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Title: EFFECTS OF SAFETY MEASURES ON DRIVER'S SPEED BEHAVIOR AT PEDESTRIAN CROSSINGS

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Abstract: This paper reports the results of a multi-factorial experiment that was aimed at the following: (a) analyzing driver's speed behavior while approaching zebra crossings under different conditions of vehicle-pedestrian interaction and with respect to several safety measures and (b) comparing safety measures and identifying the most effective treatment for zebra crossings. Three safety countermeasures at pedestrian crossings (curb extensions, parking restrictions and advanced yield markings) and the condition of no treatment (baseline condition) were designed on a two-lane urban road and implemented in an advanced driving simulator. Several conditions of vehicle-pedestrian interaction (in terms of the time left for the vehicle to get to the zebra crossing at the moment the pedestrian starts the crossing) were also simulated. Forty-two drivers completed the driving in the simulator. Based on the recorded speed data, two analyses were performed.

The first analysis, which focused on the mean speed profiles, revealed that the driver's speed behavior was affected by conditions of vehicle-pedestrian interaction and was fully consistent with previous findings in the literature and with the Threat Avoidance Model developed by Fuller.

Further analysis was based on variables that were obtained from the speed profiles of drivers (the speed at the beginning of the deceleration phase, the distance from the zebra crossing where the deceleration began, the minimum speed value reached during the deceleration, the distance from the pedestrian crossing where the braking phase ended and the average deceleration rate). Multivariate variance analysis (MANOVA) revealed that there was a significant main effect for safety measures and for pedestrian conditions (the presence and absence of a pedestrian). The results identified that the curb extension was the countermeasure that induces the most appropriate driver's speed behavior while approaching the zebra crossing. This conclusion was also confirmed by outcomes of the questionnaire on the countermeasure's effectiveness. More than 80% of the drivers perceived that the curb extensions were effective, which indicates that when this countermeasure was present, the drivers were more willing to yield and that the visibility of the pedestrian crossing was better. For this countermeasure, the lowest number of interactions in which the drivers did not yield to a pedestrian was also recorded.

EFFECTS OF SAFETY MEASURES ON DRIVER'S SPEED BEHAVIOR AT PEDESTRIAN CROSSINGS

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ABSTRACT

This paper reports the results of a multi-factorial experiment that was aimed at the following: (a) analyzing driver's speed behavior while approaching zebra crossings under different conditions of vehicle-pedestrian interaction and with respect to several safety measures and (b) comparing safety measures and identifying the most effective treatment for zebra crossings. Three safety countermeasures at pedestrian crossings (curb extensions, parking restrictions and advanced yield markings) and the condition of no treatment (baseline condition) were designed on a two-lane urban road and implemented in an advanced driving simulator. Several conditions of vehicle-pedestrian interaction (in terms of the time left for the vehicle to get to the zebra crossing at the moment the pedestrian starts the crossing) were also simulated. Forty-two drivers completed the driving in the simulator. Based on the recorded speed data, two analyses were performed.

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1. INTRODUCTION

All around the world, pedestrians represent one of the road user categories that is the most exposed to high-risk levels. Each year, more than 270,000 pedestrians lose their lives on the world's roads (WHO, 2013). In Italy, every year, about 600 pedestrians are killed, and more than 21,000 are injured in traffic-related crashes (ACI-ISTAT, 2014).

More than 50% of accidents that involve pedestrians occur at pedestrian crossings (ACI-ISTAT, 2014). The relevance of the phenomenon, therefore, is considerable and implies the need to conduct studies with the aim of improving the safety of this vulnerable road user. In the literature, many issues that concern pedestrians are investigated. The main research area concerns pedestrian behavior in urban areas and focuses especially on the route choice and the crossing behavior (an exhaustive review is reported in Papadimitriou et al., 2009 and in Papadimitriou et al., 2013). Interactions between pedestrians and vehicles have received notably less attention (Papadimitriou et al., 2013); in particular, few studies of drivers' behaviors are available in the literature. However, it is generally agreed that pedestrian-vehicle crashes are associated with a lack of driver compliance, that drivers often fail to yield to a pedestrian (Mitman et al., 2010) and that pedestrian safety at zebra crossings depends mainly on the speed of the vehicle. With an increase in the speed, in fact, the probability of a vehicle-pedestrian conflict and a pedestrian fatality accident is higher (Pasanen, 1992; Várhelyi, 1998; Rosen and Sander, 2009; Rosen et al., 2011; Tefft, 2013; Kroyer et al., 2014). For example, (Pasanen, 1992) found that, for a collision at a speed of 50 Km/h, the risk of a fatal accident is approximately eight times higher compared to an event that occurs at a speed of 30 Km/h. Similarly, (Rosen and Sander, 2009) found that the fatality risk at 50 km/h is more than twice that at 40 km/h and more than five times higher than the risk at 30 km/h. Tefft (Tefft, 2013) found that the average risk of death reaches 10% at an impact speed of 24.1 mph, 25% at 32.5 mph, 50% at 40.6 mph, 75% at 48.0 mph, and 90% at 54.6 mph. Despite the inconsistency in the values of the actual risk at a given speed (Kroyer et al., 2014), it is commonly thought to consider that a modest speed reduction/increase has a considerable effect on the probability of a fatality and, thereby, on the number of fatal accidents.

According to Várhelyi (Várhelyi, 1998), when drivers approach pedestrian crossings, they do not adapt their speed to avoid endangering pedestrians who are already on the zebra crossing or who are about to step onto it. Therefore, interactions between vehicles and pedestrians at zebra crossings are critical situations, in which the drivers must be influenced to adapt their speeds in the presence of the pedestrian, to avoid the need for evasive maneuvers and limit the risk of fatal injury of a pedestrian. Inducing a proper speed adaptation is deemed to have great potential for improving pedestrian safety.

A number of safety treatments at zebra crossings have been evaluated with positive results (see the next section, literature review). However, such results do not allow a comparative analysis of the effectiveness of the safety measures, for the following reasons:

- the effectiveness of each countermeasure is provided by specific parameters (i.e., the operating speed, number of drivers that yield to a pedestrian, distance at which the driver yields to the pedestrians), which are not used in all studies;
- the results are mainly obtained from field studies with specific experimental conditions of vehicle-pedestrian interactions and geometrical configurations of the sites, which are different for each study, and therefore, the findings are not comparable.

The present study aims at the following:

- analyzing a the driver's speed behavior while approaching a zebra crossing under different conditions of vehicle-pedestrian interaction and in the presence of several countermeasures, to add to the body of knowledge that concerns the complex process of the interaction between the driver and pedestrian;
- comparing several countermeasures and identifying the most effective treatment for zebra crossings, on the basis of having the same parameters that describe the driver's behavior and under fixed conditions of a vehicle-pedestrian interaction.

Accomplishing these aims is possible by the use of a driving simulator that, mainly, allows risk avoidance for the experimenters and full control of the experimental conditions, avoiding confounding factors, which are common in field studies.

This study included the following three main steps: (1) a literature review on vehicle–pedestrian interaction and countermeasures at zebra crossings, (2) driving simulator experiment for the driver behavior data collection and data processing, and (3) data analysis and results on the driver's behavior during the approaching phase to the pedestrian crossings and on the countermeasure that induces the most appropriate driver's speed behavior.

2. LITERATURE REVIEW

2.1 Vehicle-pedestrian interaction

The theoretical framework of the vehicle-pedestrian interaction is provided by the "Threat Avoidance Model" developed by Fuller (Fuller, 1984). The threat-avoidance model of the driver's behavior proposes that within the context of the motivation for a particular journey (usually a specific destination within a specific period of time), the driver behavior is focused on the avoidance of averse or potentially averse stimuli in the road-traffic environment (Fuller, 1987). This model implies that when confronted with a discriminative stimulus for a potential aversive event, what a driver does depends specifically on the rewards and punishments for alternative responses. In a vehicle-pedestrian interaction at a zebra crossing, the pedestrian presence is the discriminative stimulus. Such an adverse stimulus can cause: a) an "anticipatory avoidance response" or b) a "non-avoidance response".

In the first case, the driver considers the pedestrian presence to be a "threat", and then, he slows down; in this way, the pedestrian can pass before the driver. In this case, the driver is "punished" with a loss of time.

In the second case, the driver maintains the same speed because he considers the pedestrian presence to be a "threat" but chooses a "non– avoidance response", signaling to the pedestrian that he has no intention to yield; then, two possible conditions could occur, as follows:

- the driver passes first. This action is a "reward" for the driver because he does not stop and, thus, does not suffer delay;
- the pedestrian assumes a "competitive behavior", and therefore, the driver is forced to a delayed avoidance response (braking) or a collision occurs.

Finally, this model suggests that the driver can experience a "no discriminative stimulus" (he does not see the pedestrian), and therefore, he does not expect a "threat". In this case, two possible conditions could also occur: a) the interaction with the pedestrian does not cause a risk (the pedestrian does not start to cross) or b) a delayed avoidance response is required to avoid an accident.

According to the literature, the vehicle-pedestrian interaction is affected by driver characteristics (that produce "availability" of the driver to yield), pedestrian characteristics (assertiveness and the risk levels that a pedestrian is willing to accept) (Harrel, 2001) and parameters that are related to the vehicle dynamics (Geruschat et al., 2005), such as the vehicle speed, distance from the conflict area, and maximum comfortable deceleration rate.

A significant role is played by the vehicle dynamic parameters because these variables affect the arrival time of the vehicle at the zebra crossing and, consequently, the pedestrian decision. Such a time, called Time-To-Zebra arrive (TTZ_{arr}), is used in the literature (Varheli, 1998) to discuss the vehicle-pedestrian interaction at zebra crossings. TTZ_{arr} is defined as the time left for the vehicle to arrive at the zebra crossing at the moment the pedestrian arrives at the curb. TTZ_{arr} is obtained by calculating the distance of the vehicle from the zebra crossing divided by the vehicle's speed when the pedestrian arrives at the curb.

Varhelyi studied the drivers' speed behavior while approaching the pedestrian crossing under different pedestrian times of arrival at the curb and compared the mean speed profiles for different TTZ_{arr} values with the mean speed profile with respect to pedestrian absence. The hypothesis was that drivers' speed behavior while approaching the pedestrian crossing depends on the arrival of the pedestrian at the curb relative to the time at which the driver expects to reach the crossing. If pedestrian behavior threatens the undisturbed passage of the vehicle, then the driver will adopt a higher speed to ensure his priority.

