Investigating the Effectiveness of Perceptual Treatments on a Crest Vertical Curve: a Driving Simulator Study

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Abstract

Rural roads are characterized by a high percentage of run-off-the-road accidents and head-on collisions, mainly caused by inappropriate speeds and failure to maintain a proper lateral position along the roadway alignment. Among several road safety treatments, low-cost perceptual measures are considered an effective tool, as they generally increase the risk perceived by drivers, or even alter the drivers' speed perception, and consequently tempting them to decrease their speeds. Their effectiveness has been widely recognized in a number of studies, especially with respect to road intersections and curves.

The overall aim of this study is to investigate the effects of different perceptual treatments on driving speed, along a crest vertical curve of an existing two-lane rural road, in order to identify the most effective measure to reduce speed and define its subsequent implementation in the field. Three perceptual treatments were tested using a driving simulator: white peripheral transverse bars, red peripheral transverse bars and optical speed bars, with each one being painted along the approaching tangent to the crest vertical curve. The effects of these speed-reducing measures were investigated using a sample of forty-four participants, by comparing the driving speeds with those recorded under a baseline condition (without a treatment); these were also used to validate the driving simulator's speed measurements with those found in the field. Moreover, subjective measures were collected, consisting of the driver's static evaluation of the desired speed, risk perception and markings comprehension, based on screen shot pictures that represented the simulated configurations of the treatments.

The findings demonstrated an overall effectiveness of the perceptual treatments, although only the red peripheral transverse bars were found to significantly reduce the driving speeds (-6 km/h). The analysis of the questionnaire yielded interesting information and demonstrated the importance of performing driving simulation tests for evaluating the effectiveness of perceptual treatments.

Finally, the results confirmed the enormous potential of using driving simulators to pinpoint a number of speed-reducing measures, and consequently select the most effective one that reduces cost and promotes safety before its actual implementation in the field.

Keywords

Driving Simulator; Road Safety; Perceptual Treatments; Speed Reduction

1. Introduction

Worldwide, the use of inappropriate or excessive speeds by drivers is widely recognised as one of an overall safety issue (*WHO, 2015*). Several crash analyses and reports, studies and research works do agree that speeding is a primary factor in more than one third of fatal accidents and an aggravating factor in all accidents (*WHO, 2015, 2017; ITF, 2017; ETSC, 2017*).

For this reason, it is quite important to focus research efforts on pinpointing effective measures that could tackle this crucial safety problem and reduce speed-related crashes. In order to address the latter, an interdisciplinary approach, consisting of education, enforcement and engineering measures, is required.

Amongst the measures that have been adopted for tackling speeding it must be cited improvements in procedures for setting up speed limits, driver education programs, speed enforcement programs and engineering features along the roadway environment. Each of these measures and interventions has been widely analysed and studied, resulting in different levels of success (*WHO, 2017; ERSO, 2015;*

FHWA, 2012). In example, setting appropriate speed limits (speed limits that reflect a "reasonable and prudent" behaviour on the part of the majority of motorists) are deemed very important, since speed limits that promote inconsistency may be ignored by drivers, and consequently contribute to lack of respect for speed limits and other traffic laws. Therefore, to set effective speed limits that could improve the respect from a driving point of view, it is crucial to take into consideration the surrounding context of the roadway (including overall operating and geometric characteristics of the road and roadside, as well as collision frequency) in order to meet the driver's expectations. Another aim of reducing inappropriate and excessive speeds consists of improving the drivers' awareness of speed-related crashes, by informing the drivers of the high risks that are associated with speeding and, consequently, encouraging the drivers to obey the speed limits and drive at speeds that are compatible with the roadway environment. Moreover, the effectiveness of speed enforcement efforts can be improved by increasing the drivers' perception of the hefty speeding fines that might result.

Besides education and enforcement interventions, engineering measures have been also found to significantly affect the speeding behaviour (i.e. *Jamson, Lai, & Jamson, 2010; Montella et al., 2010*). In this respect, it is essential that the roadway design supports appropriate and safe speeds, meaning that the roadway alignment and roadside need to reflect the speeds expected by drivers. A good road design is the one that is able to provide a balance between the road features and the actual operating speeds. If such balance is not achieved, then countermeasures have to be provided to reduce the speeds of drivers, especially at critical locations (i.e., approaching sharp curves and intersections; entering interchange ramps; driving near schools, through work zones or small towns on rural roads, etc.). Further, it is equally important to prompt the driver to adopt appropriate speeds by obeying the traffic control devices: from permanent speed limits to variable speed limits and speed warnings; from traffic calming measures to various designs of the roadway section; from pavement markings to traffic signs.

Among all the engineering treatments, the perceptual countermeasures have been demonstrated to be highly cost-effective in reducing driving speeds under several roadway situations and conditions. Basically, perceptual treatments endeavour to increase the driver's perceived workload and risk (altering driver's perception of speed, risk, comfort) related to a driving situation, inducing drivers to adopt more appropriate speeds. Moreover, they are based on a visual or an optical illusion that encourage speed reduction by drivers.

2. Literature Review

During the last decades, several studies, mainly based on field tests and driving simulator experiments, have evaluated the effectiveness of different perceptual treatments in improving the driving performance, reducing the speeds and maintaining a more appropriate lane position. Moreover, several reports have been published and provided guidelines and summaries of research works on identifying potential safety problems and proposing countermeasures.

