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EFFECT OF TRAFFIC-CALMING COUNTERMEASURES ON VEHICLE SPEED NEAR A PEDESTRIAN CROSSING – A DRIVING SIMULATOR STUDY

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Abstract

The complexity of contemporary road environments has raised the need for effective strategies to mitigate risks and improve the safety of drivers and pedestrians. This study uses a driving simulator to analyse the impact of traffic-calming countermeasures., offering a detailed and quantitative perspective. State-of-the-art reveals previous research addressing the topic, highlighting the relevance of implementing countermeasures to reduce crashes and improve driver behaviour. This study selected a representative sample of 60 drivers to participate in experiments with four countermeasures implemented in a driving simulator. These countermeasures were "dragon´s teeth", red median, broken edge line and green longitudinal marks. The case study was a section of a Spanish road near a school with a history of crashes. Various analyses were conducted to evaluate the effectiveness of the alternatives with traffic-calming countermeasures compared to implementing no countermeasures: analysis of differences in average speed, overall driver behaviour along the section (evaluated by the root mean square of the differences), and analysis of variance with post-hoc comparisons. The results highlight that all the alternatives achieved reductions in the average speed, with the broken edge line being the most effective, with a decrease of 9 km/h at the critical point corresponding to the pedestrian crossing.

Keywords: driving simulator, traffic-calming, perceptual countermeasures, road markings, road safety

1 Introduction

Ensuring road safety in interurban areas is a global imperative, as road crash are a pervasive societal challenge and a leading cause of mortality [1]. Although rural roads witness lower traffic volumes than urban locales, they account for 54% of total crashes [2]. Speed management is crucial for road safety, particularly in transition zones where speed limits change abruptly. The complexity of driving tasks in transition zones emphasizes the need for appropriate countermeasures [3]. Simulator-based studies, such as those by Wynne et al. [4], unravel the intricacies of driver behaviour in these areas. Perceptual countermeasures, such as dragon's teeth, herringbones, and transverse rumble lines, have been research subjects in simulator studies to induce alterations in drivers' speeds at specific locations [5]. Road centre markings (medians) have also been used as traffic-calming countermeasures. Charlton et al. [6] observed that these markings led to better compliance with speed limits, especially in the presence of oncoming traffic. The maximum mean speed reduction was 13.07 km/h at one section with a green median.

Babic and Brijs [7] found that wide-painted centerlines were more effective in speed reduction than horizontal warning signs before horizontal curves. Recently, the red median has begun to be used as a traffic-calm countermeasure on some Spanish road sections. However, it is not included in the draft of the new Spanish road-marking standard [8]. Longitudinal Speed Reduction Markings (LSRM) have been the subject of several studies examining their impact on vehicle speed and driver behaviour. According to Zhao [9], LSRM in a driving simulator have the potential to reduce travel speeds effectively and dissuade drivers from exceeding speed limits. In a similar vein and not in a driving simulator, Zhang et al. [10] noted a reduction of 5.1 km/h with a longitudinal yellow-red colour mark. In Spain, green LSRM are included in the new Spanish road-marking standard draft [8]. These green LSRM signals drivers that they are approaching a road section with unique characteristics, where they must adjust their driving to specific environmental conditions. These unique features may include winding curves, hazards due to the presence of animals, or other circumstances requiring a speed reduction [8].

A broken edge line might be used to decrease the width of the lane and warn of a pedestrian crossing. The broken edge line is intended to alert drivers to the proximity of a pedestrian crossing, encouraging them to reduce their speed and be more attentive to pedestrians crossing the road. This countermeasure is included in the draft of the new Spanish road-marking standard [11]. However, the authors do not know any research about the performance of this countermeasure. Hence, this study using a simulator might be suitable. Triangular road markings, placed on both sides of the lane (with equal or not equal spacing), are known as Dragon's Teeth Markings (DTM). Montella et al. [12] used DTM alongside rumble strips, increasing the teeth size as the hazard is approaching to affect the perception of the lane width through a tunnelling effect, making the lane appear narrower as drivers approach the end of the treatment and they noted a reduction of 12 km/h. Galante et al. achieved a speed reduction of 15.4 km/h [13], implementing with another countermeasure involving two fences converging toward the roadway. Also, DTM are included in the draft of the new Spanish road-marking standard [8]. These studies highlight the diverse range of traffic-calming countermeasures and their varying impacts on speed reduction, underlining the importance of selecting the most suitable countermeasures for specific road conditions and objectives. As mentioned, the Spanish Government is developing a new road-marking standard [8], [11] that includes several traffic-calming countermeasures.

