 0.103 | 0.034 | 0.105 | 0.032 |

PD = Pathologic discomfort; DT = dispersion of trajectory; L = .

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**Table 2**

Average and standard deviation of speed, PD, and DT for every combination of geometric element, visibility condition, and transition curve on Road B

| | | | | Speed (km/h) | | PD/L ($m/s^2$) | | DT/L (m) | |
|---|---|---|---|---|---|---|---|---|---|
| Road Configuration | Geometric Element | Visibility | Clothoid | Average | SD | Average | SD | Average | SD |
| Road B<br>Two-lane rural road<br>2 × 3.25 m lanes<br>with shoulder | Sharp<br>right curve | yes | yes | 88.01 | 13.99 | 0.149 | 0.084 | 0.109 | 0.051 |
| | | | no | 88.92 | 15.16 | 0.343 | 0.173 | 0.162 | 0.076 |
| | | no | yes | 88.03 | 11.40 | 0.126 | 0.050 | 0.108 | 0.060 |
| | | | no | 85.46 | 13.54 | 0.290 | 0.104 | 0.157 | 0.072 |
| | Sharp<br>left curve | yes | yes | 91.82 | 15.22 | 0.183 | 0.080 | 0.107 | 0.062 |
| | | | no | 86.89 | 14.59 | 0.341 | 0.159 | 0.218 | 0.104 |
| | | no | yes | 89.33 | 12.44 | 0.153 | 0.080 | 0.105 | 0.072 |
| | | | no | 88.02 | 10.79 | 0.317 | 0.100 | 0.147 | 0.065 |
| | Medium<br>right curve | yes | yes | 97.12 | 16.09 | 0.128 | 0.070 | 0.111 | 0.070 |
| | | | no | 96.30 | 13.72 | 0.256 | 0.090 | 0.199 | 0.061 |
| | | no | yes | 96.20 | 11.46 | 0.112 | 0.046 | 0.104 | 0.050 |
| | | | no | 91.95 | 14.27 | 0.196 | 0.081 | 0.158 | 0.067 |
| | Medium<br>left curve | yes | yes | 95.89 | 16.62 | 0.128 | 0.065 | 0.121 | 0.069 |
| | | | no | 95.98 | 14.45 | 0.192 | 0.065 | 0.168 | 0.095 |
| | | no | yes | 95.37 | 11.92 | 0.102 | 0.068 | 0.082 | 0.040 |
| | | | no | 91.93 | 12.39 | 0.155 | 0.035 | 0.130 | 0.047 |
| | Shallow<br>right curve | yes | yes | 102.40 | 15.04 | 0.160 | 0.064 | 0.172 | 0.048 |
| | | | no | 102.35 | 15.06 | 0.162 | 0.063 | 0.173 | 0.050 |
| | | no | yes | 98.11 | 14.58 | 0.100 | 0.034 | 0.166 | 0.065 |
| | | | no | 98.07 | 14.63 | 0.101 | 0.033 | 0.168 | 0.062 |
| | Shallow<br>left curve | yes | yes | 105.31 | 14.58 | 0.131 | 0.059 | 0.148 | 0.041 |
| | | | no | 105.28 | 14.62 | 0.133 | 0.058 | 0.149 | 0.039 |
| | | no | yes | 97.88 | 14.59 | 0.093 | 0.034 | 0.105 | 0.034 |
| | | | no | 97.84 | 14.63 | 0.094 | 0.033 | 0.106 | 0.033 |

PD = Pathologic discomfort; DT = dispersion of trajectory; L = length.

