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# Driving behavior towards vulnerable road users: effects of safety countermeasures and driving assistance systems

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*[...] Those who can imagine anything,*
*can create the impossible [...]*

*Alan Turing*

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# List of Symbols

In the following list the main symbols that appear in the chapters of the thesis are reported.

| | |
|---|---|
| $\beta$ | Vector of estimable parameters |
| $\lambda$ | Location parameter |
| $\varepsilon$ | Error term |
| $ADASs$ | Advanced Driving Assistance Systems |
| $AEB$ | Autonomous Emergency Braking |
| $AFT$ | Accelerated Failure Time |
| $AIC$ | Akaike's information criterion |
| $BIC$ | Bayesian information criterion |
| $CG$ | General average costs for accident |
| $CM$ | Average human costs for death |
| $CM_{\mathrm{f}}$ | Average human costs for injury |
| $CT$ | Total social cost |
| $CWS$ | Collision Warning System |
| $d$ | Lateral position |
| $d_{\mathrm{av}}$ | Average lateral position |
| $d_{\mathrm{m}}$ | Driver average deceleration |
| $F(t)$ | Cumulative distribution function |
| $f(t)$ | Probability density function |
| $GDP$ | Gross Domestic Product |
| $HUD$ | Head Up Display |
| $L_{\mathrm{i}}$ | Distance from crossroad at which the $V_{\mathrm{i}}$ is recorded |
| $L_{\mathrm{Vmin}}$ | Distance at which the $V_{\mathrm{min}}$ is located |

$LT$ Length of tangent

$MANOVA$ Multivariate Analysis of Variance

$NF$ Number of injuries

$NI$ Number of Accidents

$NM$ Number of deaths

$PH$ Proportional Hazard

$PPSs$ Pedestrian Protection Systems

$R$ Curve radius

$RT$ Driver reaction time

$s$ Seconds

$S(t)$ Survival probability

$SRT$ Speed Reduction Time

$TT_{\mathrm{arr}}$ Time to Arrive at cyclist crossroad

$TTC$ Time To Collision

$TTZ_{\mathrm{arr}}$ Time to Zebra arrive

$V$ Overtaking speed

$V_{\mathrm{av}}$ Average overtaking speed

$V_{\mathrm{i}}$ Driver initial speed

$V_{\mathrm{min}}$ Driver minimum speed

$VRU$ Vulnerable Road User

# Abstract

The accident statistics all around the world show that the problem of the Vulnerable Road Users (VRUs) safety is relevant and much efforts are needed to improve the safety levels and decrease the accident events involving VRUs, as reported in the major government action safety plans.
The higher probability of fatal event for pedestrians and cyclists in collision with vehicles leads to the definition of Vulnerable Road users. This definition implicitly takes into account the lack of protection that, together with the high difference in the physical mass, increases the risk of death in case of accident involving VRUs. However, as imaginable, reducing the mass difference is not possible, as it is an intrinsic characteristic of each road user. On the contrary, it is possible to improve the road configuration or the VRU facilities to induce proper driving behavior and reduce the probability of accident and, thus, the risk at which the VRUs are exposed to.
Most of the literature is focused to analyze the behavior of the VRUs in the moment in which they interact with the drivers. However, it is highly important to understand how the drivers' behavior change in the moment in which an interaction with the VRU occurs and how intervene to optimize this interaction and make it safer. Considering the safety conditions of VRUs, the caveats of literature and the actual body of knowledge the present research focused on the analysis of the driver - VRU interaction (pedestrian and cyclist) to provide further insights of this particular kind of road interaction. Furthermore, the research aimed also at assessing the effects of safety countermeasures at pedestrian crossing, cyclist crossroad and cyclist paths to detect the most effective driver/cyclist facility layouts and cross - section configuration that can decrease the risk at which VRU are exposed to. In addition, the assessment of driving behavior also under unexpected situation was analyzed to understand and verify the potential benefits of advanced warning systems aimed at timely alerting the driver about possible imminent collisions.
The study of the driving behavioral models and how driver and VRU interact were the basis to achieve the research objectives. The foundations of the research are individuated in the theoretical framework of the driver behavior in response to a "threat" that is, in the present study, the presence of a pedestrian or a cyclist that should inevitably induce a change in the driving behavior.
Several experiments have been carried out and specifically designed for the driver - pedestrian and driver - cyclist interaction. In particular, for the driver - pedestrian interaction, several countermeasures at the pedestrian crossing where assessed in the urban environment to identify the most effective one. Moreover, in addition to the improvement of the safety characteristics of the pedestrian crossing layout, dedicated experiments were designed to assess the effects of Pedestrian Protection Systems (PPSs) aimed at improving the pedestrian safety at the zebra crossing in urban, sub - urban and rural environments. The particular case of a pedestrian that

crosses outside of the crosswalk (called jaywalking pedestrian) was also analyzed, for which the effectiveness of the PPS on helping the driver in this unexpected situation was assessed.