The results showed very low proportions of drivers giving way to pedestrians, and a consistent pattern was observed according to which drivers would maintain a high speed or even accelerate in order to warn the pedestrians of their intention to not give way. More specifically, for a pedestrian approaching from the right, three driver behaviors were found:

- for TTZ_{arr} values of less than 1 second, the mean speed profile does not differ statistically significantly from those situations in which there is no pedestrian presence. This circumstance can be explained by the fact that the driver estimates that at the moment at which the pedestrian reaches the curb, the vehicle is very close to the conflict point, and the driver will not be able to stop; even the pedestrian realizes this fact, and therefore, the pedestrian does not start to cross, allowing the vehicle to continue without forcing it to brake;
- for TTZ_{arr} values that are from 1 to 4 seconds, the pedestrian could reach the conflict point before the driver and force him to brake. The mean speed profiles are statistically significantly higher than situations in which there is no pedestrian presence. This behavior can be explained by the driver's willingness to take priority in passing the crosswalk before the pedestrian. To make this scenario occur, the driver accelerates, increasing his speed, which communicates to the pedestrian that he wants priority;
- for TTZ_{arr} values that are higher than 4 seconds, the pedestrian has a good safety margin to pass the conflict point before the driver reaches it; and the mean speed profiles are statistically significantly lower than in situations in which there is no pedestrian presence. The driver realizes that he cannot pass before the pedestrian and, thus, adopts a lower speed.

2.2 Countermeasures

Several countermeasures that are aimed at modifying the drivers' speed behavior while approaching unsignalized pedestrian crossings are shown in the literature (e.g., Hakkert et al. 2002; Fitzpatrick et al., 2006; Zegeer and Bushell, 2012; Pulugurtha et al., 2012). The most often-used driver oriented countermeasures are the following:

- advanced yield lines to improve the visibility of the crossing pedestrians;
- removal of parking to clear the line of sight to approaching vehicles;
- installation of curb extensions to improve visibility;
- pedestrian-activated flashing beacons to warn motorists of crossing pedestrians;
- motorist signs to indicate that pedestrians have the legal right-of-way;
- in-pavement warning lights with advance signing to inform the drivers of the crossing

Among these safety countermeasures, curb extensions, parking restrictions and advance yield markings, which are characterized by low cost, simple installation and high potential effectiveness on driver behavior, were investigated in this study.

Curb extensions are an extension of the edge of the sidewalk and are commonly made along roads that are equipped with parking places on the sides of the lanes. The curb extends up to the line that separates the lane from parking stalls that are made on the side of the roadway. The effects that are expected from this safety countermeasure are to slow down the vehicles, reduce the pedestrian exposure and increase his visibility. Several experiences show their effectiveness in terms of operating speed reduction (up to 40%) of the vehicle (Repogle, 1992; Macbeth, 1995; Hawley et al., 1992) and increments in the number of drivers that yield to the pedestrian (Randal, 2005).

Parking restrictions are parking rules that are designed to not allow parking upstream of the zebra crossing, to improve pedestrian visibility. The presence of on-street parking, in fact, is associated with an increased risk of accidents. A model for the prediction of accidents showed that the contribution of the presence of parking on the roadside increases the accident levels more than the road width (Greibe, 2003). Edquist (Edquist et al., 2012) found that the effect of the presence of on-street parking was statistically significantly for several variables, such as the time to brake, time to accelerator release, minimum time to collision, and number of collisions.

Advanced yield markings consist of a series of triangular pavement markings that are placed across the travel lane between 6 and 15 m in advance of the zebra crossing. A "Yield Here to Pedestrian" vertical sign is also placed at the location of the markings. This countermeasure is aimed at improving the yielding compliance; it should alert the driver further upstream of the crosswalk to the possible presence of pedestrians and prompt the driver to yield. Several studies have shown the effectiveness of this treatment because it increases the distance at which the driver yields to pedestrians, reduces the number of conflicts and increases the number of drivers that yield (Van Houten et al., 2001; Van Houten et al., 2002; Samuel et al, 2013).

3. METHODS

This study was conducted using the advanced driving simulator of the Inter-University Research Centre for Road Safety (CRISS). Several studies have demonstrated that driving simulators are useful tools for the evaluation of the driver's behavior as induced by the road configuration (e.g., Bella, 2008a., 2013, 2014a, 2014b, 2014c; Rosey et al. 2008; Shechtman,et al. 2009; Daniels et al.2010; Bella and Calvi, 2013; Bella et.al. 2014). Moreover, driving simulators are ideal tools for studies whose field survey is made impossible by the implicit high risks that the experimenters would be subjected to and the difficulty of ensuring controlled experimentation conditions. Several studies show the high potential and reliability of driving simulators for studying the effect of safety countermeasures at zebra crossings or for studying the driver's perception of pedestrians. Fisher and Garay-Vega (Fisher and Garay-Vega, 2012) studied the driver performance for advance yield markings at marked mid-bloc crosswalks in multi-threat scenarios (two-way/four lane road). Salamati et al. (Salamati et al., 2012) analyzed the effects of three different pedestrian crosswalk treatments at the exit leg of multilane roundabouts. Gomez et al. (Gomez et al., 2011) compared potential vehicle-pedestrian conflict under different types of pavement markings when a driver's view of the pedestrians in a crosswalk is obstructed. Regè et al. (Rogè et al, 2014) examined the ability of elderly drivers to detect pedestrians. Garay-Vega et al. (Garay-Vega et al., 2007) evaluated the hazard anticipation skills of novice and experienced drivers when a potential threat (such as the presence of pedestrians at crosswalks) was experienced.

A multi-factorial experiment was designed to analyze the effects on drivers′ speed behavior while approaching the zebra crossings of the following:

- four pedestrian crossing configurations: three countermeasures (curb extensions, parking restrictions, advanced yield markings) and the condition of no treatment (baseline condition);
- four conditions of vehicle-pedestrian interaction: in addition to the absence of a pedestrian, three conditions of vehicle-pedestrian interaction were implemented in the driving simulator. Such three conditions were obtained because the pedestrian was set to start to cross from the right side of the driver when the vehicle was at 13.9 m, 34.7 m and 55.6 m before the zebra crossing. For a driver's speed of 50 km/h, these distances represent the values of TTZ_{arr} (the time left for the vehicle to arrive at the zebra crossing at the moment the pedestrian starts the crossing) equal to 1 second, 2.5 seconds and 4 seconds, respectively. It should be noted that these values are theoretical because they depend on the actual speed of the driver when the pedestrian starts to cross.

Combining four pedestrian crossing configurations and four conditions of vehicle-pedestrian interaction (including pedestrian absence), 16 combinations of zebra crossing/pedestrian were included in an urban scenario.

3.1 Road scenario, countermeasures and vehicle-pedestrian interactions

A two-lane urban road approximately 15 km long and with the 16 zebra crossing/pedestrian combinations was implemented in the driving simulator. The pedestrian crossing was the mid - block type. To ensure the same approaching condition, 16 signalized intersections were placed in advance of each zebra crossing. Each driver was obligated to stop at the signalized intersection, due to the red light that turned on when the driver was at approximately 100 m from the intersection. The distance between the signalized intersection and pedestrian crossing was equal to 400 m, which allowed the drivers to reach a congruous speed for the simulated urban scenario. The posted speed limit was 50 km/h. The cross-section was 13 m wide formed by two 3.00 m wide lanes, two 2.00 m wide lateral parking lanes and two 1.50 m wide sidewalks (fig. 1a). This configuration was chosen because it is representative of most Italian urban areas, where parking is allowed until the zebra crossing. According to the Italian Highway Code (Ministry of Infrastructures and Transports, 1992), the strips of crosswalks were 1.50 m long, 0.50 m wide and spaced 0.50 m from one another. In addition, two vertical signals that were related to the pedestrian crossings were placed: first, at the pedestrian crossing and, second, at 150 m in advance of it. This configuration represents the baseline condition, in other words, a typical pedestrian crossing without any treatment (fig. 1a).

In addition to the baseline condition, three countermeasures were placed in the scenario: curb extensions, parking restrictions and advanced yield markings.

The first (Curb Extensions) was designed according to the Road Design and Construction Standards (Washington County, 2011) (fig 1b).

Parking restrictions were designed following the Italian road design guidelines (Ministry of Infrastructures and Transports, 2001) and the Italian Highway Code (Ministry of Infrastructures and Transports, 1992). The length of the upstream zone of the pedestrian crossing where parking is not allowed is a function of the stopping sight distance. According to the Italian road design guidelines, for a speed of 50 km/h, the stopping sight distance is 55.3 m, and the parking restrictions length to allow the driver to see the pedestrian and react from that distance is 13.2 m (fig 1c).

The reference for the advanced yield markings was the Manual on Uniform Traffic Control Devices (FHWA, 2012). The triangular pavement markings are placed across the lane and to 15.0 m from the pedestrian crossing. At this point, a vertical signal is also placed that indicates to the driver that he must yield to the pedestrian. Triangles have a base of 0.4 m, a height of 0.5 m and are separated by 0.2 m from one another. Each pedestrian crossing is preceded by two parked cars on the right side of the driver, to reproduce the low visibility of a pedestrian (fig 1d).

Figure 1 - a) Baseline condition b) Curb Extensions c) Parking Restrictions d) Advanced Yield Markings

Concerning the vehicle-pedestrian interaction, in addition to the pedestrian absence condition, 3 conditions of the vehicle-pedestrian interaction (i.e. 3 theoretical values of TTZ_{arr}, equal to 1 s, 2.5 s and 4 s) were considered. Pedestrian crossing from the right side of the vehicle was simulated. This condition is the most critical because of the following:

- the occlusion of the line of sight of an approaching vehicle due to the parking on the right, which does not allow the advanced detection of the pedestrian;
- low pedestrian times of arrival to the potential conflict point with the driver.

The condition of a pedestrian from the right should emphasize the effect of the safety measures on the driver behavior; such an effect is determined by comparing the behavior that was adopted when the safety measures were present and the behavior that was adopted for the baseline condition.