Q5

**Table 3**

Average and standard deviation of speed, PD, and DT for every combination of geometric element, visibility condition, and transition curve on Road C

| Road Configuration | Geometric element | Visibility | Clothoid | Speed (km/h) |  | PD/L ($m/s^2$) |  | DT/L (m) |  |
|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  | Average | SD | Average | SD | Average | SD |
| Road C Highway 4 × 3.50 m lanes with shoulder | Sharp right curve | yes | yes | 105.71 | 15.64 | 0.329 | 0.188 | 0.050 | 0.023 |
|  |  |  | no | 99.99 | 15.64 | 0.452 | 0.186 | 0.282 | 0.163 |
|  |  | no | yes | 99.40 | 12.57 | 0.227 | 0.120 | 0.104 | 0.090 |
|  |  |  | no | 98.64 | 17.79 | 0.436 | 0.214 | 0.254 | 0.176 |
|  | Sharp left curve | yes | yes | 103.10 | 17.64 | 0.266 | 0.111 | 0.111 | 0.051 |
|  |  |  | no | 98.53 | 16.42 | 0.457 | 0.155 | 0.275 | 0.131 |
|  |  | no | yes | 103.22 | 14.02 | 0.252 | 0.134 | 0.052 | 0.030 |
|  |  |  | no | 99.92 | 15.29 | 0.446 | 0.158 | 0.276 | 0.129 |
|  | Medium right curve | yes | yes | 108.53 | 16.13 | 0.121 | 0.055 | 0.122 | 0.083 |
|  |  |  | no | 108.61 | 15.76 | 0.271 | 0.110 | 0.219 | 0.124 |
|  |  | no | yes | 108.89 | 13.05 | 0.143 | 0.070 | 0.146 | 0.092 |
|  |  |  | no | 104.09 | 18.51 | 0.232 | 0.079 | 0.241 | 0.135 |
|  | Medium left curve | yes | yes | 114.40 | 16.80 | 0.154 | 0.069 | 0.120 | 0.076 |
|  |  |  | no | 108.23 | 16.00 | 0.272 | 0.106 | 0.264 | 0.130 |
|  |  | no | yes | 110.06 | 15.01 | 0.146 | 0.078 | 0.106 | 0.063 |
|  |  |  | no | 104.01 | 15.87 | 0.245 | 0.101 | 0.198 | 0.087 |
|  | Shallow right curve | yes | yes | 114.40 | 14.79 | 0.159 | 0.055 | 0.193 | 0.084 |
|  |  |  | no | 114.35 | 14.76 | 0.160 | 0.056 | 0.195 | 0.085 |
|  |  | no | yes | 110.16 | 16.71 | 0.127 | 0.048 | 0.196 | 0.120 |
|  |  |  | no | 110.10 | 16.75 | 0.129 | 0.047 | 0.201 | 0.117 |
|  | Shallow left curve | yes | yes | 116.15 | 14.68 | 0.136 | 0.047 | 0.175 | 0.108 |
|  |  |  | no | 116.05 | 14.71 | 0.138 | 0.048 | 0.178 | 0.105 |
|  |  | no | yes | 110.80 | 16.58 | 0.123 | 0.039 | 0.139 | 0.069 |
|  |  |  | no | 110.66 | 16.60 | 0.124 | 0.040 | 0.141 | 0.071 |

PD = Pathologic discomfort; DT = dispersion of trajectory; L = length.

**Table 4**
Main and interaction effects data

| IV Effects | Dependent Variables | | |
|---|---|---|---|
| | Driving Speed | PD | DT |
| Main Effects | | | |
| Road configuration | $F = 11.14, p < .001$ | $F = 19.60, p < .001$ | $F = 26.80, p < .001$ |
| Geometric element | $F = 103.34, p < .001$ | $F = 210.80, p < .001$ | $F = 12.96, p < .001$ |
| Visibility | $F = 18.74, p < .001$ | $F = 119.80, p < .001$ | $F = 19.15, p < .001$ |
| Transition curve | $F = 36.99, p < .001$ | $F = 477.64, p < .001$ | $F = 300.67, p < .001$ |
| Interaction Effects | | | |
| Road Configuration * Geometric Element | $F = 1.09, p = .445$ | $F = 1.75, p = .168$ | $F = 1.19, p = .295$ |
| Road Configuration * Visibility | $F = 3.91, p = .025$ | $F = 4.57, p = .014$ | $F = 8.61, p = .001$ |
| Road Configuration * Transition Curve | $F = 2.55, p = .098$ | $F = 10.64, p < .001$ | $F = 33.54, p < .001$ |
| Geometric Element * Visibility | $F = 3.98, p = .011$ | $F = 1.42, p = .220$ | $F = 1.98, p = .153$ |
| Geometric Element * Transition Curve | $F = 6.26, p < .001$ | $F = 100.44, p < .001$ | $F = 57.44, p < .001$ |
| Visibility * Transition Curve | $F = 2.45, p = .128$ | $F = 1.09, p = .445$ | $F = 1.13, p = .432$ |

IV = ; PD = Pathologic discomfort; DT = dispersion of trajectory.