The main objective of this research study is to analyse the effect of four traffic-calming countermeasures on vehicle speed in a Spanish case study. This case study is a pedestrian crossing located at a road tangent. Considering the literature review and the aforementioned Spanish draft standard, the selected countermeasures were green LSRM, DTM, red median and broken edge line.

2 Method

The driving simulator is located at the Road Laboratory of the Escuela Técnica Superior de Ingenieros de Caminos, Canales y Puertos (Universidad Politécnica de Madrid). The simulator consists in a computer with three 32-inch screens and a set of steering wheel, pedals and gear lever. This simulator has been validated with previous speed studies [14].

The sample comprised 60 participants, with a gender distribution of 57% men and 43% women. 6% of both men and women fell in the 18-24 age range, 49% of men and 58% of women aged 25-49, and 45% of men and 36% of women were 50 years or older. These ages and genders mirror the real-world proportions of drivers in Spain.

This study analyses four traffic-calming countermeasures at a specific section of a rural road in the Region of Madrid (Spain) (M-608 road between Cerceda and Manzanares El Real).

The road has two lanes of 3.5 m wide with 1.5 m wide shoulders. The studied section is at kilometre station 28+300, where the road passes in front of a school. At this point, the road has a history of high crash rates. These four countermeasures begin 150 meters before the pedestrian crossing coinciding with this School. The posted speed at that section is 50 km/h. The studied section is a tangent with a length of 436 m. In that section, the average daily intensity of vehicles on the road is 9501. Five sceneries (or alternatives) were created to study the effect of these four traffic-calming countermeasures on the speed: base scenery (without any traffic-calming countermeasure), DTM, red median, broken edge line and green LSRM.
Fig. 1 shows the four sceneries with countermeasures. All the countermeasures start 150 m before the pedestrian crossing. The first marking countermeasure (DTM) is a set of isosceles triangles with a base of 0.75 meters (Alt. 1 in Fig. 1). Regarding their height, those located in the first third of the section are 0.60 meters, those in the next third are 0.75 meters and those in the last third are 0.90 meters. The second countermeasure is a red median (Alt. 2 in Fig. 1). The red median is 0.5 m wide with 0.15 m solid white road markings on both sides. The third countermeasure is a broken edge line (Alt. 3 in Fig. 1). The broken line extends 0.5 m on both sides of the lane, narrowing the lane by 1 m. The fourth countermeasure use a green LSRM (Alt. 4 in Fig. 1) located 0.1 m from the usual roadside mark. The width of the green line is 0.15 m.
For the experimental trials, the procedure involved five stages designed to ensure the collection of comprehensive data regarding participants' driving experiences. The first stage lasted approximately 1 minute, explaining the controls of the simulator to each participant. In the second stage, participants performed a 3-minute training ride inside the simulator to familiarize themselves with its functions. The third stage involved filling out a pre-travel questionnaire and collecting personal data. In the fourth stage, each participant drives three sceneries in random order to exclude the potential learning effect (two sceneries with countermeasures and the scenery without countermeasures), each lasting 4 to 5 minutes, followed by a short 1-minute rest period. Finally, in the fifth stage, after all driving tests, participants completed an evaluation questionnaire to obtain information about their driving preferences and any problems experienced while driving, such as nausea or fatigue. The experimental procedure lasted 25 to 30 minutes per participant, including breaks between runs.