The pedestrian did not appear suddenly (he was always displayed when the driver was at about 300 m from the pedestrian crossing) and the driver, while approached the zebra crossing, could observe the pedestrian who was waiting to cross the road, as typically occurs in the real life. As mentioned above, the movement of the pedestrian was triggered when the driver was at three distances from zebra crossings (13.9 m, 34.7 m and 55.6 m, corresponding, for a driver’s speed of 50 km/h, to the theoretical values of TTZ_{arr} equal to 1 second, 2.5 seconds and 4 seconds, respectively). Therefore, the pedestrians started to cross only with respect of the position of the vehicle from the zebra crossing and regardless of the driver behaviour (i.e. speed of vehicle).

To avoid a potential effect of the order on the driver's behavior, 3 road scenarios that have a different sequence of the 16 combinations of zebra crossing/pedestrian were implemented in the driving simulator. Each scenario was driven by one of the 3 groups into which the participants were divided (see next section on participants).

3.2 Driving Simulator

The CRISS simulation system is an interactive fixed-base driving simulator. It was previously tested, calibrated, and validated (Bella, 2005; Bella, 2008b; Bella et al., 2007) as a reliable tool for the study of the driver's speed behavior. The hardware interfaces (wheel, pedals and gear lever) are installed on a real vehicle. The driving scene is projected onto three screens: one in front of the vehicle and one on either side, which provide a 135° field of view (fig. 2). The resolution of the visual scene is 1024×768 pixels with a refresh rate of 30 to 60 Hz. The system is also equipped with a sound system that reproduces the sounds of the engine. The simulator provides many parameters for describing the travel conditions (e.g., vehicle barycenter, relative position in relation to the road axis, local speed and acceleration, steering wheel rotation angle, pitching angle, and rolling angle). Data can be recorded at time or space intervals of a fraction of a second or a fraction of a meter.

Figure 2 - CRISS driving simulator

3.3 Procedure

The experiment was conducted with the free vehicle in its own driving lane. In the other driving lane, a slight amount of traffic was distributed to induce the driver to avoid driving into that lane. The simulated vehicle was a standard medium-class car with automatic gears. The data recording system acquired all of the parameters at spatial intervals of 2 m.

The driving procedure consisted of the following steps: (a) communicating to the driver about the duration of the driving and the use of the steering wheel, pedals, and automatic gear; (b) training at the driving simulator on a specific alignment with a length of approximately 5 Km; (c) filling in a form with personal data, years of driving experience, average annual distance driven; (d) driving one of the three road scenarios with a specific zebra crossing-pedestrian sequence; (e) filling in of a questionnaire about the discomfort that is perceived during driving, to eliminate from the sample driving performed under anomalous conditions. This questionnaire consisted of 5 questions, with each question addressing a typed of discomfort: nausea, giddiness, daze, fatigue, other. Each question could be answered by a score of 1–4 in proportion to the level of discomfort experienced: null, light, medium, and high. The null and light level for all four types of discomfort is considered to be the acceptable condition for driving; (f) filling in of a questionnaire about the perceived effectiveness of the countermeasures. This questionnaire consisted of 3 questions: the first was related to the effective influence perceived by the driver, the second (only for drivers that perceived an influence on their behavior) was related to the type of influence (slowing down, more willingness to yield, more visibility of a pedestrian), and the third related to the self-reported distance from the zebra crossing, where they modified their speed. For this last question, drivers could choose between the following values: less than 20 m; from 20 to 30 m; from 30 to 40 m; from 40 to 50 m, from 50 to 60 m and higher than 60 m. Drivers were instructed to drive as they normally would in the real world.

3.4 Participants

Forty-two drivers (24 men and 18 women), whose ages ranged from 23 to 59 (average 29) and who had regular European driving licenses for at least three years were selected to perform the driving in the simulator. They were chosen from students, faculty, and staff of the University and volunteers from outside of the University. The drivers had no prior experience with the driving simulator and had an average annual driven distance on urban roads of at least 2500 km. The average number of years of driving experience was approximately 9. According to the questionnaire on perceived discomfort, all of the participants experienced null or light levels of discomfort. Thus, the sample used for the analysis consisted of all 42 drivers, which were divided into 3 groups; the 3 groups drove different scenarios, which were each characterized by a specific sequence of zebra crossing/pedestrian.

4. DATA PROCESSING

To analyze the drivers' speed behavior while approaching the pedestrian crossings, the speed data were recorded starting from 150 m in advance of each one of the 16 zebra crossings.
On the basis of the collected data, the following were determined:

- the actual conditions of the vehicle-pedestrian interaction that occurred during the tests;
- the variables of the driver's speed behavior.

4.1 Vehicle-pedestrian interactions recorded by the driving simulator

Three conditions of vehicle-pedestrian interaction were implemented in the driving simulator. The pedestrian started crossing when the vehicle was at 13.9 m, 34.7 m and 55.6 m before the zebra crossing, to reproduce – for a vehicle speed of 50 km/h – three theoretical values of TTZ_{arr} (the time left for the vehicle to arrive at the zebra crossing at the moment the pedestrian starts the crossing), specifically, 1 second, 2.5 seconds and 4 seconds, respectively.
The implemented scenarios in the driving simulator determined the occurrence of actual conditions of vehicle-pedestrian interactions in which the driver changed his speed as soon as he perceived the pedestrian (i.e. before that the pedestrian started to cross). Therefore, the actual conditions of vehicle-pedestrian interaction (which were used in the following analyses) were related to the cinematic conditions (speed and distance from zebra crossing) of the driver at the moment in which he perceived the presence of the pedestrian and not at the moment in which the pedestrian started to cross. Considering the actual speeds of the drivers and their distances from the pedestrian crossings at the moment when they perceived the pedestrian presence, many conditions of vehicle-pedestrian interaction, were recorded during the simulated drives. These conditions of vehicle-pedestrian interaction were determined as follows. The first step was the plotting of each driver's speed profile for each selected section (150 m in advance of the pedestrian crossing). A total of 504 speed profiles were plotted (3 theoretical TTZ_{arr} x 4 countermeasures x 42 drivers). Afterward, from each speed profile, the following variables were determined (fig. 3):

- V_i: the driver's initial speed value, identified at the moment in which the driver starts to decrease his speed, releasing the accelerator pedal or pressing the braking pedal;
- L_{Vi}: the distance from the zebra crossing where the V_i value is located

Then the actual vehicle-pedestrian interaction was obtained as

$$TTZ*_{arr} = \frac{L_{Vi}}{V_i}$$

which represents the time left for the vehicle to arrive at the zebra crossing at the moment he perceived the pedestrian presence at the zebra crossing.

Speed profiles also showed several events when drivers did not yield because they accelerated to pass the conflict point before the pedestrian. However, no case of collision was recorded.
Table 1 shows, for the 4 countermeasures, the number of vehicle-pedestrian interactions, the mean, maximum and minimum values of $TTZ*_{arr}$, the number of vehicle-pedestrian interactions for several groups of values of $TTZ*_{arr}$ and the number of interactions where the drivers did not yield.

Table1 - Actual vehicle-pedestrian interactions recorded at the driving simulator

4.2 Variables of the driver's speed behavior

Several variables were taken into account to analyze the driver's speed behavior while approaching the pedestrian crossings under different configurations of pedestrian crossing and conditions of vehicle-pedestrian interaction. From all of the 672 drivers' speed profiles (42 drivers x 16 combinations of zebra crossing/pedestrian), the following variables were collected (fig. 3):

- V_i and L_{Vi}: initial speed and distance from the zebra crossing where the initial speed value is located, respectively (these were defined in the previous section);
- V_{min} and L_{Vmin}: the minimum speed value and the distance from the zebra crossing where the minimum speed value is located, respectively;

- d_m: the average deceleration rate during the speed reduction phase from V_i to V_{min}; this variable is given by the following equation:

$$d_m = \frac{V_i^2 - V_{\min}^2}{2S}$$

where S is the distance between the points where the speed is equal to V_i and V_{min}.

Figure 3 - Variables of the driver's speed behavior

5. DATA ANALYSIS AND RESULTS

Two analyses were performed. The first analysis was based on the mean speed profiles for different groups of TTZ^*_{arr} values. It should be noted that the classification of the vehicle-pedestrian interactions by the TTZ^*_{arr} (defined as the ratio of L_{vi} to V_i) implicitly determined a classification of the interactions based on the driver's characteristics. Drivers with low "availability" to yield (or aggressive drivers) determined low TTZ^*_{arr}, because they tended to start to slow down when they were close to the zebra crossing and/or from high initial speeds. Drivers with high "availability" to yield (or careful drivers), instead, determined high values of TTZ^*_{arr} because they tended to start to reduce the speed when they were far from zebra crossing and/or from low initial speeds. The table 2 shows the number of interactions for different groups of TTZ^*_{arr} values that were obtained from the three theoretical values of TTZ_{arr}.

Table 2 - Number of actual vehicle-pedestrian interactions that were obtained from the three theoretical values of TTZarr.

The purpose of this analysis was to assess how the driver's speed adaptation while approaching the pedestrian crossing was affected by the conditions of vehicle-pedestrian interaction (and therefore implicitly by the driver's characteristic) and how this influence occurred for the several countermeasures. The findings of this analysis were discussed in relationship to the results obtained from mean speed profiles collected on the field by Varhelyi. A further and more in-depth analysis was based on variables that were obtained from the speed profiles of drivers to highlight the effectiveness of the countermeasures for the conditions of absence and presence of a pedestrian. This analysis was not performed for different values of TTZ^*_{arr} (i.e. for different drivers' characteristics) because the aim was the assessment of the effectiveness of the countermeasures both for the absence and presence of pedestrian in the common conditions of vehicle-pedestrian interaction that occur at pedestrian crossings. It should also be noted that the pedestrian presence condition implicitly includes a wide range of vehicle-pedestrian interactions (see table 1). The analysis was conducted by means of a multivariate variance analysis (MANOVA) procedure, to investigate all of the interaction and main effects on the dependent variables of the driver's behavior (V_i, V_{min}, L_{Vi}, L_{Vmin}, d_m) due to the two factors: countermeasures (with 4 levels*:* baseline condition, curb extensions, parking restrictions and advanced yield markings) and pedestrian conditions (with 2 levels: presence and absence of a pedestrian).

5.1 Mean Speed Profiles

Mean speed profiles were plotted for each countermeasure, for 4 groups of TTZ^*_{arr} values and for the pedestrian absence condition (fig. 4).