Q7 Other interaction effects between three and four variables were not significant.

### *3.2. Driving Speed*

The effects of road configuration, geometric element, visibility condition, and transition curve on average driving speed along a curve were examined, using within-subjects ANOVA with repeated measures. All the driving speeds along each curve were normally distributed (Kolmogorov-Smirnov test was performed for each distribution). Bonferroni correction was used for the multiple comparisons.

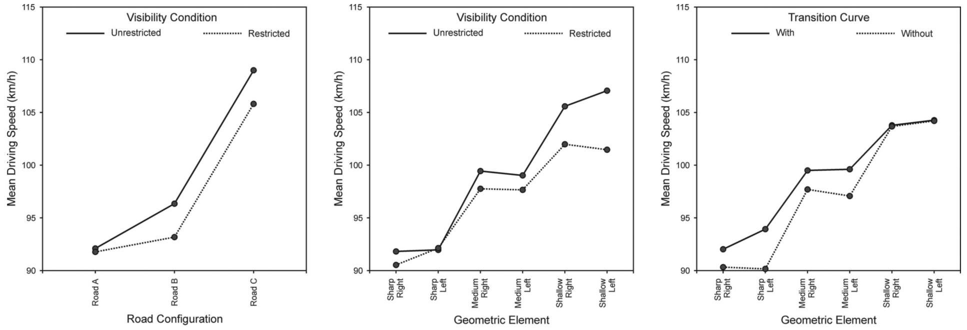
ANOVA revealed a significant main effect of road configuration, $F(2, 58) = 11.14$, $p <$ .001, partial Eta squared = .278, observed power = .989; geometric element, $F(2.77, 80.40)$ = 103.34, $p < .001$, partial Eta squared = .781, observed power = 1.000; visibility, $F(1, 29) = 18.74$, $p < .001$, partial Eta squared = .393, observed power = .987; and transition curve, $F(1, 29) = 36.99$, $p < .001$, partial Eta squared = .561, observed power = 1.000.

ANOVA showed also a significant interaction effect between road configuration and visibility, $F(2, 58) = 3.91$, $p = .025$, partial Eta squared = .119, observed power = .683; between geometric element and visibility, $\underline{F}(2.95, 85.45) = 3.98$, $p = .011$, partial Eta squared = .121, observed power = .814; and between geometric element and transition curve, $F(5, 145) = 6.26$, $p < .001$, partial Eta squared = .178, observed power = .996. No other significant interaction effects were found.

Post-hoc comparisons with Bonferroni correction allowed the evaluation of the main effects of the independent variables, as well as their interaction effects, on the average driving speed. For the main effect of road configuration, pairwise comparison based on post-hoc tests indicated that the average speeds recorded along the two-lane rural roads were not significantly different (average difference = 2.82 km/h, $p = 1.000$), with speed on Road A (91.94 km/h) lower than that on Road B (94.76 km/h). On the contrary, the average speed on Road A was significantly lower than that on Road C (107.41 km/h). A significant difference was revealed also when comparing the speed on Road B with that on Road C. Drivers adopted almost the same speed on curves along the two-lane rural roads but drove with higher speeds when the cross-section was wider. The speed significantly increased on the highway where the cross-section was characterized by wider lanes and divided carriageways; this induced drivers to adopt higher speeds along the same curve geometries.