As for the driver-pedestrian interaction at zebra crossings, several countermeasures at the bicyclist crossroads were evaluated in the urban environment, as well as the reorganization of the road cross - section to ensure the highest safety levels or the VRU during the driver overtaking maneuver of a cyclist in the rural environment.

To achieve the objectives of the present research, the main tool used was the driving simulator. The experimental design followed several phases: a) literature review about the state of art of each specific topic investigated b) specific design of simulated scenarios c) simulated test on a significant diving sample d) robust statistical analyses on variables explaining the driver behavior. This approach ensured the objective comparison of the safety measures as well as the full control of the boundary conditions of the experimental road scenarios and the removal of the confounding factors that are often present in the field studies and that could affect the output of the analysis. Moreover, with the use of the driving simulator a huge amount of data are provided that can be used to produce significant statistical analyses and reliable outputs.

# Chapter 1

# Introduction

## 1.1 The issue of the Vulnerable Road Users safety

Who are Vulnerable Road Users? VRU are non - motorized road users, such as pedestrians and cyclists as well as motor-cyclists and persons with disabilities or reduced mobility and orientation [1]. Among these categories of road users, surely pedestrians and cyclists represent the majority of road user exposed to risky situations.

Overall, in case of accident event against other road users, VRUs suffer the worst consequences due to the lack of physical protections compared, for instance, to the vehicle occupants.

In case of crash with a motor vehicle the quantity of damage which is intended the pedestrian or the cyclist is incomparably higher.

Several governments transport policies promote the increasing of walking and cycling as alternative transport mode, which is also in line with other health objectives like fight obesity and heart issues, as well as improve the quality of the environment by reducing traffic and related pollution. However, these strategies should be strictly related to other effective measures such as speed management or safety countermeasures. The risk at which VRUs are exposed to, in fact, is often compromised by incorrect behaviors and poor facilities layout which does not help both the driver and VRUs in prevent risky situations.

The reason behind the unsafe walking and cycling is that pedestrian and cyclist share their paths with vehicles which travel with higher speeds. This condition is detrimental for the VRUs, which also increases the probability of death in case of impact with the vehicle. The dramatic situation of the pedestrian and cyclist safety is largely highlighted by the accident statistics. Every year all - around the world, about 270.000 pedestrians and 48.000 cyclists die in road related crashes [2], which represent in total over the 27% of all the road deaths. Focusing on the European area, the data related to the accident statistics between 2002 and 2013 provided by the European Transport Safety Council (ETSC) show that the fatalities of VRUs decreased at a slower rate than those of the vehicle occupants. Specifically, the reduction among pedestrians and cyclists was of 41% and 36%, respectively, while in the same period the reduction among vehicle occupants was of 53% [3], as reported in Figure 1.1.

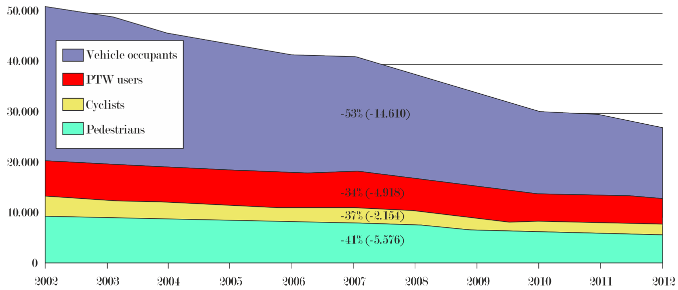



Figure 1.1: Fatalities reduction in the EU since 2002 to 2013.

In addition, the European Road Safety Observatory (ERSO) accident data show that in 2015, 5.435 pedestrians and 2.043 cyclists were killed in road accidents in the EU [4, 5], which represent the 21% and the 8% of the total fatalities in the continent, respectively. Despite in the decade 2006 - 2015 the pedestrian fatalities and the cyclists fatalities reduced by 36% and 27%, the trend of the percentage of the fatalities of the VRUs on the total road fatalities had a slightly increasing trend (Fig. 1.2 and 1.3).