The majority of studies around this field of research were aimed at ascertaining the effectiveness of perceptual treatments in reducing the drivers' approaching speeds to sharp curves. *Comte & Jamson (2000)* developed a driving simulator study and tested four speed-reducing measures on curves (Variable Message Sign, in-car advice, speed limiter and transverse bars). Although speed limiters were the most effective measure, they represented the least preference of drivers in terms of acceptability. In any case, all the other measures significantly reduced the speeds. *Charlton (2004)* compared the relative effectiveness of various types of warnings (diamond, chevron and road marking types) on drivers' speed selection at curves using a driving simulator. All the warnings were found to be effective on severe curves, whilst, in general, curve warnings that contained perceptual components or emphasized the physical features of the curve worked best. In a later study, *Charlton (2007)* tested two groups of curve treatments by using a driving simulator: warning signs, designed to alert drivers to the presence of curves and produce a speed reduction while approaching the curve, and road markings, designed to affect the speed and lane position of drivers, as they drove through curves. The results indicated that advance-warning signs were more effective when they were used in conjunction with chevron sight boards and/or repeater arrows. Rumble strips were found to be the only road markings that produced an appreciable reduction in speed, while a herringbone road marking was found to be effective in improving the drivers' lane positions. The author concluded that treatments highlighting perceptual cues are the most effective means of moderating drivers' speeds on curves.

Katz, Duke, & Rakha (2006) analysed the design and evaluation of peripheral transverse bars to reduce speeds. Overall findings demonstrated that markings placed at 4 bars per second did result in a significant reduction in speed measured in the field, specifically on approaches to curves. In a later study, developed using a driving simulator, *Katz, Molino, & Rakha (2008)* investigated the differences between four pavement marking spacing designs (constant, exponential, 2 bars per second, and 4 bars per second) of peripheral transverse bars. No overall significant differences were found between the treatments that were found to be all effective anyway. Moreover, the authors evaluated the drivers' lateral position to determine whether the markings could cause drivers to have fewer encroachments toward the centre line, which could potentially have a safety benefit on two lane roads. The authors found that, for the two bars per second and four bars per second design alternatives, the driver did travel significantly further away from the centre line. *Gates, Qin, & Noyce (2008)* evaluated the effectiveness of an experimental white transverse bar marking installed with decreasing spacing between successive markings to reduce speeds on freeway curves. Overall findings confirmed that the treatment was effective in reducing speeds on curves. Recently, *Ariën, Brijs, Vanroelen, Ceulemans, Jongen, Daniels et al. (2017)* investigated the effect of two pavement markings (transverse rumble strips and a backward pointing herringbone pattern) on speed and lateral control on and nearby curves using a driving simulator. Both of the treatments did significantly affect the driving speeds (transverse rumble strips were found to be more effective in reducing the speed) but not the lateral control. Transverse rumble strips generated an earlier and more stable speed reduction than herringbone pattern, which induced speed reductions along the curve.

Several reports have been also published with the overall aim to evaluate the effectiveness of perceptual treatments in improving safety on curves. *Godley, Fildes, Triggs, & Brown (1999)* systematically evaluated the effectiveness of perceptual countermeasures to speeding using a driving simulator. Specifically, different treatments (transverse lines, peripheral transverse lines, a herringbone pattern, the Wundt illusion, trees on the road edge) were evaluated on the approach to an intersection, while other countermeasures (narrower lane widths, and several treatments on medians and edge lines) were selected for continuous driving along roads. Moreover, other treatments (i.e., inside hatching, centre line hatching and reflector post positioning) were evaluated specifically for curve. The report highlighted a significant reduction in speeds, especially in case of full lane width and peripheral transverse lines, hatched median and enhanced reflector post spacing. *McGee & Hanscom (2006)* published a report on the evaluation of low-cost treatments for addressing identified or potential safety problems. Several treatments had been studied including basic traffic signs and markings, enhanced traffic control devices, additional traffic control devices, rumble strips, minor roadway improvements and innovative and experimental treatments (i.e., optical speed bars and curve advance markings). The report provided a description of each treatment including design features, and shows some practical examples, suggesting when the treatment might be applicable. The report also provided information on the safety effectiveness and costs of treatments.

Other studies analysed the effectiveness of perceptual treatments in reducing the driving speed approaching an intersection. *Fildes, Corben, & Newstead (2005)* developed a field test to evaluate the potentialities of two perceptual treatments (an enhanced curve post treatment and peripheral transverse edge lines) in reducing speed on the approach to an intersection. The authors concluded that although the effectiveness of the tested treatments may be site specific to some degree, they do offer a low-cost solution to reduce driving speed at hazardous locations anyway. *Montella, Aria, D'Ambrosio, Galante, Mauriello, & Pernetti (2010)* studied the effects of different perceptual treatments on several driving performance on major approaches of a rural intersection, reproduced in a driving simulator. The authors found that the most effective speed-reducing treatments were the dragon teeth markings, the coloured intersection area and the raised median island. *Zamora, Allaby, & Charters (2011)* developed a research project to evaluate the effectiveness of both peripheral and transverse pavement markings to reduce the speeds of vehicles approaching some key gateway intersections. Specifically, five pavement marking patterns (transverse rectangular bars, peripheral square markings (staggered and non-staggered), peripheral triangles, and width-increasing peripheral rectangular markings) were designed, installed and evaluated as low-cost countermeasures to encourage drivers to reduce speeds as they approached intersections at urban gates. Based on statistical analyses, the peripheral square markings showed the best performance.

The application of perceptual treatments has been also tested in several other road environments and conditions. *Allpress & Leland Jr. (2010)* evaluated the effectiveness of two perceptual countermeasures (i.e., drivers had to pass between a 3.5 meters wide passage of either evenly or decreasingly spaced cones) to decrease speeds within roadwork sites. Both interventions were highly effective at reducing speed. *Manser & Hancock (2007)* verified if the type of visual pattern (vertical segments that decreased, increased, and remained a constant width throughout the length of a tunnel) and presence of texture applied to road tunnel walls differentially affected driving performance. The overall results revealed that drivers adopted lower speed when a decreasing width visual pattern was applied, while they increased speed with the increasing width visual pattern. The presence of texture attenuated overall driving speed. *Jamson S., Lai, & Jamson H. (2010)* developed a driving simulator study to test twenty speed-reducing treatments in urban and rural road environments. The results demonstrated that increasing risk perception is highly effective in reducing driving speed. Moreover, treatments alerting drivers had more effect at junctions than on straight sections, particularly in an urban environment; the most effective treatments for curves were those that highlighted the curve radius. Finally, *Rosey, Auberlet, Bertrand, & Plainchault (2008)* reproduced in a driving simulator four perceptual treatments (painted centre line, post delineators, rumble strips on both sides of the centre line and sealed shoulders) to verify their effectiveness in supporting the drivers to keep in the centre of lane along a straight rural road with different crest vertical curves. The results demonstrated that the rumble strips on both sides of the centre line along with the sealed shoulders were the most effective treatments in improving the driver's lateral control. Similar results were obtained in a field study (*Auberlet, Rosey, Anceaux, Aubin, Briand, Pacaux et al., 2012*), developed few years later, where the centre line rumble strips, those identified as the most effective in the previous driving simulator study, were installed and tested on a crest vertical curve. The study demonstrated the utmost importance of driving simulators in the road design process.