Pairwise comparisons that were performed to investigate the main effect of the geometric element revealed significant differences between all the curves investigated, except for those characterized by the same radius but different directions. In fact, the maximum speed difference recorded between right and left curves of the same radius was 0.87 km/h for sharp curves, demonstrating that the curve direction did not affect the average speed of drivers. As expected, the lowest speeds were recorded on sharp curves (91.61 km/h), followed by medium curves where the average speed was significantly higher (98.47 km/h) than the speed on sharp curves but lower than that on shallow curves (104.02 km/h). As can be expected, there was a significant difference (12.41 km/h) in speeds on shallow and sharp curves. Therefore, the results corresponded to those expected when considering the main effect of the geometric element: the average speed on the curve increased when the curve radius was wider. Conversely, the direction of the curve did not affect driver's speed choice that depends on the radius.

With respect to the main effect of visibility, it was found that the average speed on curve with unrestricted visibility (99.15 km/h) was significantly higher than that adopted when the visibility was restricted by the steep side slope (96.92 km/h). In the latter case, the lower speed is clearly an example of the compensatory behavior of driver for the lower available visibility in front of him. However, it should be stressed that this decrement in



a) The effect of road configuration and visibility condition on mean driving speed

b) The effect of geometric element and visibility condition on mean driving speed

c) The effect of geometric element and transition curve on mean driving speed

**Figure 5.** The interaction effects of independent variables on driving speed.

speed was not enough to guarantee the safe driving condition, as the stopping sight distance was still longer than the available visibility.

Finally, the drivers adopted an average speed (98.85 km/h) that was significantly higher along the curves that presented clothoidic transition than that along curves where the clothoids were absent (97.22 km/h).

Post-hoc pairwise comparisons of the interaction effect of road configuration * visibility demonstrated that the visibility has an influence on driving speed for Roads B and C (that means for roads with higher speed limit) but not for Road A. Driving speeds on curves with restricted visibility were lower than those on curves where visibility was not restricted; it occurred for all road configurations. Figure 5a shows the interaction effect between road configuration and visibility. The average difference in speeds was not significant for Road A (0.32 km/h) probably because of the lower speed already adopted by drivers on the smaller road section.

Pairwise comparisons performed on the geometric element * visibility interaction effect revealed that the restriction used for limiting the driver's visibility induced drivers to adopt lower speeds along all the curves (except for the sharp left curve where the speed was higher under a restricted condition of visibility, by only 0.16 km/h). However, the differences were significant for only the shallow curves (right: 3.60 km/h, $p = .014$; left: 5.60 km/h, $p < .001$). Moreover, the speed differences between the curves with different radius were significant for the visibility conditions, as illustrated in Figure 5b.

Another significant interaction effect on driving speed was found between geometric element and transition curve. Pairwise comparisons revealed that by using a transition curve the driver always adopted a higher speed along the same curve radius, indicating less need to decelerate, probably due to an improved perception of the geometric element. However, the increments were found significant along sharp curves (right: 1.70 km/h, $p = .049$; left: 3.77 km/h, $p < .001$) and medium curves (right: 1.80 km/h, $p = .019$; left: 2.53 km/h, $p = .003$); no statistical significance was found for the shallow curves (for left and right: 0.06 km/h, $p = 1.000$), probably because of the wider radius that neglected the effectiveness of implementing the transition curve. Moreover, the speed differences between the six curves (except for curves with the same radii) were found to be significant in both cases, with or without the transition curve, as illustrated in Figure 5c.

### *3.3. Pathologic Discomfort*

The effects of road configuration, geometric element, visibility restriction, and transition curve on PD experienced by drivers along curves were examined, using within-subjects ANOVA with repeated measures. All PD homogenized data were normally distributed according to the Kolmogorov-Smirnov test. Bonferroni correction was used for the multiple comparisons. ANOVA revealed a significant main effect of road configuration, $F_($1.42, 41.22) = 19.60, $p < .001$, partial Eta squared = .403, observed power = .999; geometric element, $F(3.43, 99.41) = 210.80$, $p < .001$, partial Eta squared = .879, observed power = 1.000; visibility, $F(1, 29) = 119.80$, $p < .001$, partial Eta squared = .805, observed power = 1.000; and transition curve, $F(1, 29) = 477.64$, $p < .001$, partial Eta squared = .943, observed power = 1.000.