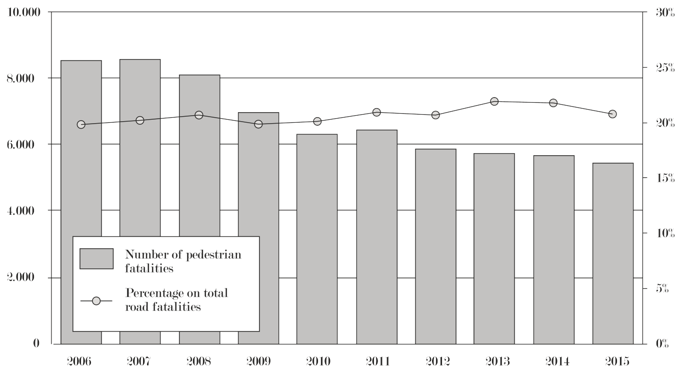



Figure 1.2: Pedestrians fatalities percentage on total road fatalities.

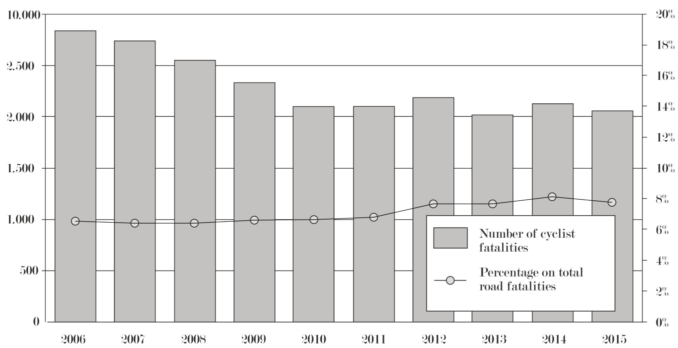



Figure 1.3: Cyclists fatalities percentage on total road fatalities.

In Italy the situation about VRUs accidents is also not positive. The last available statistics [6] report that in 2017 the pedestrians killed in road accidents represent almost the 18% of all road deaths, while in the same year the cyclists represents over the 7%. Since 2001, the percentage of pedestrian and cyclists fatalities on total road deaths increased on average by 3%. The tragedies behind these cold numbers, in addition to the caused pain to the victims families, are reflected also in the society by huge costs. The Italian Ministry of Infrastructures and Transport [7] in 2010 and then in 2013 estimated the total social costs due to the consequences of crashes by the following:

$$CT = CM_f \cdot NF + CM \cdot NM + CG \cdot NI \tag{1}$$

in which $CM_f$ represent the human average cost for the injured, CM the human average cost for death and CG the general average cost for the accident, while NF, NM and NI are the number of injured, deaths and accidents, respectively. The evaluation of the human average cost is based on the estimation of the human life cost and the health costs. The first is essentially estimated through the economic exploitation of the present and future loss of productivity due to the road accident and the non-pecuniary damages. These damages are intended to be the moral damage for a loss due to an unlawful committed by others. The second includes expenses incurred in hospitalization, first aid costs and ambulance costs. Considering the actual values of VRUs injuries, deaths and accidents, in the following table the amount of total social costs for the year 2017 are reported:

Table 1.1: Estimation of total costs of pedestrians and cyclists crashes for the 2017.

| | **€** |
|---|---|
| **Total costs of deaths** | **1.284.407.460** |
| *Average human cost for death* | *1.503.990* |
| n° of pedestrian fatalities | 600 |
| n° of cyclist fatalities | 254 |
| **Total costs of injured** | **1.459.806.363** |
| *Average human cost for injury* | *42.219* |
| n° of pedestrian injuries | 21.125 |
| n° of cyclist injuries | 13.452 |
| **Total costs of accidents** | **359.923.332** |
| *Average human cost for accident* | *10.986* |
| n° of pedestrian accidents | 20.717 |
| n° of cyclist accidents | 13.605 |
| **Total social cost** | **3.104.137.155** |

The amount of the total social costs due to pedestrians and cyclists crashes reported in the Table 1.1 represent over the 16% of the total social costs for accident events, estimated in 2017 at around 19.3 billion euros (1.1% of GDP).

In addition, it should be also noted that the walking and the cycling transport mode covers only the 18% of the total demand per transport mode and that, on average, the percentage of passenger-km of the pedestrians/cyclists is only 2.7% [8], which is much lower than that of the motorized vehicles (79.9%).
Therefore, statistical and economic data show that the impact of the VRUs is very considerable both from the safety point of view and from the economic implications that VRUs related crashes have on the society and, thus, effective countermeasures have to be developed to improve the safety of this particular road user category.