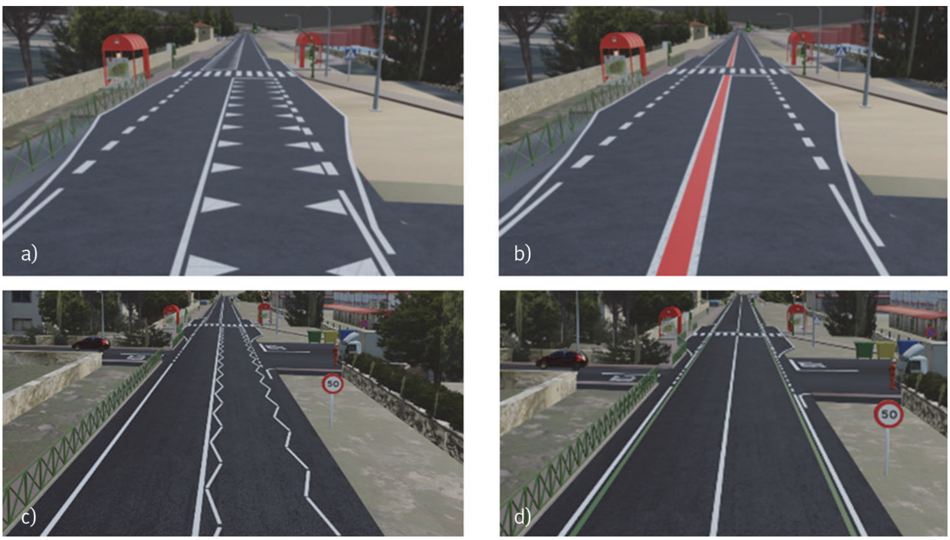

Figure 1 Sceneries with traffic-calming countermeasures: a) DTM (Alt.1); b) Red median (Alt.2); c) Broken edge line (Alt.3); d) Green LSRM (Alt.4)

Instantaneous speed data was collected at eight specific sections (cross sections) along the roadway (Fig. 2): section 1 at station 2639, which is the beginning of the tangent; section 2 at station 2688, where a posted speed limit of 70 km/h is located; section 3 at station 2699, where amber traffic light is located; section 4, at station 2716, is the start of traffic-calming countermeasures; section 5 at station 2806, where a posted speed limit of 50 km/h is located; section 6 at station 2866, where the pedestrian crossing is located; section 7 at station 2983, where a reminder posted speed limit of 50 km/h is located; section 8 at station 3075, is the end of the tangent section.

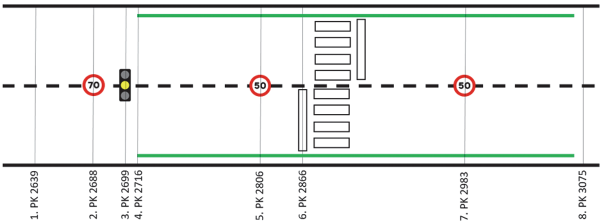

Figure 2 Detail of road design including the eight sections of interest. Example with green LSRM (Alt. 4)

3 Results

Several analyses have been carried out to evaluate the effectiveness of the countermeasures of alternatives 1, 2, 3 and 4 compared to the alternative 0 (do nothing): (1) an analysis focusing on the differences in speeds at points of interest; (2) analysis focusing on the driver's behaviour along the tangent; (3) the analysis of variance (ANOVA) and post-hoc comparisons using the Fisher's Least Significant Difference (LSD) procedure.

3.1 Analysis focusing on the points of interest

Fig. 3 shows the average speed along the tangent for each alternative recorded. The sections of interest have been indicated with vertical lines (S1 to S8). On the one hand, the analysis of the average speed graph (Fig. 3) along the section reveals a clear distinction among the alternatives in the sections of interest. The graph corresponding to the alternative without traffic-calming countermeasures (Alt. 0, depicted in grey in Fig. 3) is clearly above the lines representing the other alternatives, showing that the implementation of any traffic-calming countermeasure has effectively achieved a reduction in the average speed of vehicles along the whole stretch.

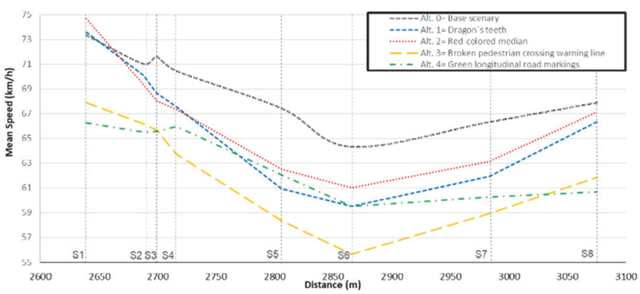

Figure 3 Profiles corresponding to the average speed for each alternative.

Section 6 is the crucial station because there is a potential conflict zone between pedestrians and vehicles (pedestrian crossing). Table 1 shows average speeds at section 6 for each alternative. All the alternatives with countermeasure reduce the speed at section 6. The average speed at this section is 8.6 km/h higher in the alternative without traffic-calming countermeasures (Alt. 0, grey line in Fig. 3) compared to the broken edge line markings (Alt. 3, yellow line in Fig. 3). Additionally, the average speed corresponding to the broken edge line alternative is at least 3.8 km/h lower than the other alternatives with countermeasures. Alternatives 1 and 4 offer the same reduction of average speed (4.8 km/h). The red median (Alt. 2) is the worst regarding average speed reduction (3.3 km/h). Therefore, considering the drivers' behaviour in section 6, the broken edge line is the most effective countermeasure to reduce the speed.