ANOVA showed a significant interaction effect between road configuration and visibility, $F(2, 58) = 4.57$, $p = .014$, partial Eta squared = .136, observed power = .755; between road configuration and transition curve, $F(2,58) = 10.64$, $p < .001$, partial Eta squared = .268, observed power = .986; and between geometric element and transition curve, $F(5, 145) = 100.44$, $p < .001$, partial Eta squared = .776, observed power = 1.000. No other significant interaction effects were established.

In analyzing the main effect of road configuration on PD using pairwise comparisons it was revealed, as previously described for driving speed, that PD values along the two-lane rural roads were not significantly different (average difference = 0.010 m/s$^2$, $p = .518$), with PD on Road A lower than that on Road B. Conversely, PD on Road A (0.163 m/s$^2$) was significantly lower than that on Road C (0.231 m/s$^2$). A significant difference was also shown when comparing PD on Road B (0.173 m/s$^2$) with that on Road C. Overall, the results show that the PDs on curves along the two-lane rural roads were almost similar but, when the cross-section became wider, the PD increased too.

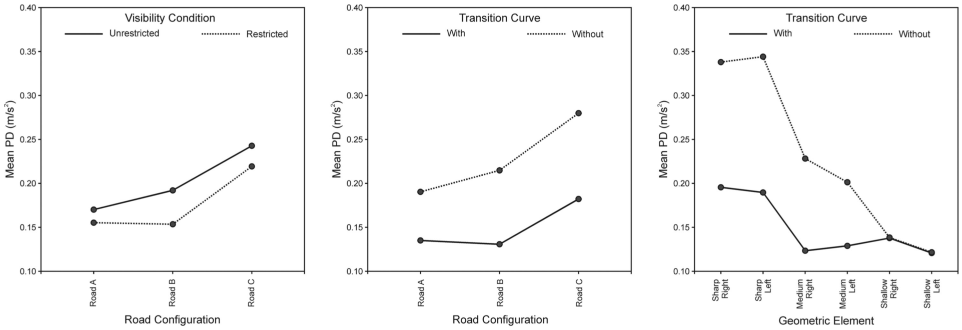
Pairwise comparisons revealed significant differences between PD recorded along all the curves investigated, except for those characterized by the same radius but different directions. Specifically, it was found that the lower the radius is, the higher the PD is, demonstrating that along sharp curves drivers experienced more difficulties to follow the road axis geometry, whereas the same behavior was found between left and right curves. The highest average PD was recorded on sharp curves (0.267 m/s$^2$) and the lowest on shallow curves (0.130 m/s$^2$); on medium curves it was 0.170 m/s$^2$. All of the differences were significant at $p < .001$.

Pathologic discomfort on curves with unrestricted visibility (0.202 m/s$^2$) was significantly higher than that recorded when visibility was restricted (0.176 m/s$^2$). It can be reasonably explained by a less need for drivers to correct their trajectories when visibility is restricted as they paid more attention when the difficulty of driving became higher (a sort of compensatory behaviour as described in the case of speed reduction). These results were fully consistent with previous findings (Calvi, 2010; Calvi et al., 2012; Calvi & D'Amico, 2013) that demonstrated how the visibility restriction of the tunnel walls could determine a guidance effect that helped drivers to correctly perceive and read road geometry.

Q8

Finally, the transition curves seem to help the driver in correctly following the trajectory. In fact, it was found that with transition curves the PD was significantly lower (0.149 m/s$^2$) than that recorded without the transition element (0.228 m/s$^2$). This result demonstrates the effectiveness of using transition curve.

Post-hoc pairwise comparisons for the interaction effect of road configuration * visibility revealed that PD values recorded along the curves with restricted visibility were significantly lower than those on curves with unrestricted visibility for all three road



a) The effect of road configuration and visibility condition on mean PD

b) The effect of road configuration and transition curve on mean PD

c) The effect of geometric element and transition curve on mean PD

**Figure 6.** The interaction effects of independent variables on pathologic discomfort (PD).

configurations. It was revealed that, under unrestricted visibility, PD on Road A was significantly lower than PD on Road B (average difference = 0.022 m/s$^2$). However, the difference was not significant when visibility was restricted, as the road configuration of two-lane rural roads did not affect PD for curves with restricted visibility. The other comparisons showed significant differences. Figure 6a shows the interaction effect between road configuration and visibility on PD.