3. Objectives

The main objective of the present study is to identify the pavement marking patterns that provide the best improvements in terms of drivers' speed reduction on a crest vertical curve of an existing two-lane rural road that is characterized by a high crash rate (mainly due to speeding behaviour) recorded on the roadway segment that encompasses the crest. In fact, while several studies have investigated the effectiveness of speed reducing measures and perceptual treatments on the approach to critical curves, intersections or small towns and villages on rural roads, there is a lack of knowledge about the way these measures could be applied and how effective could they be on another typical critical road location that is a crest curve with reduced visibility. For this aim, after validating the driving simulator for this case study, three perceptual treatments, specifically selected from amongst the most effective speeding countermeasures that have been analysed in the literature, were investigated. Specifically, the effects of white peripheral transverse bars, red peripheral transverse bars and optical speed bars on driving speeds along the crest vertical curve have been investigated and compared to actual road conditions, where no perceptual treatments are adopted (baseline condition). It was decided to also investigate the possible additional effects of the treatments' colours, as no studies have analysed that before, and consequently provide an additional contribution to the literature in the field of speed-reducing measures.

Moreover, subjective measures were collected, based on the participants' evaluations of screen shots from the simulator scenario included into a questionnaire submitted to drivers (each picture represented a different treatment painted on the road pavement, including the baseline condition). The questions were related to the safe speed the driver would adopt in the illustrated condition, the level of the risk perceived from the picture, the legibility of the road alignment and the comprehension of the treatment. This is another specific objective of the study that aims to provide an original contribution to the literature by comparing objective and subjective measures, which are both greatly important in analysing the perceptual treatment.

This paper presents the first results of the study based on a statistical analysis performed over drivers' speed profiles for evaluating the effectiveness of different perceptual treatments in reducing drivers speed along a critical crest vertical curve of an Italian two-lane rural road and identifying which treatment is the most effective, before any implementation in the real existing road.

4. Methodology

4.1 Apparatus

The experiments were performed using the fixed-based driving simulator of the Inter-Universities Research Centre for Road Safety (CRISS) at Roma Tre University (Figure 1). It consisted of a real car with a force-feedback steering wheel, brake pedal and accelerator. The road scenario is projected onto three big screens, providing the driver with 135° (horizontal) x 60° (vertical) wide-angle field of view. 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; Bella, Calvi, & D'Amico, 2014; Benedetto, Calvi, D'Amico, & Giunta, 2015; Calvi, 2015a, 2015b; Calvi, Benedetto, & De Blasiis, 2012; Calvi & D'Amico, 2013; Calvi, Bella, & D'Amico, 2015, 2018; Calvi, Benedetto, & D'Amico, 2018*).

Figure 1: The driving simulator at CRISS laboratory.

4.2 Simulated Road Scenario

The roadway geometry reproduced in the driving simulator was a virtual reconstruction of a two-lane rural road near Rome, Italy. This road is characterized by a poor level of safety; the improvement of its safety has been a priority for regional road administration for many years. More specifically, a high concentration of road crashes was revealed on the proximity and along a crest vertical curve of this road, where the crest itself limits the stopping sight distance. Road safety countermeasures, mainly addressing speeding behaviour, are strongly recommended for improving the safety level of the road. In fact, a campaign of speed measurements (it will be described in more details in section 4.6) reveals that driving speeds are quite higher than the speed limit, which is 90 km/h along the road; at 200 meters before the crest curve, it changes to 60 km/h. Along with the speed limit sign, there is an additional warning sign that alerts the driver about the upcoming crest curve and the limited visibility. Both of the vertical signs are included in the Italian Highway Code. A segment of this road, including the crest vertical curve, was therefore selected for the reconstruction in the driving simulator environment. Along this segment, the road is characterized by a 6.00 meters wide cross section, consisting of two lanes 3.00 meters wide and no hard shoulders. The road alignment is composed of a long horizontal tangent (1000 meters) located between two horizontal curves with radii of 250 meters. Along the tangent, there are three vertical grade changes (from 0% to 4%, from 4% to -4%; from -4% to 0%) with two sags and a crest vertical curve, in the middle. Specifically, the first sag vertical curve is characterized by a radius of 5000 meters and a length of 200 meters; along the sag the grade changes from 0% to 4% upgrade; the length of the grade (4%) is 200 meters; after that, the crest vertical curve begins, with a radius of 1500 meters and a length of 120 meters, connecting the 4% upgrade tangent to the 4% downgrade tangent; at the end of the crest vertical curve there is a grade tangent (-4%) of 200 meters; finally, there is the second sag vertical curve, characterized by a radius of 5000 meters and a length of 200 meters; along the sag the grade changes from -4% to 0%. Figure 2 provides the details of the horizontal and vertical alignment of the investigated road segment.