This is also in line with the specific objectives of the Member States of the European Union [e.g. 9, 10, 11, 12, 13] and of the Italian Road Safety National Plan (PNSS), which identifies for pedestrians and cyclists a reduction of fatalities up to the 60% until 2020 [14]. However, data on hand, the trend of the road deaths of the last recent years shows that for pedestrian and cyclists the situation is still remaining critical, compared to the important reduction of fatal accidents for the vehicle occupants. Furthermore, the actual decreasing trend compared with the objectives of the national plan is less pronounced than that planned (Figure 1.4); this means that much efforts are needed to achieve the expected objectives. The copious undertaken efforts to increase the safety performances of the vehicles and their occupants, should be also adopted to improve the safety of the particular road category users represented by pedestrian and cyclists, which is the one, instead, exposed to the higher risk levels year after year. This is a key-point that each government should effectively put at the center of its programs. Moreover, as showed above, the decreasing trend of road fatalities has also important social and economic feedback.

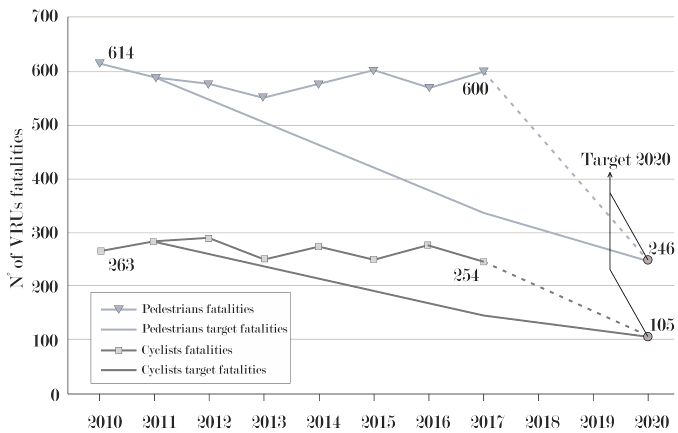



Figure 1.4: VRUs fatalities VS objectives of PNSS.

Moreover, the efforts to find effective solutions aimed at improve the VRUs safety should be strictly oriented to the concept that the road environment is a complex system in which the driver/VRUs, the road infrastructure and the vehicle interact each other. According to the Haddon matrix [15], which provides a compelling framework for identifying the causes of injury problems and for detecting several countermeasures to address those problems, these three distinct elements are the contributing factors to the crash events; in addition, according to the Highway Safety Manual (HSM) of the American Association of State Highway and Transportation Officials (AASHTO) the 93% of the road crashes are a combination of human factors and other factors [16] (Figure 1.5).

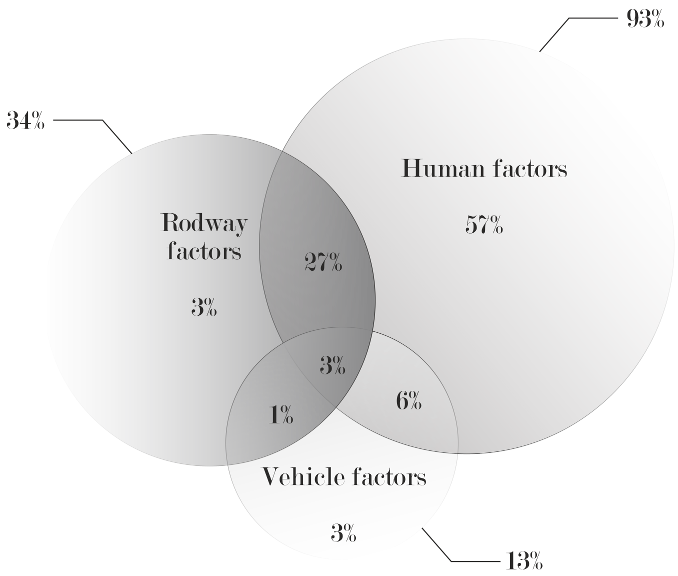



Figure 1.5: Contributing factors related to road crashes.