Post-hoc tests revealed that the transition curve had PD values that were significantly lower than those recorded along the curves where no transition element was designed, confirming the effectiveness of clothoid in terms of safety (as demonstrated in previous studies (Calvi, 2010; Calvi & D'Amico, 2006; Casolo et al., 2008) that showed that lower PDs yielded lower crash rates for all the road configurations). Moreover, it was found that without clothoid PD on Road A was significantly lower than PD on Road B (average difference = 0.024 m/s$^2$). The same difference was not significant when the transition element was present, as the road configuration of two-lane rural roads did not affect PD on curves with clothoids. The other comparisons showed significant differences. Figure 6b shows the interaction effect between road configuration and transition curve on PD.

According to the previous results that demonstrated the effectiveness of clothoid for improving the safety of driving, pairwise comparisons on the significant interaction effect of geometric element * transition curve revealed that PD values along curves with clothoid were always lower than the PD values along the same curves without clothoid. The differences were statistically significant for both of the sharp curves (right: 0.142 m/s$^2$, $p < .001$; left: 0.154 m/s$^2$, $p < .001$) and both of the medium curves (right: 0.105 m/s$^2$, $p < .001$; left: 0.072 m/s$^2$, $p < .001$), but not significant for the shallow curves (right: 0.001 m/s$^2$, $p = 1.000$; left: 0.002 m/s$^2$, $p = .986$) for which the clothoid seems to lose its effectiveness, probably because the wider radius is easier to be correctly interpreted by the drivers (as also demonstrated by the lower values of PD along curves with wider radii). Moreover, the differences between the PD values along the six curves (except for curves with the same radius) were found to be significant in both cases, with or without the transition curve, as illustrated in Figure 6c.

### *3.4. Dispersion of Trajectory*

The effects of the four independent variables on the DT parameter computed along curves were examined, using within-subjects ANOVA with repeated measures. All DT data were normally distributed according to the Kolmogorov-Smirnov test. Bonferroni correction was used for the multiple comparisons. Also, for this parameter ANOVA revealed a significant main effect of road configuration, $F(1.32, 38.27) = 26.80$, $p < .001$, partial Eta squared = .480, observed power = 1.000; geometric element, $F(3.48, 100.94) = 12.96$, $p < .001$, partial Eta squared = .309, observed power = 1.000; visibility, $F(1, 29) = 19.15$, $p < .001$, partial Eta squared = .398, observed power = .988; and transition curve, $F(1,29) = 300.67$, $p < .001$, partial Eta squared = .912, observed power = 1.000.

ANOVA showed a significant interaction effect between road configuration and visibility, $F(2, 58) = 8.61$, $p = .001$, partial Eta squared = .229, observed power = .960; between road configuration and transition curve, $F(1.37, 39.64) = 33.54$, $p < .001$, partial Eta squared = .536, observed power = 1.000; and between geometric element and transition curve, $F(5, 145) = 57.44$, $p < .001$, partial Eta squared = .665, observed power = 1.000. No other significant interaction effects were established.

Post-hoc analysis indicated that the DT along the curves on Road A (0.111 m) was significantly lower than that on Road B (0.141 m) and on Road C (0.177 m). The latter two values of DT were also significantly different from each other. This means that the dispersion of trajectories increased when the road cross-section became wider, probably due to the increase in speed that yielded, under the same condition of driver's path correction, a greater DT.