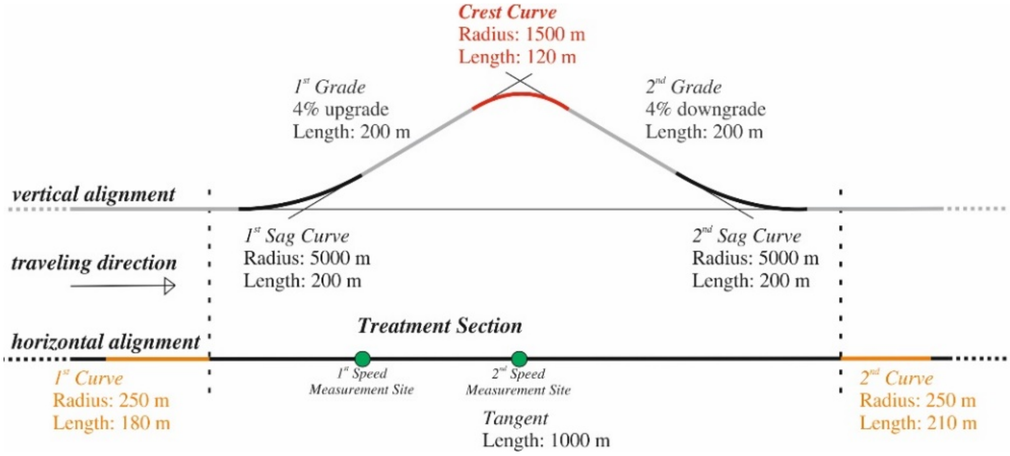

Figure 2: Horizontal and vertical alignment of the road segment.

The roadside elements were placed under exact simulation of the real locations, including a line of trees along both edges of the carriageway. The scenario was reconstructed using 3D software and then introduced into the simulator scene. All markings and signs were exactly reproduced in the simulator. Finally, to make the simulated scene as similar as possible to the real one, the background images were composed of photos of the real environment. The driving condition was daylight, clear view and full friction.

Each driver had to perform four different tests in the driving simulator; the only difference among the tests was in the way the crest vertical curve was treated. In addition to the baseline condition, which corresponded to the actual road configuration of the crest vertical curve, three other conditions, which corresponded to the treatments investigated, were reproduced. To reduce learning effects due to driving the same scenario four times, different starting points were designed for each test, in such a way that the driver reached the road segment under investigation after about 4 kilometres from the beginning of the test, driving along different horizontal and vertical road alignments. In any case, the geometries of the crest curve, as well as 1 kilometre section of the road before the beginning of the crest, were kept always the same for all the drivers and under all tests. Finally, low traffic was present in the opposite lane in order to avoid any central line crossing of the driver; moreover, drivers were not constrained by any vehicles ahead (free-vehicle condition).

4.3 Speed-Reducing Treatments

Three different perceptual treatments were tested in this experiment: peripheral transverse bars (white and red) and optical speed bars. Figure 3 provides some images from the simulation, reproducing the perceptual treatments used in approaching the crest vertical curve.

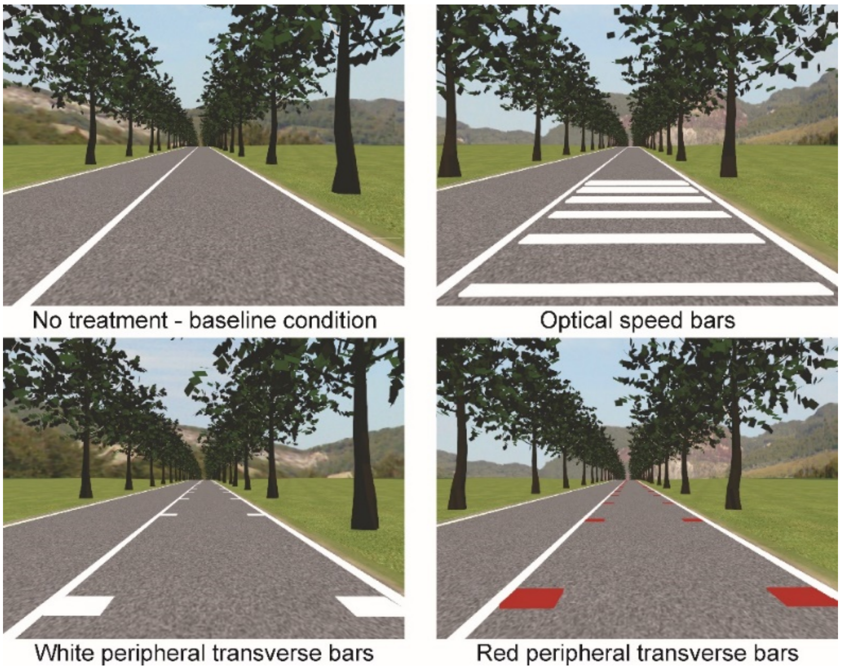

Figure 3: Frames of simulation: examples of treatments implemented on the crest vertical curve.

Peripheral Transverse Bars (PTB)

The pattern consisted of peripheral pavement markings on both sides directly opposite to one another and perpendicular to the travel lane. The patterns were designed and installed according to the following dimensions: square peripheral markings of 45 cm by 45 cm. Among the alternatives of peripheral transverse bars spacing designs (constant, exponential, *n* bars per second and others), according to literature that highlighted the most effective ones (*Katz et al., 2006, 2008; Zamora et al., 2011*), it was decided to use an exponential spacing pattern, which consisted of markings with decreased spacings between the markings throughout the road section under study. This creates an optical effect of acceleration whilst passing through it. Specifically, this illusion, generated by placing transverse bars on the pavement at increasingly closer spacings, gives the drivers the perception that they are accelerating. Consequently, this effect prompts the drivers to reduce their speeds. For the treatment design, it was decided to fix the deceleration rate of drivers (in this case, it was decided to apply 1.5 m/s^2), meaning that the driver would pass through the treated area at a rate of 4 bars per second. This deceleration rate was thought to be appropriate and comfortable for the driver, based on the posted speed limit at the test site. The initial and final speeds were supposed to be 90 km/h and 60 km/h, respectively, according to the operating speed and the speed limit on the road. Consequently, the first bars were located 200 meters before the beginning of the crest vertical curve, all along the treated road section of 200 meters.

Two different colours were used for painting the peripheral transverse bars, in such a way that two different treatments were analysed: white peripheral transverse bars, and red peripheral transverse bars. It was decided to not only test the "standard" white colour, typically used for most of Italian markings, but also the red colour in order to improve the treatment visibility and emphasize the effect of reduction in speed, by means of the potential message "dangerous road", which could be associated with the red markings. However, it should be noted that these peripheral pavement markings are not applied on Italian roads and that there exist no national guidelines that include such perceptual treatments. Therefore, Italian drivers are not used to peripheral transverse bars.