It is clear that ensure high safety levels for the VRUs means that interventions in each distinct factor is a complementary treatment that together work to contribute to make walking and cycling safer, which also means that in case of accident the released energy during the impact must remain below to a certain threshold that avoid death or serious injury. This is a key point that brings out that the speed adopted by the driver is a critical element that play a significant role in the accident consequences and to ensure adequate speed, the safety measures should work for the three contributing factors in order to:

- induce proper driving behavior (human factor)
- improve the VRUs facilities (roadway factor)
- introduce automatic systems in the vehicle to help the driver in critical situations (vehicle factor)

With these points in mind, it is also important understand where the accident events occur and where the responsibility is to effectively intervene. In general, most of the VRUs related accidents occur in urban areas where the number of interaction with the vehicle are higher; in particular, both for the pedestrians and the cyclists more than the 50% of accidents occur at crosswalk or bicycle crossroads [6]. However, despite in literature most of research is focused on the urban environment, also the situation in the rural environment it should be considered, for which the fatality rates (number of VRUs fatalities every 100 crashes involving VRUs) are six-eight times higher than the rates for urban roads [6]. In the rural roads, in fact, the interaction between drivers and VRUs, in addition to the interaction on the crossing facilities, is realized also with an overtaking maneuver that mostly occurs far from the intersections, where the driving speed are considerably higher than than adopted by the VRUs. The same statistics show also that every year about 6.500 accidents are cause by drivers that do not give way and that about 8.000 accidents are caused by incorrect behavior of the pedestrian that crosses the road outside of the zebra crossing.

Thus, according with safety condition of the pedestrians and cyclists, interaction between vehicles and VRUs are critical situations in which the driver has to be influenced in order to adapt his behavior avoiding the occurrence of accident events not only in the urban environment where the probability of crash is higher, but also in the rural context where the magnitude of the crash is higher due to higher speeds.

## 1.2 Speed and VRUs fatality risk

With aim of develop and assess the effectiveness of safety countermeasures, understand the mechanism of vehicle - VRUs crashes is fundamental. It is general agreed that accident events involving VRUs are often associated with a lack of driver compliance, that drivers fail to yield and that the pedestrian and cyclist safety mainly depends on driver speed while interacting with the VRUs, which surely affect the driver capability to yield or complete safe maneuver and at the same time increase the probability of a fatality accident [17, 18, 19, 20, 21, 22].
For example, Pasanen [17] 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 [19] 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 [21] 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. A recent study of Nie et. al [23] considered the accident data for pedestrians and cyclists and used a software to reconstruct the head dynamic response due to a crash. Results showed that the fatality risk at 50 Km/h is more than twice at 40 km/h and about 5 times higher than that at 30 km/h (Figure 1.6).

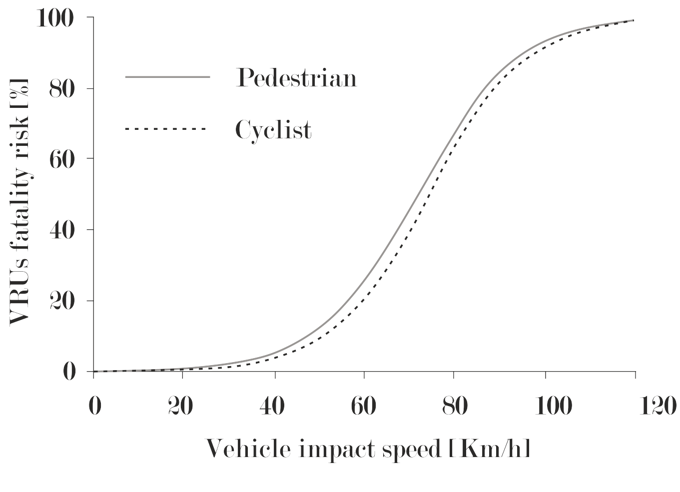



Figure 1.6: VRUs fatality risk curves.

Despite the values of the correlation of vehicle speed and VRU fatality risk reported above shows different values of the actual risk at a given speed [22] it is commonly accepted 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. Thus, the development of safety countermeasures should influence

the driver behavior in order to influence the correct propensity towards VRUs and at the same time improve their safety during the interaction situations.
The field of the safety countermeasures embraces the aspects related to the human factor and the roadway factor; but, what about the vehicle factor? Well, in the last decade several technological vehicle facilities had been developed to help the driver in critical situations, which can allow to correct improper driving behavior, avoiding potential conflicts as well as timely intervene during unexpected situation such as incorrect behavior of the VRUs. These systems, called Advanced Driving Assistance Systems (ADASs), and specifically those related to pedestrian and cyclists, are aimed at detecting the VRU and then to alert the driver about the threat by means a warning message (audio, video, combination of audio and video, haptic) inducing the driver to modify his behavior in time to avoid a collision and increasing the yielding compliance towards the VRUs and the driving performances [24], over that decreasing the occurrence of collisions [25, 26].