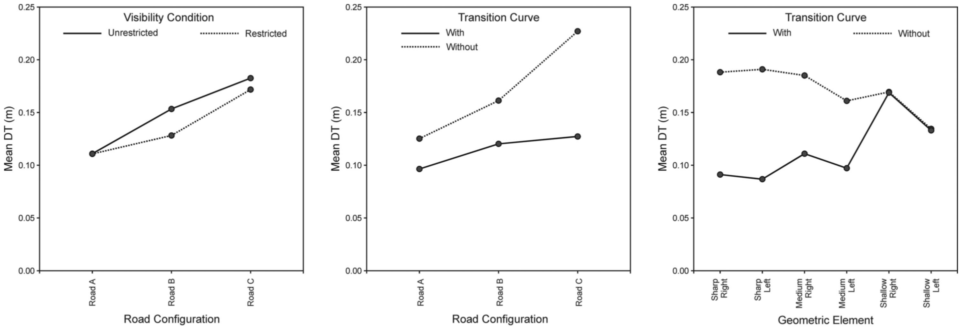
Pairwise comparisons revealed significant differences in DT recorded along most of the curves, with significant differences also between curves with the same radius but in opposite directions. Specifically, it was revealed that right curves showed higher DTs than left curves (average difference = 0.160 m). Moreover, for right curves the smaller the radius significantly the smaller the DT (0.140 m, 0.148 m, and 0.168 m for sharp, medium, and shallow right curve, respectively), whereas for left curves the differences were not significant (0.139 m, 0.129 m, and 0.133 m for sharp, medium, and shallow left curve, respectively).

The values of DT recorded along curves with unrestricted visibility (0.149 m) were significantly higher than those recorded when visibility was restricted (0.137 m), confirming once more a reduced need for drivers to correct their trajectories when visibility is restricted, probably due to a higher driver's level of attention under more difficult driving conditions, when the perceived risk was higher.

Finally, also in this case, the transition curves seem to help the driver in maintaining a constant trajectory. In fact, it was found that DT recorded along curves with clothoid was significantly lower (0.115 m) than that recorded along curves without the transition element (0.171 m).

Pairwise comparisons performed over road configuration * visibility interaction effect revealed that DT values on curves with restricted visibility were always lower than those on curves with unrestricted visibility. However, the difference was significant for Road B only (average difference = 0.025 m, $p < .001$) but not for Road A (0.000 m, $p = .957$) and C (0.011 m, $p = 0.069$). Conversely, a wider cross-section had a significantly higher DT under both visibility conditions. Figure 7a shows the interaction effect between road configuration and visibility on DT.

The presence of the transition curve resulted in DT values that were significantly lower than those recorded along the curves where clothoids were not present. This occurred for each roadway configuration, as revealed by the pairwise comparisons developed over the road configuration * transition curve interaction effect. This confirms once more the effectiveness of clothoid in lowering the dispersion of drivers' trajectories. Moreover, it was found that, without clothoid, DT was significantly different among the three configurations;



a) The effect of road configuration and visibility condition on mean DT

b) The effect of road configuration and transition curve on mean DT

c) The effect of geometric element and transition curve on mean DT

**Figure 7.** The interaction effects of independent variables on dispersion of trajectory (DT).

specifically, DT increased with the cross-section of the road. The same occurred for curves with a transition element, but the difference between DT values was lower (between Roads B and C, but not significant), as illustrated in Figure 7b which shows the interaction effect between road configuration and transition curve on DT.

Pairwise comparisons on the significant interaction effect geometric element * transition curve showed that the DT values along a curve with clothoid were always lower than the DT values along the same curve without clothoid. The differences were significant for the sharp curves (right: 0.097 m, $p < .001$; left: 0.104 m, $p < .001$) and the medium curves (right: 0.074 m, $p < .001$; left: 0.064 m, $p < .001$) but not significant for the shallow curves (for right and left curves: 0.002 m) according to previous results of PD. Moreover, the differences between DT values along the curves with same radii but with different directions were significant for medium and shallow curves in both cases, with or without a transition curve, with higher values for right curves, as illustrated in Figure 7c.

## 4. Conclusions and Further Research

This driving simulator study was developed to increase knowledge about the effects of the road design features of horizontal curves on driving performance.

The road cross-section, the radius of curve, the visibility condition, and the presence of a transition curve significantly influence driving speeds and the way a driver negotiates a curve in terms of trajectories and consequently lateral acceleration.