Figure 4 - Mean speed profiles for safety measures (a. baseline condition; b. curb extensions; c. parking restrictions; d. advanced yield markings) and groups of TTZ^*_{arr}

For all of the countermeasures and for TTZ^*_{arr}<3s, the speed profile is higher than those under higher values of TTZ^*_{arr} (except for in the last section in advance of the pedestrian crossing). In the last 50 m, the drivers change abruptly their speed from approximately 55km/h to approximately 20 km/h because they must yield to the pedestrian that started crossing. The minimum speed value is at 15 m from the zebra crossing for the baseline condition and 10 m for the other countermeasures. The minimum speed values are approximately 20 km/h; the minimum value (18 km/h) was recorded for the baseline condition, while the maximum value was 23 km/h for curb extensions.

For all of the countermeasures, for $3<TTZ^*_{arr}<4s$ and for $4<TTZ^*_{arr}<5s$, the speed profiles show that the speed values were lower than those for $TTZ^*_{arr}<3s$. The beginning of the speed reduction (less abrupt than that for the $TTZ^*_{arr}<3s$ condition) occurs farther from the zebra crossing (at approximately 55 m for $3<TTZ^*_{arr}<4s$ and of 65 m for $4<TTZ^*_{arr}<5s$). The speed at which this occurs is higher for the lower TTZ^*_{arr} values (approximately 50 km/h for $3<TTZ^*_{arr}<4s$ and approximately 45 km/h for $4<TTZ^*_{arr}<5s$) (i.e., the speed reduction is less abrupt for higher values of TTZ^*_{arr}). With increasing values of TTZ^*_{arr}, the minimum speeds are reached farther from the zebra crossing (20 m for $3<TTZ^*_{arr}<4$ s and 30 m for $4<TTZ^*_{arr}<5$ s). For the curb extension and for $3<TTZ^*_{arr}<4s$, this distance is higher (25 m) than that (20 m) for the other countermeasures. The minimum speeds are approximately 20 km/h. For the baseline condition and for $3<TTZ^*_{arr}<4s$, the minimum speed is slightly lower (15 km/h).

For all of the countermeasures and for $TTZ^*_{arr}>5s$, the speed profile is the lower. The speed reduction occurs gradually and begins at a point that is more than 100 m away from the pedestrian crossing. The corresponding speed value is less than 50 Km/h. For the baseline conditions, the minimum speed value is at 25 m from the zebra crossing; for all of the other countermeasures, the point at which the speed reached the minimum value is 30 m away from the zebra crossing. The minimum speeds are equal to 20 km/h (for the baseline condition, 18 km/h; for parking restrictions, 22 km/h).

For the no-pedestrian condition and for all of the countermeasures, the speed profiles reveal a gradual speed variation from the value of approximately 55 Km/h until the minimum speed value. The minimum speed value is reached at points that are located at different distances from the zebra crossing: at 15 m for the baseline condition and for advanced yield markings (a minimum speed of approximately 35 km/h) and at 30 m for the curb extensions and for parking restrictions (a minimum speed of approximately 38 km/h).
It should be noted that for no-pedestrian condition the mean speed profile was obtained from the speeds of all the 42 drivers that participated at the driving simulator experiment. Such drivers were not differentiated for their characteristics. Thus, it is reasonable to expect a trend of the mean speed profile in approach to the pedestrian crossing (i.e. not close to the pedestrian crossing where the behavior is affected by the presence or absence of the pedestrian) that is intermediate among of those plotted for different groups of TTZ^*_{arr}.

5.2 Driver’s speed behavior

Table 3 shows a summary of the average initial speeds (V_i), the distances from the zebra crossing where the V_i value is located (L_{vi}), the minimum speed values (V_{min}), the distances from the zebra crossing where the V_{min} is reached (L_{Vmin}), the deceleration rates (d_m), and their standard deviations for every combination of the two independent factors (safety measures and pedestrian conditions). The interaction and main effects on the driver behavior (in terms of all of the dependent variables) due to the independent factors were analyzed with the MANOVA. A Bonferroni correction was used for multiple comparisons. For the analysis, SPSS (Statistical Package for Social Science) software was used.

MANOVA revealed a significant main effect for the safety measures ($F_{(15,1607)} = 2.660$, $P = 0.001$ Wilk’s $\Lambda = 0.935$, partial Eta squared = 0.022, observed power = 0.990) and for pedestrian conditions ($F_{(5,582)} = 125.401$, $P < 0.000$ Wilk’s $\Lambda = 0.481$, partial Eta squared = 0.519, observed power = 1). No interaction effects were found. Tests of between-subject effects showed that the distance from the zebra crossing where the V_i value is located, the minimum speed value and the distance from the zebra crossing where the V_{min} is reached were statistically significantly affected by the safety measures; the pedestrian conditions affected all of the dependent variables.

Table 3 - Descriptive statistics

Initial speed

The effect of safety measures on the initial speed value (Vi) was not statistically significant ($F_{(3,586)}$ = 0.861, P = 0.461); the mean value of the initial speed was 48.27 Km/h under baseline condition, 50.74 Km/h for curb extensions, 50.32 Km/h for parking restrictions and 49.93 Km/h for advanced yield markings (fig. 5a). The results showed, instead, that there was a main effect for the pedestrian conditions with regard to the initial speed ($F_{(1,586)}$= 9.361, P = 0.002). Pairwise comparison indicated that the initial speed when the pedestrian was absent (51.59 km/h) was significantly higher than that when the pedestrian was present (mean difference = 3.54 km/h; P= 0.002).

Distance from the zebra crossing where the deceleration begins

The results indicated that there was a main effect for the safety measures on the distance from the zebra crossing where the deceleration begins ($F_{(3,586)}$=7.936, P< 0.000). Post-hoc analysis shows that only the distance from the zebra crossing for the curb extensions condition (57.45 m) was statistically significantly higher than that for the baseline condition (mean difference = 11.63 m; P<0.000), in parking restrictions (mean difference = 8.16 m; P=0.003) and for advanced yield markings (mean difference = 10.59 m; P<0.000) (fig. 5b). The results also showed a main effect for the pedestrian conditions ($F_{(1,586)}$ = 27.157, P < 0.000). Pairwise comparison indicated that L_{vi}, when the pedestrian was absent (44.45 m), was significantly less than that when a pedestrian was present (mean difference = 10.28 m; P=0.000).

Minimum speed

The results showed that there was a main effect for the safety measures on the minimum speed value (V_{min}) that was reached during the deceleration ($F_{(3,586)}$ = 4.494, P=0.004). Post-hoc analysis indicated that the minimum speed value for the curb extensions condition (23.13 Km/h) was statistically significantly higher than that for the baseline condition (mean difference = 4.48 Km/h; P<0.000), for advanced yield markings (mean difference = 3.70 Km/h; P=0.002) and was not significantly different than that for parking restrictions (mean difference = 2.36; P=0.140). All of the other mean differences between the values of V_{min} were not statistically significant (fig. 5c). The results also showed a main effect for the pedestrian conditions ($F_{(1,586)}$ = 297.238, P <_0.000). Pairwise comparison indicated that the minimum speed value when a pedestrian was absent (28.35 Km/h) was significantly higher than that when a pedestrian was present (mean difference = 15.19 Km/h; P=0.000).

Distance from zebra crossing where the deceleration ends

The main effect on the ending point of the deceleration was due to the safety measures ($F_{(3,586)}$= 2.648, P=0.048). Post-hoc analysis indicated that the distance from the pedestrian crossing where the braking phase ends (L_{Vmin}) is statistically significantly higher for the curb extensions condition (21.42 m) than that for the advanced yield markings (mean difference = 4.30 m; P= 0.029) and not significantly different than that for the baseline condition (mean difference = 3.39 m; P= 0.167) and for parking restrictions (mean difference = 2.66 m; P= 0.517). All of the other mean differences between the values of L_{Vmin} were not statistically significant (fig. 5d). The results also showed a main effect for the pedestrian conditions ($F_{(1,586)}$ = 14.672, P < 0.000). Pairwise comparison indicated that L_{Vmin}, when the pedestrian was present (21.21 m), was significantly higher than that when the pedestrian was absent (mean difference = 5.05 m; P<0.000).

Average deceleration

The results showed that the effect of the safety measures for the average deceleration rate (d_m) was not statistically significant ($F_{(3,586)}$ = 1.540, P = 0.203); however, it should be noted that the average deceleration rates for the safety measures that improved the pedestrian visibility as curb extensions (-1.92 m/s^2) and parking restrictions (-2.18 m/s^2) were less than that for the baseline condition (-2.23 m/s^2) and for advanced yield markings (-2.39 m/s^2) (fig. 5e). As expected, a main effect was due to the pedestrian conditions ($F_{(1,586)}$ = 101.285, P<0.000). Pairwise comparison indicated that the average deceleration rate when the pedestrian was present (-2.99 m/s^2) was significantly higher than that when the pedestrian was absent (mean difference = 1.63 m/s^2; P<0.000).

Figure 5. Effects of the safety measures on the dependent variables of the driver's speed behavior

5.3 Outcomes of the questionnaire on countermeasures effectiveness

The results of the questionnaire on the perceived effectiveness of the countermeasures are shown in figure 6. The first result indicated that 83% of the drivers (35 of 42) perceived an effect on their driving behavior when the curb extensions were present, 67% (28 of 42) when there were parking restrictions and 71% (30 of 42) when the treatment was the advanced yield markings. This finding means that for the curb extensions condition, the drivers were more influenced in their driving behavior.

With respect to the drivers who perceived an effectiveness on their driving behavior, the second result indicated that for the curb extensions and parking restrictions, the main effectiveness was the better visibility of the pedestrian (16 of 35 and 14 of 28, respectively); for the advanced yield markings, the main effectiveness was the willingness to yield (12 of 30). For the curb extensions, the willingness to yield was also experienced by several drivers (14 of 35). For the three countermeasures, few drivers indicated that the perceived effectiveness was the speed reduction.