Optical Speed Bars (OSB)

The other transverse pavement markings investigated in this study, defined as optical speed bars, were applied perpendicular to the direction of traffic flow, in the middle of the travel lane. Specifically, three sets of optical speed bars were located on the road, respectively at 200 meters and 100 meters before the beginning of the crest curve and at the location where the crest curve begins. Each set of optical speed bars was composed of six transverse bars, all with lengths of 2.70 meters (shorter than the 3.00 meters lane). The bar widths were increased in the travelling direction (0.20, 0.40, 0.60, 0.80, 1.00, and 1.20 meters), while the spacing between bars were decreased in the travelling direction (1.10, 0.90, 0.70, 0.50, and 0.30 meters). In this way, the driver's perception of speed is altered by the perceptual cue, meaning that he is accelerating whilst he should be decelerating. This kind of pavement markings are well-known by Italian drivers as they are the only perceptual measure that is commonly used at critical locations of both urban and rural roads, such as on the approach to a sharp curve, entering interchange ramps, approaching key intersections, etc. The Italian Highway Code provides some design features for this measure amongst the suggested speed-reducing devices.

4.4 Participants

Forty-four volunteers participated in the experiments. They were recruited from students and staff at the Department of Engineering at Roma Tre University. The participants had no previous experience with the driving simulator, have at least 4 years of driving experience, and cover an average annual driving distance of at least 3,000 km on rural roads. Two of the participants who completed the driving tests noted that they had experienced a degree of discomfort, as revealed in the post-drive questionnaire. Consequently, they were excluded from the post processing of data. Two others were also excluded due to problems with the recording system of simulation.

The validation of the drivers' simulation output was consequently performed on the sample of the forty remaining drivers. Outliers were regarded as those drivers whose average speed, recorded along the road tangent to the beginning of the crest curve, was higher than three standard deviations (SDs) from the sample's average speed on the same geometry. Under such conditions, two drivers were further excluded from analysis.

Thus, the final sample consisted of 38 drivers (26 men and 12 women) with an average age of 26.1 years (SD = 4.1 years), ranging from 22 to 47 years. Their average driving experience was 7.8 years, with an average annual driving distance on rural roads of about 9,000 km.

4.5 Procedure

Each participant had to follow a strict procedure consisting of seven steps: 1) some general instructions were given to the participant who then had to answer a pre-drive questionnaire with some personal data; 2) a training drive in the simulator was performed by the participant for approximately 15 minutes in order to familiarize him (or her) with the simulator controls; 3) driving on two of the four tests (with the order counterbalanced among drivers); 4) filling of a screen shots questionnaire (with the sequence of the pictures counterbalanced among drivers); 5) 30 minutes of rest in order to re-establish psychophysical conditions similar to those at the beginning of the experiment; 6) driving under the other two tests; 7) filling out a post-drive evaluation questionnaire about the discomfort experienced during the experiment.

4.6 Data Collection

In order to investigate the effectiveness of perceptual treatments in reducing the driver's speed on the approach and along the crest vertical curve, the driver's speeds were recorded at six measurement points: three points were fixed at 300 meters, 200 meters, and 100 meters before the beginning of the crest vertical curve; the other three points were located at the beginning (B), at the middle point (H) and at the last point (E) of the crest, respectively.

Moreover, some subjective measures were also collected. In fact, each driver had to reply and fill out a screen shots questionnaire that consisted of four pictures from the four experimental driving scenarios. Each screen shot contained a different treatment, painted on the pavement along the tangent approaching the crest vertical curve, including the baseline condition (without any perceptual treatment). All participants were shown all pictures in a different random order on a computer screen and were asked to evaluate: 1) the safest driving speed for that geometric element in km/h; 2) the perceived level of risk based on the scale 1-10 (1 - lowest risk, 10 - highest risk); 3) the legibility of the road alignment based on the scale 1-10 (1 - very difficult, 10 - very easy); 4) the comprehension of the perceptual treatment based on the scale 1-10 (1 - poor comprehension, 10 - full comprehension).

Finally, a campaign of speed measurements was developed on site using a laser speed meter at two locations: 200 meters before the beginning of the crest vertical curve (where the 60 km/h speed limit sign is placed) and at the proximity of the middle point of the crest vertical curve. Obviously, the locations were chosen so as not to interfere with the traffic flow. Specifically, the laser speed meter was installed behind a tree, in such a way that the drivers could not see the instrument and to avoid any biased behaviours. The laser speed meter was connected to a computer on which the data was saved. About 1000 vehicles were sampled during an observation period of 30 minutes for each measurement site, and for one driving direction. For each vehicle, the corresponding speed, length, and time were collected.

4.7 Data Analysis

The analysis encompassed three steps. First of all, a validation of the simulation, by comparing simulated and real data at two locations where field speeds were collected, was made. Secondly, a statistical analysis of speed data from simulation was performed by means of ANOVA with repeated measures. Specifically, an ANOVA 4x6 was performed, with respect to the treatments (baseline condition, red peripheral transverse bars, white peripheral transverse bars and optical speed bars) and the measurement points (-300m, -200 m, -100 m, B, H, E), considered as within-subject factors. The objective of ANOVA was to evaluate the differences in driving speeds amongst the four scenarios that are characterized by different treatments of the crest vertical curve (including the baseline condition with no speed-reducing measure). Finally, drivers' replies to the screen shots questionnaire were analysed in order to evaluate the subjective data and understand the drivers' perceptions and comprehension of the perceptual treatments.