## 1.3 Framework of the research

The present research focused to the improvement of the safety levels of the VRUs in the interaction situations with the motorized vehicles, whose consequences are always against the pedestrians and cyclists due to big difference in speed and mass. The research started with the analysis of how the driver and the VRUs interaction occurs, highlighting the critical aspects and complexity of these particular kind of interaction. With a robust theoretical background on how drivers behave when interact with VRUs, the following step was the identification of possible safety countermeasures and safety warning systems that can produce significant improvements in terms of yielding rates and in general in safer maneuver during the interaction phases.

Thus, the research objectives began with an in-depth analysis of the interaction between drivers and pedestrian/cyclist that occurs at crossroads or along bicycle paths, to cover caveats and limitations in the body of knowledge concerning these topics. Furthermore, an assessment of the individuated safety countermeasures, characterized also by low costs and easy installation, was performed with the aim of detect the most effective pedestrian/cyclist facility layout and cross - section reorganization that can ensure low risk levels for VRUs. In addition to VRU related countermeasures, also advanced warning systems were studied with the objective of verify their effectiveness in the improvement of the driving performances also under unexpected situations. Further details about the research objectives are provided in the Section 4.2.

Then, an objective assessment of the individuated safety measures and warning systems was built by the design of specific experimentations focused at analyzing and comparing the driving behavior during several interaction conditions with the VRUs and the presence or absence of safety countermeasures and warning systems. This goal was possible by the use of the driving simulator of the Roma TRE University, which allowed, over the complete safety conditions for the participants and the absence of confounding factors, to obtain an important amount of data related to spacial and dynamic variables useful to describe and analyze the driving behavior. These great number of data were then organized and analyzed through robust statistical analyses to understand the driving behavior towards the VRUs. The results allowed to identify the most appropriate and affective solutions to preserve and improve the VRUs safety conditions during the interaction with the motorized vehicles. Finally, the conclusions were exposed as well as further research opportunities.

# Chapter 2

# Driver - VRUs interaction: framework background

In literature, several studies focused on the interaction between driver and pedestrian/cyclist at crossroads. The general theoretical framework of the present research is based on the “Threat Avoidance Model“ developed by Fuller in 1984 [27]. The threat-avoidance model of the driver’s behavior is based on the driver experience of the subjective risk, which motivates the driver to escape or avoid those situations that could lead to aversive events. The model, in fact, proposes that within the context of the motivation for a particular journey (usually a specific destination within a specific period of time), the driver is focused on the avoidance of averse or potentially averse stimuli in the road-traffic environment [28]. The model suggests 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. According to the model, the complex integration of the driver capability, the driving speed behavior and the road environment conditions can lead to a “discriminative stimulus“ for a potential threat or to a “no discriminative stimulus“. Each one of these situations if function of the driver expectation of the “threat“ or “no threat“, respectively (Figure 2.1).

In a vehicle-VRUs interaction at a crossroad, the presence of a pedestrian or a cyclist represent the discriminative stimulus. Such an adverse stimulus can cause: a) an “anticipatory avoidance response” or b) a “non-avoidance response”. The choice made by the driver is partly explained by the driver’s subjective probability of expected threat and partly from the punishment or rewards that follow his choice. In the first case, the driver considers the presence of the VRU to be a “threat”, and then, he slows down; in this kind of interaction, there is good probability that the pedestrian or the cyclist can pass before the driver. However, the interaction with the VRU will produce a “punishment” for the driver with a loss of time. In the second case, the driver maintains the same speed because he considers the VRU presence to be a “threat” but chooses a “non– avoidance response”, signaling to the pedestrian or to the cyclist 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.