The last result is related to the self-reported distance from the zebra crossing where the driver modified his speed. In the baseline condition, most drivers (25 of 42, 59%) selected the lowest distance interval (from 20 to 30 m), which means that they changed their speed when they were too close to the zebra crossing. For the curb extensions, most of the drivers (13 of 42 and 12 of 42, globally equal to 60%) selected the highest values of the distance from the zebra crossing (from 40 to 50 m and from 50 to 60 m, respectively); this finding is consistent with the potential effectiveness of the countermeasure, which allows better visibility of the pedestrian. For parking restrictions, most of the drivers (19 of 42, 45%) selected the distance interval from 30 to 40 m. This outcome is also consistent with the aim of the countermeasure, that of clearing the line-of-sight to the pedestrian crossing, but the outcome was less than that observed for the curb extensions. For the advanced yield markings, most of the drivers (16 of 42, 38%) selected the distance interval of 30 to 40 m; this result can be attributed to the markings and the vertical signs that advise the drivers in advance about the presence of the pedestrian crossing.

Figure 6 - Outcomes of the questionnaire on the effectiveness of the countermeasures: a) drivers affected by the countermeasures; b) type of perceived effectiveness; c) distance from the zebra crossing where the drivers modified their speed.

6. DISCUSSION

6.1 Yielding compliance

As reported in table 1, the lowest value of the interactions where drivers did not yield (6, equal to 5% of 126 interactions) was reached when the curb extensions were present, while the highest value (17, equal to 13%) was obtained when the safety measure was the parking restrictions. The value for the advanced yield markings (8, equal to 6%) is slightly lower than that under the baseline condition (11, equal to 9%). Although these values are small for all of the countermeasures, a trend of the effects produced by the countermeasures on the yielding compliance was observed.

The lowest number of interactions in which drivers did not yield to a pedestrian was recorded for curb extensions, and this result is likely because the driver can anticipate his maneuver because the visibility of the pedestrian is improved; this characteristic, combined with the narrowing of the lane, leads to a more correct driver behavior. This result supports the findings of Randal et. al (Randal et.

al., 2005), who found that the number of vehicles that pass before the pedestrian decreases after the installation of the treatment, due to the anticipated drivers' yielding behavior.

For advanced yield markings, the number of interactions where the driver did not yield was lower than that under the baseline condition; this result is consistent with the findings of Samuel et al. (Samuel et al, 2013), who found that the number of drivers who yielded to pedestrians increased after the installation of this countermeasure. For the parking restrictions, the highest value (12%) was recorded; this result was unexpected. The large number of drivers who did not yield to a pedestrian could be linked to the fact that this countermeasure improves the visibility of the pedestrian and, at the same time, allows the driver to perceive a wider lane, due to the absence of parked cars. This combination leads the driver to maintain the same speed until the pedestrian crossing; when the pedestrian is perceived, the driver is too close to the zebra crossing and cannot adopt a comfortable deceleration rate; therefore, he decides to not yield to the pedestrian.

6.2 Mean speed profiles

As expected, the analysis of the mean speed profiles revealed that the driver's speed behavior is affected by the vehicle-pedestrian interaction conditions (.i.e., different groups of TTZ^*_{arr} values and therefore different drivers' characteristics). In fact, for all the countermeasures, the mean speed profiles highlighted:

- lower initial speed with the increase of the TTZ^*_{arr}
- less abrupt speed reductions with the increase of TTZ^*_{arr}

More specifically, for all of the countermeasures and for $TTZ^*_{arr}<3s$, the driver is approaching the pedestrian crossing with high speed values and adopts the most abrupt speed reductions. This behavior highlights a low "availability" of the driver to yield (or a certain driver's aggressiveness). The driver would have the priority at the zebra crossing, and thus, he maintains the same speed until he is close to the pedestrian crossing; then, he is forced to brake to avoid hitting the pedestrian.

This result is consistent with the findings of Varhelyi (Varhelyi, 1998), which were obtained for TTZ_{arr} values from 1 to 4 s. However, it should be noted that the shape of the mean speed profiles near the pedestrian crossing is not the same as in Varhleyi's study, where the driver speed profile shows high speed values (approximately 50 Km/h), which highlights that the driver does not yield and passes before the pedestrian. This result is the outcome of the vehicle-pedestrian interaction where the pedestrian is affected by the driver's behavior (the driver maintains a high speed) to give up crossing before the arrival of the driver. The mean speed profile plotted from the driving simulator data instead highlights an abrupt speed reduction (from approximately 50 Km/h to approximately 20 Km/h) near to the zebra crossing, which means that the driver has yielded to the pedestrian. This observation is because the pedestrian is set to start crossing regardless of the driver's behavior.

For $3<TTZ^*_{arr}<4s$ and $4<TTZ^*_{arr}<5s$, the driver adopts lower speed and less abrupt speed reductions than those shown for TTZ^*_{arr} <3s. This behavior reveals that the driver realizes that he cannot pass before the pedestrian and starts to decelerate farther from the zebra crossing. This behavior is more accentuated for $TTZ^*_{arr}>5s$, where the driver adopts the lower speeds and the less abrupt speed reductions highlighting a careful behavior. Additionally, this result is fully consistent with the findings of Varhelyi (Varhelyi, 1998), which were obtained for TTZ_{arr} values that were higher than 4 s.

It should be noted that these drivers' behaviors are completely consistent with the "Threat Avoidance Model" developed by Fuller. In particular, the behavior observed for $TTZ^*_{arr}<3s$ can be related to the "non-avoidance response". The driver, in fact, maintains the same speed because he considers the pedestrian presence to be a "threat" but chooses a non-avoidance response, signaling to the pedestrian that he has no intention to yield. However, because the pedestrian assumes a competitive behavior (into the simulated scenario, the pedestrian starts to cross regardless of the driver's behavior), the driver is forced to a delayed avoidance response (braking) or a collision occurs.

The behavior observed for $TTZ^*_{arr}>5s$ (and to a lesser extent, also that for $3<TTZ^*_{arr}<4s$ and $4<TTZ^*_{arr}<5s$) can be related, instead, to the case of "anticipatory avoidance response". The driver considers the pedestrian presence to be a "threat" and he slows down; in this way, the pedestrian can pass before the arrival of the driver.

It is important to observe that these results highlight the reliability of the driving simulation, which returns drivers' behaviors qualitatively similar to those recorded in the real world and fully consistent with the driver's behavioral model while approaching the pedestrian crossings.

Only slight differences were observed among the countermeasures for different values of TTZ*$_{arr.}$. These differences were not observed in approach (i.e. far from zebra crossing) to the pedestrian crossing, but were revealed close to the pedestrian crossing (V_{min} and L_{Vmin} were different among the countermeasures). This highlights that far from zebra crossing the driver's speed behavior is affected only by the conditions of the vehicle-pedestrian interaction (i.e., by the different drivers' characteristics) while close of the zebra crossing also the configuration of the pedestrian crossing seems to play a role. Close to the pedestrian crossing, however, the slight differences that were revealed from the analysis of the mean speed profiles did not highlight a clear trend that enables to express considerations on the induced effects by the several countermeasures.

More evident differences between the countermeasures were observed for the pedestrian absence condition. For this condition, advanced yield markings and baseline condition have the same shape for the mean speed profile, due to having a similar effect on the drivers' behavior. In fact, the driver cannot clearly see if the pedestrian is present at the zebra crossing, and thus, he reached the minimum speed value (approximately 35 km/h) close to the pedestrian crossing (at a point 15 m from the zebra crossing). For curb extensions and parking restrictions, the driver has better sight of the zebra crossing and can clearly see if the pedestrian is present or not, and thus, he reaches the minimum speed value (approximately 38 Km/h) farther from the zebra crossing (30 m). In other words, for these countermeasures, the driver does not need to slow down as much to ensure whether the pedestrian is present or not. Moreover, the speed value at the zebra crossing for the curb extensions (40 Km/h) is lower than that for the parking restrictions (43 Km/h). This relationship was expected because the curb extensions cause a narrowed cross-section and induce the driver to adopt a lower speed.

6.3 Driver's speed behavior

Effects of the countermeasures

Statistical analysis indicated that the driver's initial speed value (V_i), identified at the moment when the driver starts to decrease his speed, was not statistically affected by the countermeasures. This result is consistent with the expected behavior of the driver: he is not affected by the safety measures with respect to his speed selection when he is far from the zebra crossing. The distance from the zebra crossing where V_i is located (L_{Vi}) was significantly higher for the curb extensions. This distance gives an indication of how clear the information perceived by the driver is. Higher values of this variable indicate that the driver anticipates the maneuver of adapting his speed at the pedestrian crossing. This result confirms the expected effectiveness of the curb extensions, which are aimed at improving the visibility of the zebra crossing. The minimum speed value (V_{min}) was also significantly higher for the curb extensions. The consequence of an anticipated maneuver is that the driver does not need to reach a low speed value during the speed reduction phase because he starts to slow down when he is farther from the zebra crossing. This arrangement means that the driver is not forced to brake, and thus, to adopt an abrupt maneuver while approaching the zebra crossing. Additionally, the distance where V_{min} is located (L_{Vmin}) was higher for the curb extensions (the difference was statically significant only with advanced yield markings). This outcome is consistent with previous results, and it highlights that when the driver can anticipate the maneuver, he ends the deceleration phase farther from the zebra crossing.

Finally, the statistical analysis showed that the effect of countermeasures on the average deceleration rate (d_m) was not statistically significant. However, the lowest value was recorded for curb extensions (-1.92 m/s^2). Despite the fact that the differences in the average deceleration rates were not statistically significant, this outcome is also consistent with the results on the other variables and supports the expected effects on the driver's speed behavior due to the improving of the visibility of crossing pedestrians caused by the curb extensions.

Effects of the pedestrian conditions

Statistical analysis showed that the pedestrian conditions significantly affected all of the variables of the driver's speed behavior. This result was expected. According to the "Threat Avoidance Model" (Fuller, 1984), the driver behaves in different ways depending on whether he perceives the discriminative stimulus (i.e., the presence of the pedestrian) or not.

The initial speed (V_i) for the pedestrian absence case (51.59 Km/h) was significantly higher than the speed for the case of pedestrian presence (48.05 Km/h), which shows that the driver reaches a higher speed when he does not perceive interference with a pedestrian.

For the distance from the zebra crossing where V_i is located (L_{Vi}), as expected, the lowest value was for the pedestrian absence case (44.45 m); under this condition, the driver delays the moment of his reaction because he does not perceive that there is an interaction with the pedestrian.

The minimum speed (V_{min}) also reaches a higher value for the pedestrian absence condition (28.35 Km/h). As expected, when a pedestrian is absent, the driver does not have to slow down as much and reaches a higher speed value because he does not perceive that there is an interaction with a pedestrian.