5. Results and Discussion

5.1 Validation of Simulation

Although the driving simulator used in this study has been already validated (*Bella, 2008*) for speeds along rural roads under different driving conditions and road geometries, and given the results of previous studies (e.g., *Godley, Triggs, & Fildes, 2002*) that have demonstrated a relative validity of driving simulators for use in evaluating speeding countermeasures, the scenarios of speed measurements that were developed on site along the crest vertical curve under study allowed the validation of the CRISS driving simulator in comparing the speeds measured on site with the speeds recorded under the baseline condition of the simulation experiment. The simulator validation was conducted with the assumption that driving was mainly affected by the road configuration with the speed being the dependent variable. Therefore, only the speeds of vehicles that were not affected by traffic operations were used in this analysis (free-vehicle condition).

For the purpose of analysis validation, and amongst the 1000 speed data that were collected in the field test, only the free-flowing vehicles were considered, according to the following characteristics: vehicle length of at most 5 meters (this value corresponds to passenger cars only); headway time of at least 5 seconds (this value is suggested in the literature in order to pinpoint free-flowing vehicles). Under such requirements, the free-flowing vehicles that were identified were 58 for the first measurement point (200 meters before the beginning of the crest curve) and 67 for the second measurement point (at the middle point of the crest). Therefore, the collected data allowed the analysis of the speeds that were adopted by drivers approaching the crest vertical curve and then driving through it.

Table 1 gives the average speeds and standard deviations that were measured in the field, as well as those that were recorded in the driving simulator at the same locations. It is interesting to note that in the field the driver approached the crest curve with a high average speed (84.22 km/h) in proximity of the speed limit sign and then decreased the speed till the middle of the crest vertical curve (73.95 km/h). However, and as previously noted, these values are much higher than the set speed limit (60 km/h). Similar behaviour was recorded in the driving simulator (see Table 1).

Table 1: Descriptive Statistics
for Field and Simulation Tests at the Measurement Sites

Measurement site	Field test			Simulation test (baseline condition)		
	Average Speed V_R [km/h]	Number of measures N_R	Standard Deviation SD_R [km/h]	Average Speed V_S [km/h]	Number of measures N_S	Standard Deviation SD_S [km/h]
-200	84.22	58	13.37	87.43	38	13.21
H	73.95	67	13.01	76.37	38	12.73

Noteworthy is that the speeds from simulation (V_S) were quite similar (a bit higher) to those collected in the field (V_R). The differences between the average speeds (V_S-V_R) were only 3.21 km/h and 2.42 km/h, respectively. Such values seem to demonstrate the reliability of the simulation and are consistent with the results of previous studies (*Bella, 2005, 2008*). However, in order to affirm the reliability of the simulator, a bilateral Z-test for non-matched samples was used to ascertain whether the differences in average speeds between the two samples were statistically significant. The application of the Z-test was prompted by the Kolmogorov Smirnov test of normality which proved that the distribution of speeds in the field and under the baseline condition of the driving simulator were normally distributed. The statistical analysis confirmed the outcomes of the comparative analysis for both sites, with a level of significance of 5%. In other words, it was found that the differences between the field speeds and the simulation speeds were not statistically significant, prompting promising results in the applicability of the research findings in identifying the most effective perceptual countermeasure for improving the road safety of the section under study.

5.2 Effectiveness of the Perceptual Treatments

Table 2 gives the average values and standard deviations (*SD*) of the drivers' speeds that were recorded under simulation for every combination of independent variables for the ANOVA 4x6 test (treatment and measurement point). Moreover, the speed reductions between the baseline condition (V_B) and each treatment (V_T) are also provided. Table 3 gives both the main and interaction effects of the independent variables on the driving speed.

Table 2: Descriptive Statistics for Combinations of Treatment and Measurement Point

Treatment	Measurement Point	Speed [Km/h]		Speed Reduction	
		Average	*SD*	V_B - V_T	$(V_B - V_T)/V_B$
Baseline Condition	-300	90.18	12.73		
	-200	87.43	13.21	V_B = speed in the Baseline Condition	
	-100	81.52	13.07		
	B	77.18	12.59	V_T = speed in the Treatment Scenario	
	H	76.37	12.73		
	E	79.55	12.49		
Red Peripheral Transverse Bars	-300	90.13	14.22	0.05	0.06
	-200	85.70	13.90	1.73	1.98
	-100	76.87	12.56	4.65	5.70
	B	71.23	11.59	5.95	7.71
	H	70.79	10.94	5.58	7.31
	E	76.26	10.52	3.29	4.14
White Peripheral Transverse Bars	-300	90.24	12.27	0.06	0.07
	-200	86.41	13.17	1.02	1.17
	-100	78.15	12.83	3.37	4.13
	B	72.47	12.00	4.71	6.10
	H	72.10	10.49	4.27	5.59
	E	77.35	9.39	2.20	2.77
Optical Speed Bars	-300	90.13	12.64	0.05	0.06
	-200	87.12	13.18	0.31	0.35
	-100	80.74	14.13	0.78	0.96
	B	74.75	12.37	2.43	3.15
	H	74.27	12.53	2.10	2.75
	E	78.58	12.73	0.97	1.22

Table 3: Main and Interaction Effects

Independent Variables	F	p	Partial Eta squared	Observed Power
Treatment	$F_{(2.39,88.48)} = 1.34$	.266	.035	.307
Measurement Point	$F_{(1.57,58.15)} = 152.74$	< .001	.805	1.000
Treatment*Meas. Point	$F_{(4.83,178.72)} = 2.21$	.046	.044	.570

The ANOVA results revealed a significant interaction effect between the type of treatment and the measurement point. Moreover, and as expected, a significant main effect of the measurement point was found. It is evident that the effectiveness of the different perceptual treatments strongly depends on the type of the treatment that is applied on the road pavement and on the point where the speed was measured. In fact, in all of the investigated cases, the highest speed reduction was reached at the beginning of the crest vertical curve and up to the middle point of the crest. Afterwards, the speeds reached levels that were quite comparable under the different scenarios at the end of the crest. This trend is clearly depicted in Figure 4 which shows the speed profile for each scenario on the approach and through the crest vertical curve.