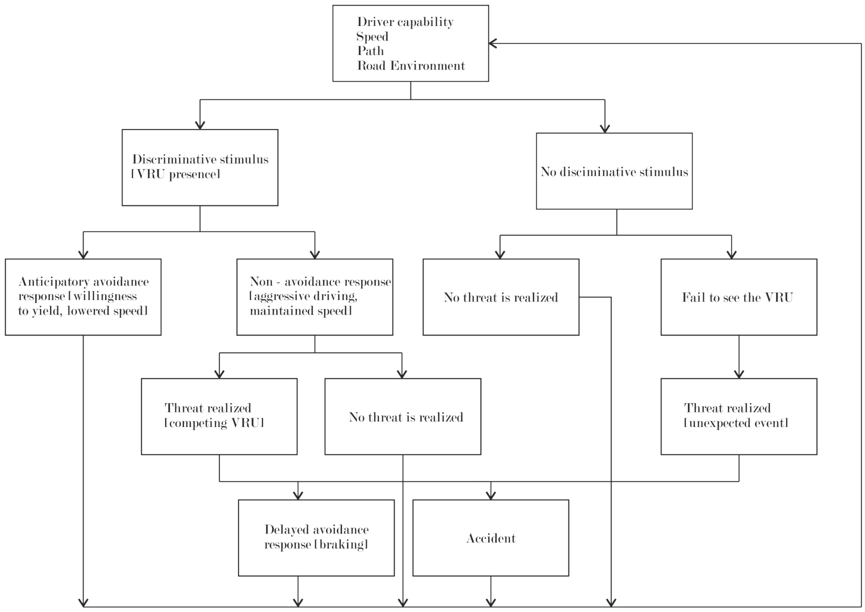



Figure 2.1: Flowchart of the theoretical driver behavioral model.

Finally, this model suggests that the driver can experience a "no discriminative stimulus" (he does not see the VRU), and therefore, he does not expect a "threat". In this case, two possible conditions could also occur: a) the interaction with the VRU does not cause a risk (the pedestrian or cyclist does not start to cross) or b) a delayed avoidance response is required to avoid an accident.
A similar approach was proposed by Silvano et al.[29, 30], which assumed a hierarchical discrete model to explore the decision making process to explain the drivers' yielding behavior in vehicle – cyclist interactions. The assumption, which can be similar and also extended to the driver - pedestrian interaction, is that in order to avoid the collision due to the conflicting trajectories (driver and cyclist are arriving at the conflict zone, which is the common crossing area where collision occurs if both of them maintain their current trajectories), a "negotiation" begins upstream the conflict zone, where the driver can decide if the situation could produce a potential conflict or not (Figure 2.2).

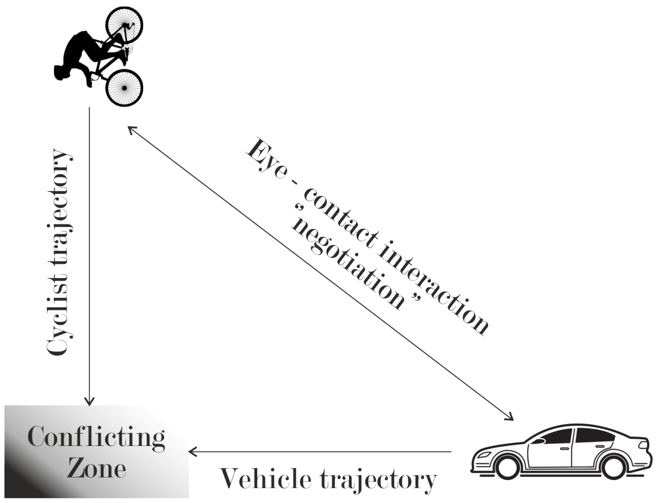



Figure 2.2: Vehicle and cyclist approaching the conflict zone.

In this situation, the driver has the responsibility to yield; however, if the driver perceives the potential conflict with the cyclist he can further decide, at a certain point, if yield or not. On overall, the decision process of the driver supposes two levels: a) a conflict event is perceived with potential collision or b) a yield event decision is made given that the driver perceives the potential conflict. Several factors can contribute to the yielding process, as the actual possibility to stop the vehicle to yield, the actual possibility to detect the cyclist, the attitudes of the driver and also of the VRU.

Thus, a significant role is played by the vehicle dynamic parameters because these variables influence the arrival time of the vehicle at the crossroad and, consequently, the decision to cross or wait made by the pedestrian or the cyclist and the actual possibility of the driver to yield or stop the vehicle. Such a time, called Time-To-Zebra arrive ($\mathrm{TTZ}_{\mathrm{arr}}$) was introduced by Varhelyi [18] and was used in the literature to discuss the vehicle-pedestrian interaction [18, 31, 32] and the vehicle-cyclist interaction at crossroads [33, 34]. The variable $\mathrm{TTZ}_{\mathrm{arr}}$ is defined as the time left for the vehicle to arrive at the crossroad at the moment the pedestrian or the cyclist arrives at the curb and is obtained by calculating the distance of the vehicle from the crosswalk divided by the vehicle's speed when the VRU arrives at the curb (2):

$$TTZ_{arr} = \frac{L_i}{V_i} \tag{2}$$

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 $\mathrm{TTZ}_{\mathrm{arr}}$ values with the mean speed profile related to pedestrian absence. The hypothesis is that drivers' speed behavior while approaching the pedestrian crossing depends on the arrival of the pedestrian at the curb compared to the vehicle time of arrival to the pedestrian crossing when the driver perceives the presence of the pedestrian. 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 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 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 and the mean speed profiles are 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.