The distance from the zebra crossing where the minimum speed is located (L_{Vmin}) (similar to L_{Vi}) was lower for the pedestrian absence condition (16.16 m), which shows that the driver, when he does not perceive an interaction with a pedestrian, ends the deceleration phase at a point that is nearest to the zebra crossing.

The average deceleration rates (d_m) confirm how the driver reacts when he perceives an interaction with the pedestrian. When the pedestrian was present, the average deceleration reached the highest value (-2.99 m/s^2). As expected, to yield or to avoid the conflict, the driver adopts a more abrupt maneuver than that of the pedestrian absence condition. For this last pedestrian condition, the driver does not experience a "threat", and therefore, he performs a smoother maneuver.

7. CONCLUSIONS

The main aims of this driving simulator study were the following:

1) to provide useful insights for a better comprehension of the drivers' speed behavior while approaching the zebra crossings under different conditions of vehicle-pedestrian interaction and several countermeasures;
2) to perform a comparative evaluation of the effectiveness of several countermeasures on the drivers' speed behavior while approaching the zebra crossing.

Two analyses were performed. The first analysis focused on the mean speed profiles. A further analysis was based on variables that were obtained from the speed profiles of drivers.

The study provided several interesting findings.

Concerning the driver yield compliance, a trend in the effects produced by the countermeasures was observed. The lowest number of interactions where the drivers did not yield (5%) was recorded for the curb extensions. This result could reasonably be due to having better visibility of the pedestrian, which was caused by this countermeasure.

The analysis of the mean speed profiles revealed that the driver's speed behavior was affected by the conditions of the vehicle-pedestrian interaction (different groups of TTZ^*_{arr} values and therefore different drivers' characteristics). However, only slight differences between the countermeasures were observed for different TTZ^*_{arr} values; specifically, the main differences were observed for the pedestrian absence condition. Under this condition, for the countermeasures that improve visibility, such as curb extensions and parking restrictions, the minimum speed value was reached farther from the zebra crossing than that for the baseline condition and advanced yield markings, due to the possibility of advancing the maneuver.

The drivers' speed behaviors that were recorded for different groups of TTZ^*_{arr} were fully consistent with the findings of Varhelyi (Varhelyi, 1998) and with the "Threat Avoidance Model" developed by Fuller (Fuller, 1984), according to which the driver could adopt a "non– avoidance response", warning the pedestrian of his intention to not give way, or could adopt an “anticipatory avoidance response”, slowing down and giving way to the pedestrian.

The analysis that was focused on the variables that were obtained from the speed profiles of the drivers identified that curb extensions was the countermeasure that induces the most appropriate driver’s speed behavior while approaching the zebra crossing. For this countermeasure, the higher (statistically significant) values for the following were obtained: the distance from the zebra crossing where the driver starts to decrease his speed (L_{Vi}); the distance from the pedestrian crossing where the braking phase ends (L_{Vmin}); and the minimum speed value (V_{min}) reached during the deceleration. For this countermeasure, we also found the lowest value (statistically not significant) of the average deceleration rate (d_m). Such results indicate that this countermeasure improves the visibility of the zebra crossing and effectively allows the driver to advance the maneuver to adapt his speed at the pedestrian crossing and, therefore, to perform a smoother maneuver.

This result was also confirmed by outcomes of the questionnaire on countermeasures effectiveness. For curb extensions, in fact, over 80% of the drivers perceived effectiveness, which indicates that when this countermeasure was present, they were more willing to yield and that the visibility of the pedestrian crossing was better. Finally, the self-reported distance from the zebra crossing showed that the drivers started to change their speed farther from the zebra crossing when the curb extensions were present, which confirms the findings of the statistical analysis.

These outcomes highlight that the pedestrian crossings should be provided with curb extensions, which are the most effective countermeasures to be used in order to improve the pedestrian safety at unsignalized pedestrian crossings.

The present study was conducted using the advanced driving simulator of the Inter-University Research Centre for Road Safety (CRISS), which allowed for full control of the experimental condition and no risk to the participants. However, it should be recognized that one of the major concerns with the use of driving simulators is that the simulated drive can determine a driver behavior that is different from that in the real world. The CRISS driving simulator was previously validated as being a reliable tool for the study of drivers’ speed behaviors on two-lane rural roads (Bella, 2008). Such a result does not allow generalizations to be drawn because of concerns about the validation of the simulator for different experiments and road types (Bella, 2009). A rigorous validation study of the CRISS driving simulator that compares the driver performance at pedestrian crossings in the simulation with data from the real world under the same conditions has not yet been developed. However, considering the aim of the present study, only the relative validity (which refers to the correspondence between the effects of different variations in the driving situation) is required (Tornos, 1998). Concerning this point, the obtained results on the drivers’ speed behaviors that were recorded for different groups of TTZ^*_{arr} (these drivers’ behaviors were qualitatively similar to those recorded in the real world and fully consistent with the driver’s behavioral model while approaching the pedestrian crossings) confirm the reliability of the driving simulation. In addition, considering the reliability of the results on the drivers’ behavior at zebra crossings from previous driving simulator studies (Garay-Vega et al., 2007; Gomez et al., 2011; Fisher and Garay-Vega, 2012; Salamati et al., 2012; Rogè et al, 2014) in which the driving simulators had the same characteristics as the CRISS driving simulator, it can be stated that there are sufficient guarantees for the validity of the method used.

Further studies might examine combinations of treatments, such as curb extensions and advanced yield markings or parking restrictions and advanced yield markings. Such combinations of treatments remain inexpensive and easy to install and could determine additional effects on the driver’s behavior than those found for the single treatment.

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TABLE CAPTIONS

Table 1 - Actual vehicle-pedestrian interactions recorded at the driving simulator

Table 2 - Number of actual vehicle-pedestrian interactions that were obtained from the three theoretical values of TTZ_{arr}.

Table 3 - Descriptive statistics

Counter measures	**N° of vehicle-pedestrian interaction**	**TTZ^*_{arr}**							**N° interactions where drivers did not yield**
		Mean [s]	max [s]	min [s]	$TTZ^*_{arr} \leq 3$ s	$3 < TTZ^*_{arr} \leq 4$s	$4 < TTZ^*_{arr} \leq 5$s	$TTZ^*_{arr} > 5$s	
Baseline condition	115	4.1	9.1	1.4	31	28	28	28	11
Curb extensions	120	4.6	10.7	1.2	13	43	26	38	6
Parking restrictions	109	4.2	9.0	1.1	24	29	22	34	17
Advanced Yield Markings	118	4.0	11.4	0.9	37	31	20	30	8

Table 1 - Actual vehicle-pedestrian interactions recorded at the driving simulator

	theoretical vehicle-pedestrian interactions implemented in the driving simulator			
actual vehicle-pedestrian interactions	TTZ_{arr}= 1s	TTZ_{arr} = 2.5s	TTZ_{arr} = 4s	total number of interactions
$TTZ^*_{arr} <3$	21	30	54	105
$3<TTZ^*_{arr}<4s$	46	51	34	131
$4<TTZ^*_{arr}<5s$	35	30	31	96
$TTZ^*_{arr}>5s$	40	43	47	130

Table 2 - Number of actual vehicle-pedestrian interactions that were obtained from the three theoretical values of TTZ_{arr}.

Safety Measure	Pedestrian Condition	V_i [Km/h]		L_{Vi} [m]		V_{min} [Km/h]		L_{Vmin} [m]		d_m[m/s^2]	
		Average	SD	Average	SD	Average	SD	Average	SD	Average	SD
Baseline condition	Pedestrian absence	49.94	12.83	39.48	18.73	26.83	14.02	15.38	12.71	-1.39	1.29
	Pedestrian presence	46.61	11.87	50.82	18.13	11.41	6.04	20.34	13.05	-3.07	1.74
Curb Extensions	Pedestrian absence	51.44	14.36	52.64	13.53	30.48	13.26	19.09	11.50	-1.19	0.93
	Pedestrian presence	50.04	10.38	62.26	20.53	15.78	8.46	23.75	14.37	-2.64	1.43
Parking Restrictions	Pedestrian absence	52.89	14.24	42.79	15.52	29.44	10.70	17.09	8.34	-1.30	1.41
	Pedestrian presence	47.75	11.22	54.54	22.23	13.11	8.54	20.87	12.70	-3.06	2.04
Advanced Yield Markings	Pedestrian absence	52.07	12.76	42.89	18.05	26.66	12.36	13.07	10.58	-1.57	1.19
	Pedestrian presence	47.80	10.95	51.29	22.17	12.34	6.90	19.85	15.34	-3.21	1.75

Table 3 - Descriptive statistics

FIGURE CAPTIONS

Figure 1 - a) Baseline condition b) Curb Extensions c) Parking Restrictions d) Advanced Yield Markings

Figure 2 - CRISS driving simulator

Figure 3 - Variables of the driver's speed behavior

Figure 4 - Mean speed profiles for safety measures (a. baseline condition; b. curb extensions; c. parking restrictions; d. advanced yield markings) and groups of TTZ^*_{arr}

Figure 5 - Effects of the safety measures on the dependent variables of driver's speed behavior

Figure 6 - Outcomes of the questionnaire on the effectiveness of the countermeasures: a) drivers affected by the countermeasures; b) type of perceived effectiveness; c) distance from the zebra crossing where the drivers modified their speed.