It was found that drivers adopted almost the same speed on curves along the two-lane rural roads but drove with higher speeds when the cross-section was wider. Moreover the average speed on the curve increased when the curve radius was wider. Conversely, the direction of the curve did not affect driver's speed choice. With respect to the visibility, it was found that the average speed on curve with unrestricted visibility was significantly higher than that adopted when the visibility was restricted. This can be considered as an example of driver's compensatory behavior for the lower available visibility in front of him that, however, did not guarantee safe driving conditions, as the stopping sight distance remained still longer than the available visibility. Finally, it was found that the average speed on curves with clothoid was higher than that on curves where clothoids were not present, probably due to an improved perception of the geometric element. However, this was not revealed on shallow curves.

The results of the analysis on PD show that the PDs on curves along the two-lane rural roads were almost similar; but, when the cross-section became wider, the PD increased too. Moreover, the lower the radius the higher the PD, meaning that along sharp curves drivers experienced more difficulties to follow the road axis geometry. Similar PDs were found between left and right curves. Pathologic discomfort on curves with unrestricted visibility was higher than that recorded when visibility was restricted, where the driver had to pay a greater attention for the higher difficulty of driving (again, a sort of compensatory behavior). Finally, the effectiveness of using transition curve for helping the driver to correctly follow the trajectory was once more demonstrated, as PDs on curves with transition were significantly lower than those recorded on curves without transition. It occurred only on sharp and medium curves, confirming that for shallow curves the implementation of the transition curve seems to be not effective.

The DT increased when the road cross-section became wider, probably due to the increase in speed that yielded, under the same condition of driver's path correction, a greater DT. Significant differences in DT were found between curves with different radii (for right curves, the smaller the radius significantly the smaller the DT, whereas for left curves the differences were not significant) and also with the same radius but opposite directions (right curves showed higher DTs than left curves). The values of DT recorded along curves with unrestricted visibility were significantly higher than those recorded when visibility was restricted, confirming the lower need of drivers to correct trajectories when visibility is restricted. Finally, also in this case, the transition curves seem to help the driver in maintaining a constant trajectory. In fact, it was found that DT recorded along curves with clothoid was significantly lower than that recorded along curves without the transition element.

The results of this study are surely promising and show the effectiveness of the driving simulation for road design recommendations. However the limitations of the results presented here should be acknowledged as well as the recommendations for further researches.

The main limit of simulation tests is related to the lower risk perceived by drivers during the driving due to the possible occurrence of a virtual crash that does not cause any kind of damages. Although the drivers are immersed in a simulated environment that is very consistent with the real one, their perceptions and behaviors can be different than those on a real road, mainly because of the lack of motivational and emotional context. Therefore it is essential to verify the validation of driving simulation. Although the CRISS simulator has been already successfully validated for different driving situations (Bella, 2005, 2008), a validation study is needed to enable its use for in depth analysis of driving performance along different road configurations and geometries, for proposing effective design guidelines that take into consideration drivers' behaviors, before any design recommendations or applications of results for legislative purposes.

In this study a homogeneous sample of participants was selected (mean age of 26 years, range 22 – 35 years). As many studies demonstrated that driving performances are mostly affected by age and the goal here was to assess how horizontal curves characteristics influence drivers' performance, a homogeneous sample of participants was preferred, in such a way any bias from sample heterogeneity was reasonably negligible or strongly limited. In future programs, it would be expected to test other categories of drivers to extend the results as much as possible.

Moreover, though the curves here investigated were quite numerous, a wider sample of geometries (curve radii, cross-sections, different parameters of curve transitions, visibility conditions) should be considered, analyzing also the location of a curve in relation to other curves to provide results based on spatial considerations that are not typically included in the safety analysis of a roadway design.

Finally further studies with varying traffic volume are planned in order to confirm the findings and strengthen and generalize the results. Particularly the investigation of driving performance should be enlarged among different traffic conditions to promote the use of driving simulators among the road design community and provide practical applications in traffic engineering.

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