The Student's two-tailed paired t-tests were also used; their results are given in Table 4. As can be noted, significant speed reductions, as compared to the baseline condition, were observed when using the red peripheral transverse bars at the beginning of the crest vertical curve (-5.95 km/h, -7.71%) and at the middle point of the crest (-5.58 km/h, -7.31%). Such speed reductions are fully in line with previous findings. *Comte & Jamson (2000)* reported significantly reduced speeds of approximately 6 km/h when using transverse bars on the approach of a curve using a driving simulator. Overall findings of *Gates et al. (2008)* showed that transverse bars were effective in reducing curve speeds (from 1 to 4 mph). Higher speed reductions (between 13 and 23 km/h) were found in the simulator study of *Montella et al. (2010)* for several perceptual treatments that were applied on the approach to an intersection. Finally, in the field study of *Zamora et al. (2011)*, the peripheral square markings showed the best performance in terms of statistically significant speed reductions of vehicles approaching gateway intersections (ranging from approximately 6% to 13%).

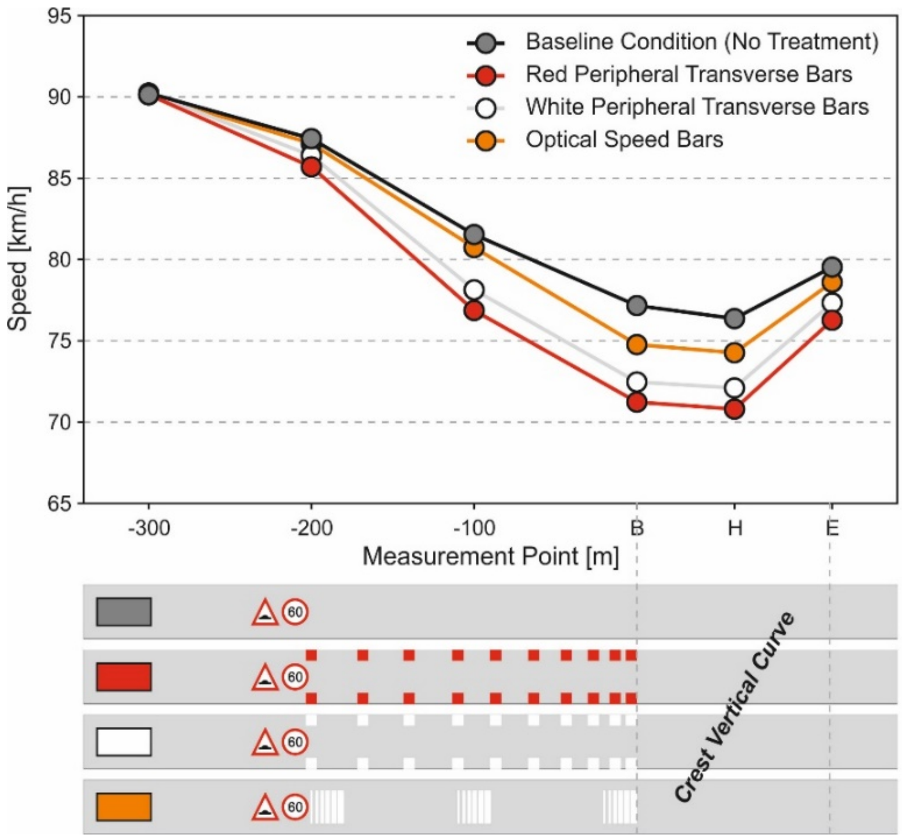

Figure 4: Speed profiles along the crest vertical curve under different treatment conditions

Table 4: Results of the Student's t-tests

Measurement Point	Treatment	Baseline Condition	Red PTB	White PTB	OSB
-300	Baseline Condition	1	1.000	1.000	1.000
	Red PTB	-	1	1.000	1.000
	White PTB	-	-	1	1.000
	OSB	-	-	-	1
-200	Baseline Condition	1	1.000	1.000	1.000
	Red PTB	-	1	1.000	1.000
	White PTB	-	-	1	1.000
	OSB	-	-	-	1
-100	Baseline Condition	1	.213	.970	1.000
	Red PTB	-	1	1.000	.663
	White PTB	-	-	1	1.000
	OSB	-	-	-	1
B	Baseline Condition	1	**.041**	.445	1.000
	Red PTB	-	1	1.000	.909
	White PTB	-	-	1	1.000
	OSB	-	-	-	1
H	Baseline Condition	1	**.032**	.569	1.000
	Red PTB	-	1	1.000	.969
	White PTB	-	-	1	1.000
	OSB	-	-	-	1
E	Baseline Condition	1	.553	1.000	1.000
	Red PTB	-	1	1.000	1.000
	White PTB	-	-	1	1.000
	OSB	-	-	-	1

PTB = Peripheral Transverse Bars; OSB = Optical Speed Bars

No other significant speed reductions were observed. However, it should be noted that under all scenarios involving treatment and at each of the measurement points (except at -300 meters where drivers could not see any treatments on the road ahead), the recorded speeds were always lower than the speeds adopted by the drivers in the baseline condition, demonstrating that the expected effect of the perceptual treatments was obtained anyway.

Moreover, it is interesting to note that the lowest speed reductions were recorded when using the optical speed bars that Italian drivers in general and the study participants in particular were familiar with ahead of any dangerous incidents on Italian roads. However, it should be noted that in many instances this treatment is mishandled or is applied very often; consequently, this diminishes its potential positive effects on reducing speeds. Therefore, it is reasonable to assume that any previous knowledge of a treatment and its wrong application in the field could have prompted the drivers not to reduce their speeds accordingly. This finding prompts the use, in the long run, of peripheral transverse bars on Italian roads, in order to study their effectiveness in adjusting the behaviour of drivers who are exposed a number of times to the same treatment. Positive results are expected, as previous studies (*Gates et al., 2008; Zamora et al., 2011*) have already shown with respect to a lasting effect of such a treatment over time; by all means, there is no evidence of a novelty effect, at least during the first 4 months after the installation of the markings.

5.3 Subjective Measures

The drivers' responses to the screen shots questionnaire were collected and then analysed using the one-way ANOVA. Table 5 gives the descriptive statistics, like average and standard deviation, for each of the treatments under study.