Table 1 Average speeds at section 6 (near the pedestrian crossing)

Alternative	0	1	2	3	4
Speed (km/h)	64.3	59.5	61.0	55.7	59.5

3.2 Analysis considering the whole section

Additional analysis has been carried out considering the root mean square of the differences (RMSD) between the speeds along the section (Eq. 1). This approach provides a quantitative measure of the differences along the tangent between the speeds of each alternative versus the alternative 0 (do nothing). The sections considered have been 4 to 7. Sections 4 to 6 are located before the pedestrian crossing, within the traffic-calming countermeasure area. Section 7 has been considered to see the effect of the countermeasures after the pedestrian crossing and how the speed values are recovered after them.

$$RMSD=\sqrt{\frac{\sum_{i=1}^{N}\left(V_{0i}-V_{ji}\right)^{2}}{N}} \quad (1)$$

N is the number of data sections (in this case, 4 sections); V_{0i} is the average speed at section i of Alt. 0; V_{ji} is the average speed at section i of Alt. j (with traffic-calming countermeasures j = 1,..., 4).

Table 2 shows an RMSD of 5.7 km/h between alternatives 3 and 0, which means that the average speed along the whole tangent in alternative 3 is, approximately, 5.7 km/h lower than alternative 0. Alternative 4 reduces the average speed by 3.7 km/h. The other options have achieved a smaller reduction, 3.4 km/h (Alt.1) and 2.6 km/h (Alt. 2). Therefore, considering the drivers' behaviour along the stretch (sections 4 to 7), alternative 3 (broken edge line) is the most effective to reduce the speed.

Table 2 RMSD between the speeds of each alternative and alternative 0.

Alt. j vs Alt 0.	1	2	3	4
Speed (km/h)	3.4	2.6	5.7	3.7

3.3 ANOVA and post-hoc results

In the statistical analysis of the speed at the selected sections, a Kolmogorov-Smirnov test was done to assess the normality of the data distribution. The speed distributions were normal at a 95% confidence level.

Table 3 shows the ANOVA of the speeds by alternatives in sections 4-7. The null hypothesis is that the alternative factor does not affect the mean speeds at each section. The results show that the alternative factor does affect in section 5 with a 95% confidence level (p-value ‹ 0.05) and in section 6 with a 90% confidence level (p-value ‹ 0.1). This factor is not significant in sections 4 and 7. Note that section 4 is the start of traffic-calming countermeasures, and it is far from the pedestrian crossing. Section 7 is after the pedestrian crossing.

Table 3 Statistical analysis of the alternative factor (*Statistically significant at 5% level; **Statistically significant at 10% level).

Section	ANOVA Test	Fisher´s LSD test
	p-value	Significant Alt. j vs Alt.0
4	0.144	Alt. 3*
5	0.027*	Alt. 3* and Alt. 2*
6	0.078**	Alt. 3*
7	0.160	Alt. 3*

Additionally, the post-hoc analysis (Fisher's LSD test in Table 3) has been carried out to know which alternative or alternatives have the most effect on the speeds. The results reveal significant differences between some alternatives with traffic-calming countermeasures versus alternative 0 (base scenery). The effect of the broken edge line (Alt. 3) is significant in sections 4 to 7. The effect of the red median (Alt. 2) is significant in only one study section (section 5). Alternative 1 (DTM) and green LSRM (Alt. 4) results are insignificant in these sections. Therefore, considering the drivers' behaviour along the tangent (sections 4 to 7), alternative 3 (broken edge line) is the most effective in reducing the speed.

4 Conclusion and discussion

The traffic-calming countermeasures implemented have shown positive results in reducing speed compared to the option without countermeasures. All alternatives with countermeasures presented lower speeds in most of the sections analysed. In the most conflictive area (pedestrian crossing), a significant speed reduction is observed with the broken edge line (8.6 km/h). Considering the drivers' behaviour along the tangent (sections 4 to 7), the broken edge line (Alt. 3) is also the most effective countermeasure to reduce the speed (5.7 km/h). The post-hoc analysis confirms the positive effect of this alternative along the tangent.
The speed reduction of DTM (4.8 km/h) is lower than the literature mentioned (12 or 15.4 km/h). However, the conditions of the studies are different because DTM were implemented together other countermeasures in the literature [12], [13]. The speed reduction of the red median (3.3 km/h) is lower than the green median (13.07 km/h), according to the literature review [6]. The speed reduction of the green LSRM (4.8 km/h) is similar to the yellow-red LSRM (5.1 km/h) of the literature review [10]. The broken edge line cannot be compared with existing literature because the authors do not know any research about the performance of this countermeasure.

Acknowledgments

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