Figure 1

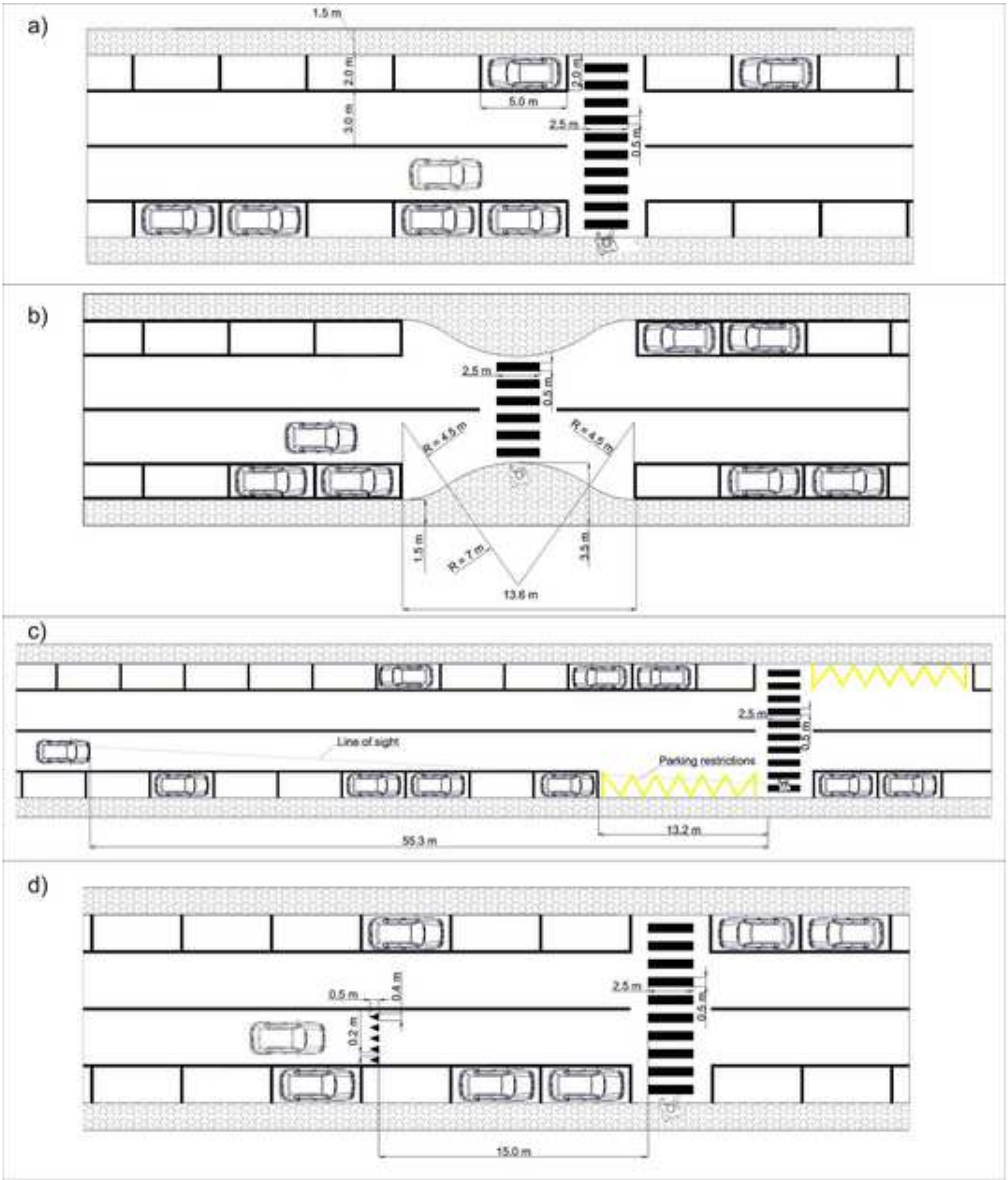

a)
1.5 m
2.0 m
3.0 m
2.0 m
5.0 m
2.5 m
0.5 m
b)
2.5 m
0.5 m
R = 4.5 m
R = 4.5 m
1.5 m
R = 7 m
3.5 m
13.6 m
c)
2.5 m
0.5 m
Line of sight
Parking restrictions
13.2 m
55.3 m
d)
0.5 m
0.4 m
0.2 m
2.5 m
0.5 m
15.0 m

Figure 2

Figure 3

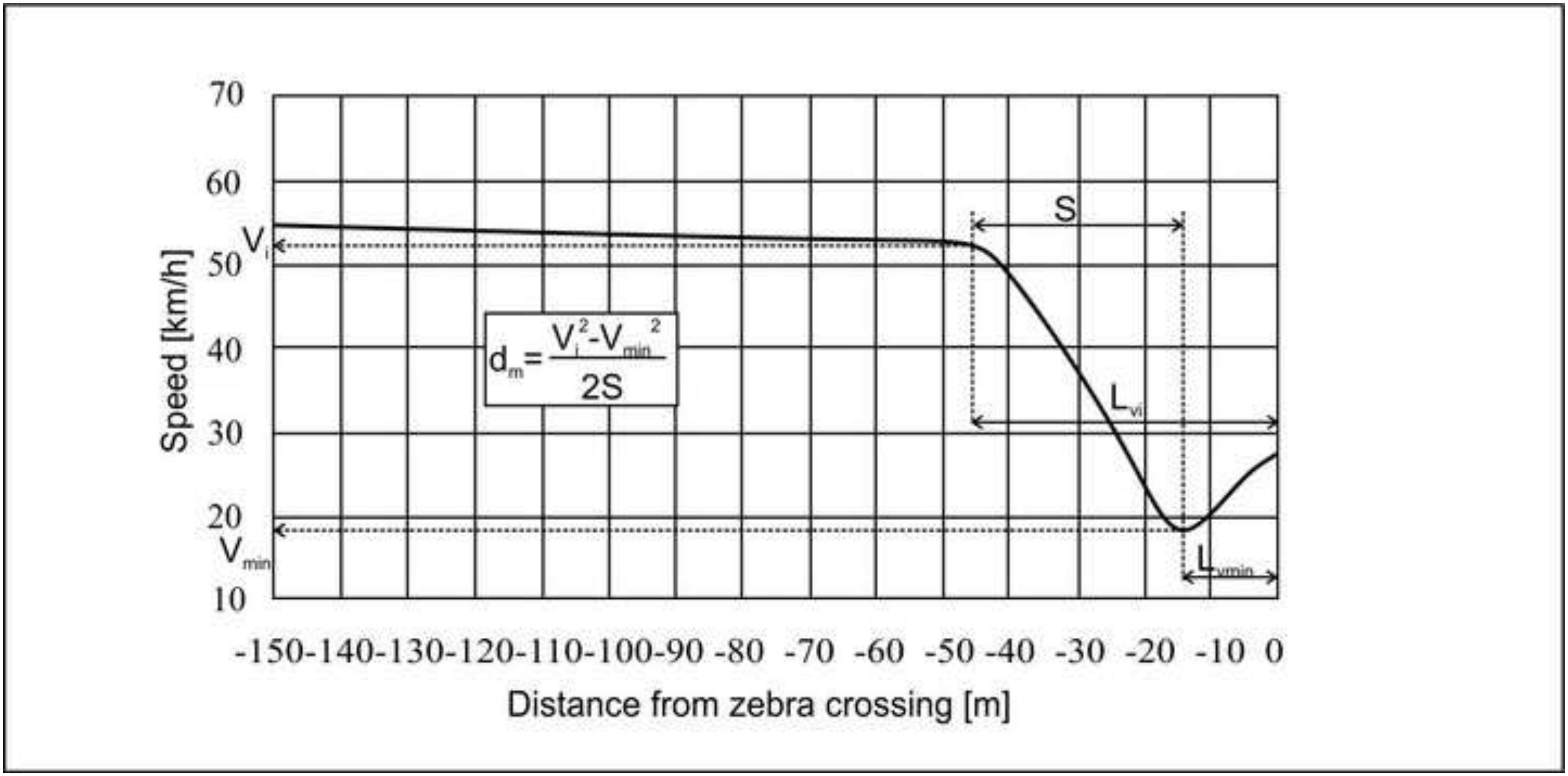

70
60
50
40
30
20
10
V_i
V_{min}
Speed [km/h]
$d_m = \frac{V_i^2 - V_{min}^2}{2S}$
S
L_{vi}
L_{vmin}
-150 -140 -130 -120 -110 -100 -90 -80 -70 -60 -50 -40 -30 -20 -10 0
Distance from zebra crossing [m]