Table 5: Descriptive Statistics, as based on the Drivers' Responses to the Screen Shots Questionnaire

Treatment	Safe Speed [km/h]		Risk perceived*		Road alignment legibility**		Treatment comprehension***	
	Average	SD	Average	SD	Average	SD	Average	SD
Baseline Condition	69.08	9.56	5.61	1.90	4.32	2.24	-	-
Red Peripheral Transverse Bars	68.16	10.03	6.50	2.15	4.61	2.09	5.08	2.40
White Peripheral Transverse Bars	68.22	9.39	6.03	1.90	4.63	2.03	5.03	2.17
Optical Speed Bars	67.09	9.72	6.71	1.35	4.42	2.34	7.74	1.46

* *Risk perceived*: based on the 1-10 scale, where 1 corresponds to very low risk perceived and 10 to very high risk perceived

** *Road alignment legibility*: based on the 1-10 scale, where 1 corresponds to very difficult legibility and 10 to very easy legibility

*** *Treatment comprehension*: based on the 1-10 scale, where 1 corresponds to very poor comprehension and 10 to full comprehension

Although drivers noted the safest speed suitable for the scenario with optical speed bars as the lowest, probably due to their knowledge of the message given by the treatment (confirmed by the high rate given to treatment comprehension), ANOVA did not reveal any significant differences ($F_{(3,148)} = .269$, $p = .848$) between the safe speeds that were noted by drivers under different treatment conditions.

Conversely, the statistical analysis yielded a significant difference ($F_{(3,148)} = 2.723$, $p = .046$) between the rates noted by drivers and the risk perceived by viewing the screen shots. Specifically, post-hoc comparisons yielded a significant difference between the baseline condition and the optical speed bars ($p = .040$), confirming that the presence of this last treatment did in fact increase the risk perceived by drivers who recognized it but then did not reduce their speeds significantly. Although not statistically significant, it is however interesting to note that the risk associated with the red peripheral transverse bars was rated higher than the one noted for the white peripheral transverse bars, indicating a higher risk associated with the red colour, which, in the driving simulation, was demonstrated to be quite effective in increasing speed reduction.

No significant differences were noted between drivers' replies to the question related to road alignment legibility ($F_{(3,148)} = .182$, $p = .908$), meaning that the treatments did not modify the driver's understanding of the road alignment, which was rated quite poor in all the cases (caused by a limited stopping sight distance).

Finally, significant differences were noted for treatment comprehension ($F_{(2,111)} = 21.693$, $p < .001$). Specifically, post-hoc comparisons yielded significant differences between comprehending the optical speed bars, which, as expected, achieved a high rate (as already known and experienced by Italian drivers), and the red and white peripheral transverse bars, for which the corresponding message was not easily understood by drivers ($p < .001$, in both cases). Such outcome is quite interesting; although drivers did not previously know these perceptual treatments (as they had never been exposed to them, and resulting in a somewhat poor comprehension of the treatment demonstrated by the replies to the screen shots questionnaire), the objective measures of their speeds under driving simulation demonstrated the effectiveness of the treatments, anyway. In fact, such countermeasures are meant to alter the speed perception of drivers by inducing them to unconsciously reduce their speeds, almost independently of the comprehension of the direct message given by the treatment itself. Therefore, it is quite evident that, in case of evaluating the effectiveness of such perceptual treatments, a driving simulator experiment is needed, as it allows the testing of drivers' perceptions and driving performance whilst being actually involved in driving.

6. Conclusions

The effects of three perceptual treatments (white peripheral transverse bars, red peripheral transverse bars, and optical speed bars) on driving speed, whilst approaching (and driving through) a crest vertical curve of a two-lane rural road, were investigated using a driving simulator. The overall objective was to identify the most effective treatment and then apply it on the road pavement of an existing road, which is characterized by a poor safety level, mainly attributed to speeding along a crest vertical curve.

The first phase of the research allowed the validation of the use of a driving simulator for this case study. In fact, the results of a comparative and statistical analysis of field measurements of speeds at two points were not significantly different from the corresponding speeds that were recorded in the baseline condition (representing the actual state of the road reproduced in the virtual environment) of the driving simulator experiment.

Then, the second phase of the study was carried out by comparing the speed data recorded under three simulation scenarios (representing the same road scenario reproduced in the baseline condition), with each one being characterized by a different perceptual treatment, approaching the crest vertical curve, versus the speeds recorded in the baseline condition. It was found that the peripheral transverse bars, and specifically the red ones, provided the highest speed reductions (near to 6 km/h along the crest vertical curve), confirming the effectiveness of such perceptual treatment in reducing the driving speeds under several road conditions (i.e., approaching (and driving through) curves, as well as approaching intersections, as revealed by *Godley et al., 1999; Katz et al., 2006, 2008; Zamora et al., 2011*). Therefore, the peripheral transverse bars will be selected for field application along the crest vertical curve of the road reproduced in this driving simulator study, monitoring their short-term and long-term effectiveness.

7. Limitations and Future Research

Research is underway to overcome the limitations of this study. The effects of perceptual treatments are being investigated with respect to other driving performances, such as deceleration rates and lateral positions, which could provide interesting additional findings (e.g., *Ariën et al., 2017; Katz et al., 2008; Rosey et al., 2008*). Moreover, the red peripheral transverse bars will be investigated for evaluating their effectiveness in reducing speeds along other critical road conditions, such as when approaching intersections or severe curves, crossing towns via rural roads, where a reduction in speed is strongly recommended, and during night driving conditions, when red markings could result in reduced visibility.

Finally, the long-term effects of these perceptual treatments will be investigated in a forthcoming driving simulator study in order to verify whether their positive effects do endure over time. In fact, as the peripheral transverse bars were not known by the sample of drivers under study, they will be needed in order to investigate their effect on drivers that have been exposed a number of times to the same treatment and, consequently, validate their effectiveness in the long term (e.g., *Gates et al., 2008; Zamora et al., 2011*).

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