Figure 4

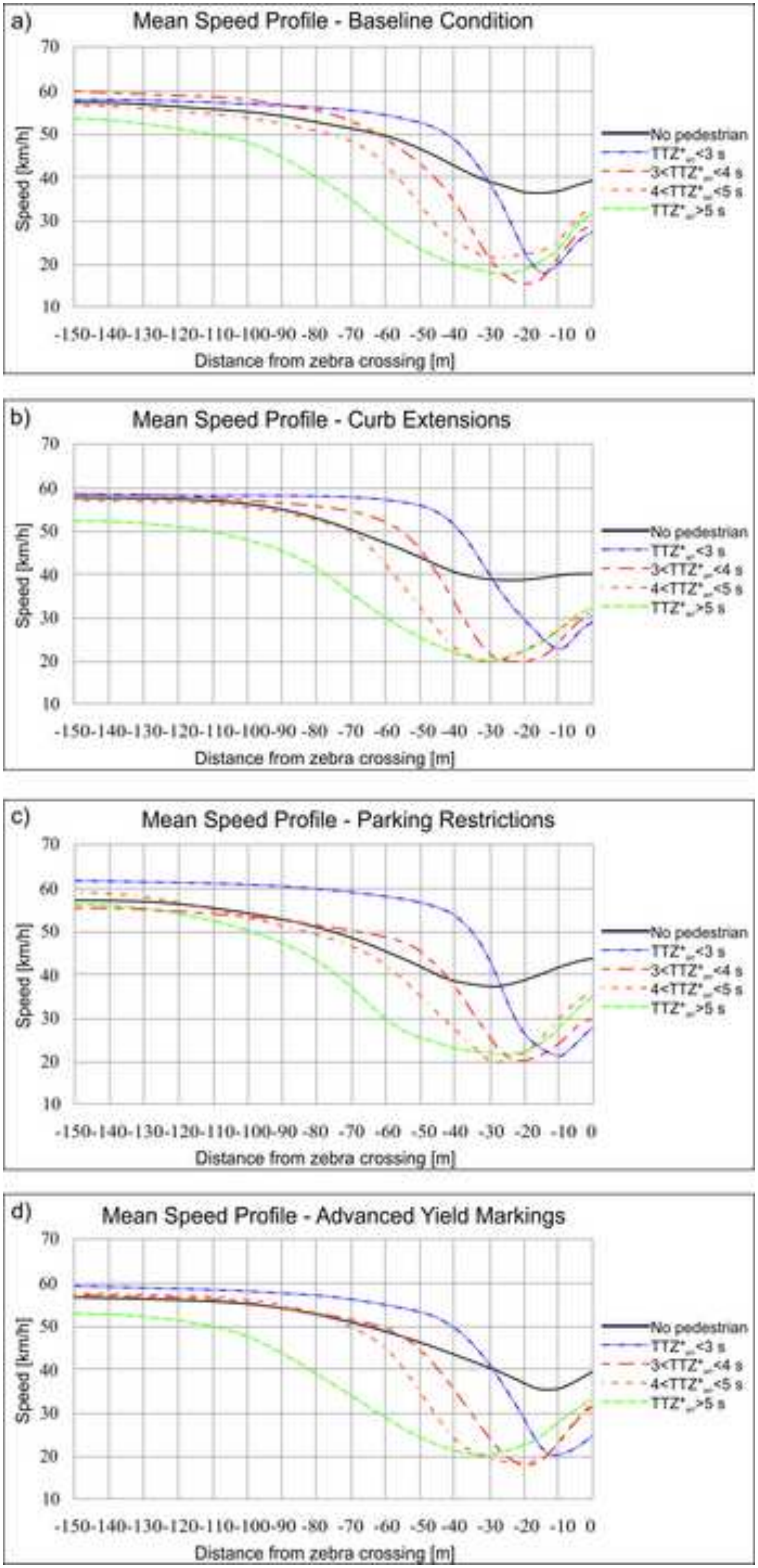

a)
Mean Speed Profile - Baseline Condition
b)
Mean Speed Profile - Curb Extensions
c)
Mean Speed Profile - Parking Restrictions
d)
Mean Speed Profile - Advanced Yield Markings
Speed [km/h]
70
60
50
40
30
20
10
-150 -140 -130 -120 -110 -100 -90 -80 -70 -60 -50 -40 -30 -20 -10 0
Distance from zebra crossing [m]
No pedestrian
TTZ*<3 s
3<TTZ*<4 s
4<TTZ*<5 s
TTZ*>5 s

Figure 5

Click here to download high resolution image

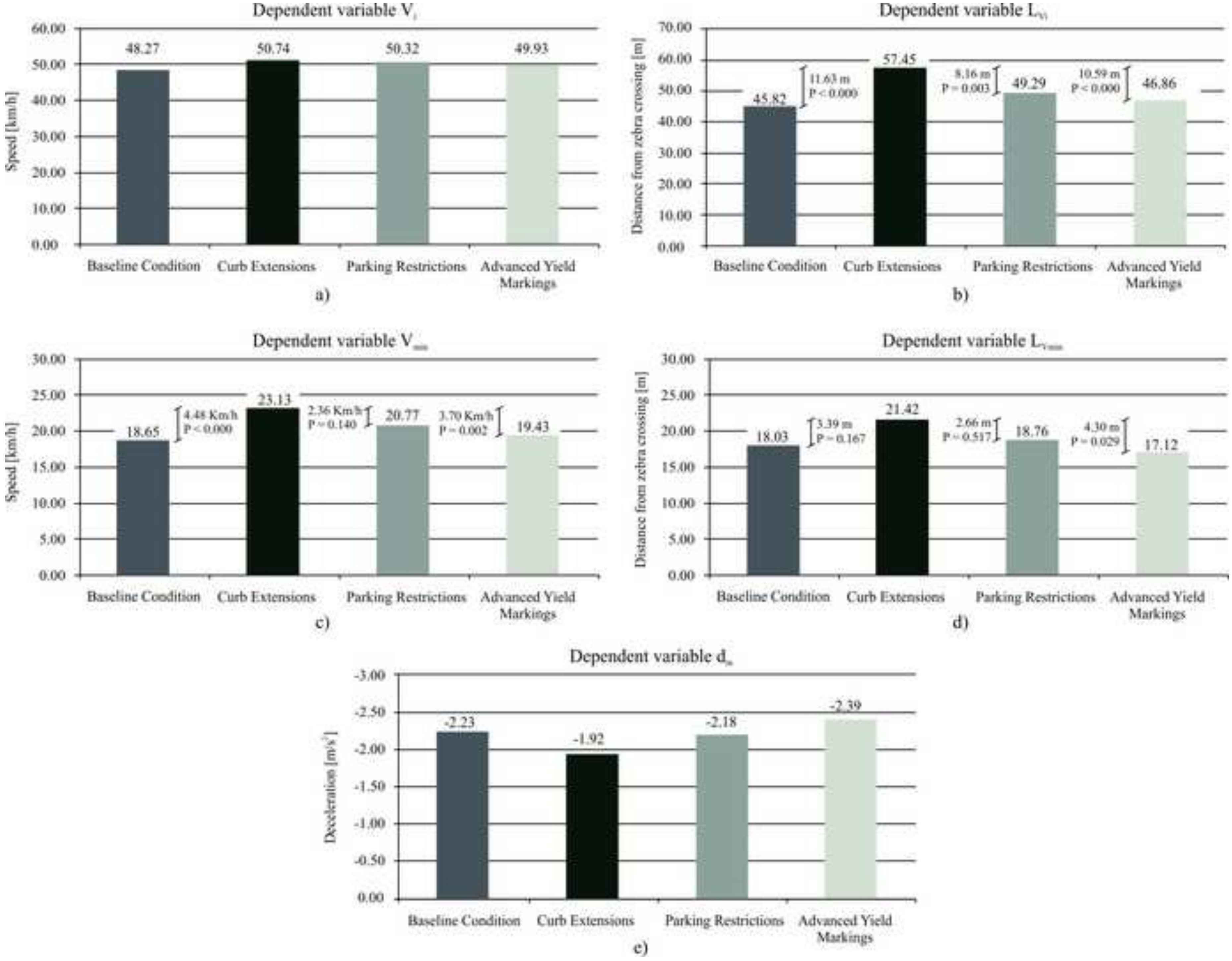
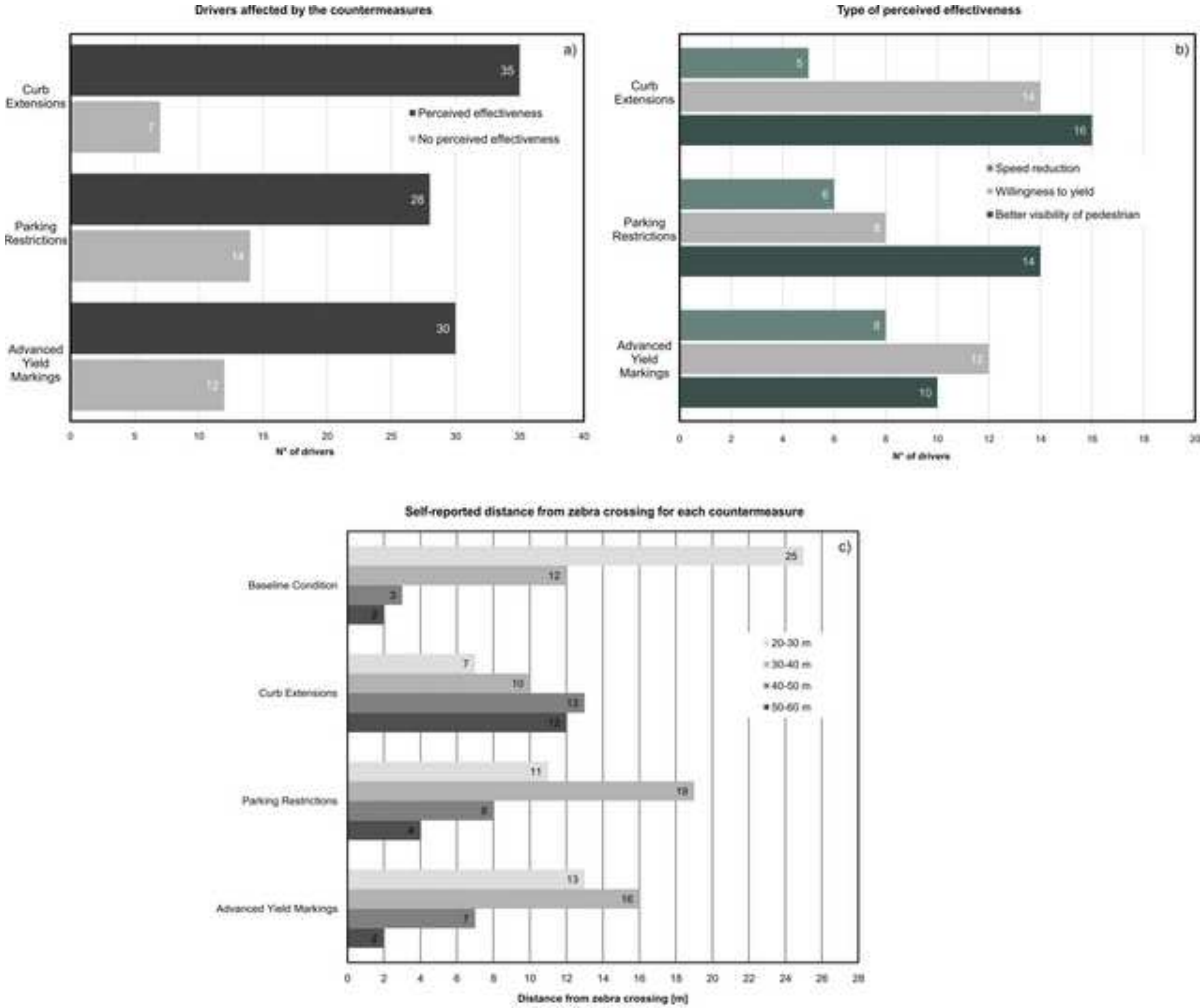


Figure 6


Drivers affected by the countermeasures
a)
Curb Extensions
Parking Restrictions
Advanced Yield Markings
35
7
28
14
30
12
■ Perceived effectiveness
■ No perceived effectiveness
0
5
10
15
20
25
30
35
40
N° of drivers
Type of perceived effectiveness
b)
Curb Extensions
Parking Restrictions
Advanced Yield Markings
5
14
16
6
8
14
8
12
10
■ Speed reduction
■ Willingness to yield
■ Better visibility of pedestrian
0
2
4
6
8
10
12
14
16
18
20
N° of drivers
Self-reported distance from zebra crossing for each countermeasure
c)
Baseline Condition
Curb Extensions
Parking Restrictions
Advanced Yield Markings
25
12
3
2
7
10
13
12
11
19
8
4
13
16
7
2
■ 20-30 m
■ 30-40 m
■ 40-50 m
■ 50-60 m
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
Distance from zebra crossing [m]