The identification of different patterns of the driving behavior while approaching pedestrian crossing were also found for the driver - cyclist interaction, in which the aggressiveness of driver was found for the low values of $TTZ_{arr}$, while more cautious driving behavior were found for high values of $TTZ_{arr}$[33, 32].

Finally, in addition to the interaction at crossroads, also the overtaking maneuver represents a critical moment of interaction especially in those road environments in which drivers travel at high speeds, such as in the rural roads. A scientific definition of "overtaking" defines it as the maneuver of a vehicle passing a leading vehicle which is traveling at a lower speed, using another lane [35]. Concerning the overtaking maneuver between a vehicle and a cyclist, Schindler and Bast [36] proposed four different phases, which where also considered by Dozza et al. [37] to analyze the comfort zones of drivers during the overtaking maneuver of a cyclist. Moreover, several studies [38, 39, 40, 41] proposed from three to five phases in which the overtaking maneuver could be divided. More recent studies [36, 37] take in consideration four phases describing the vehicle overtaking maneuver of a cyclist.
The first phase is defined "approaching phase", in which the vehicle approaches the cyclist from behind (Figure 2.3)

This phase can be of interest if the maneuver is an accelerative overtaking maneuver, while is not clearly distinguishable for a flying overtaking maneuver, in which the driver has already the desired speed and there is not the necessity to adjust the speed [41]. The second phase is defined as "Pull out phase" and begins when the driver starts to overtake the cyclist (Figure 2.4).

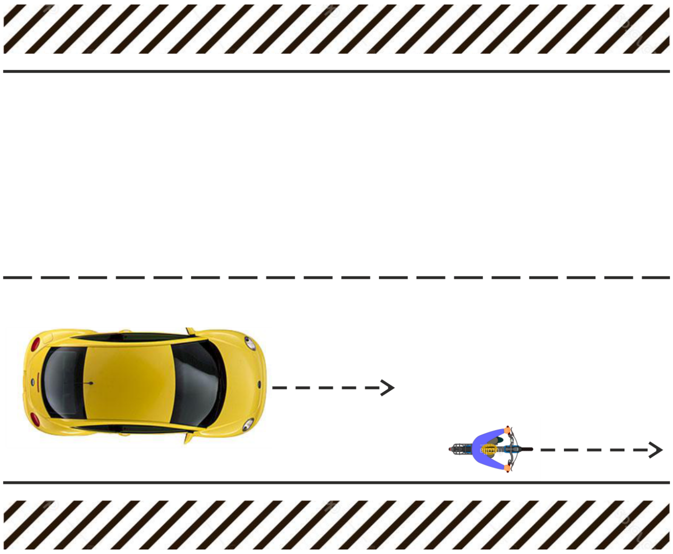


Figure 2.3: Approaching phase of the overtaking maneuver.

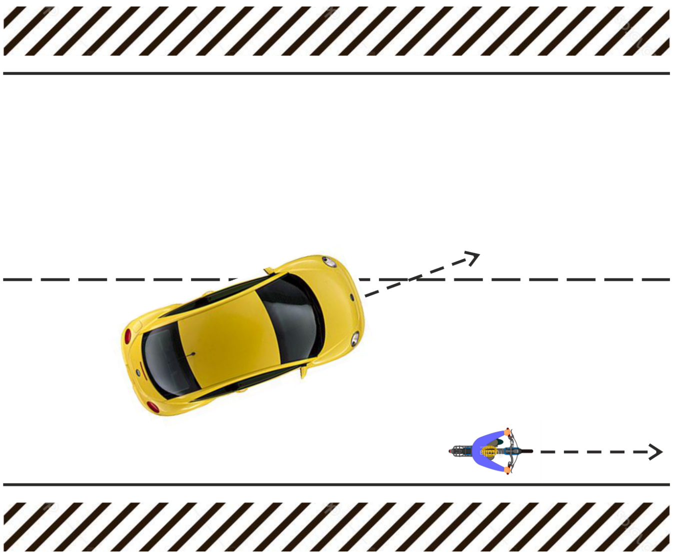


Figure 2.4: Pull out phase of the overtaking maneuver.

In this phase the vehicle leaves its position from the driving lane to pass the bicycle, increasing the lateral distance from the curb or the shoulder if present. The increasing of the distance from the curb or the shoulder is realized by the steering actions acted by the driver; for accelerative overtaking maneuvers the driver acts also an acceleration of the vehicle.
The third phase is defined as the "Passing phase" and is the moment of the overtaking maneuver in which the driver is next to the cyclist (Figure 2.5).

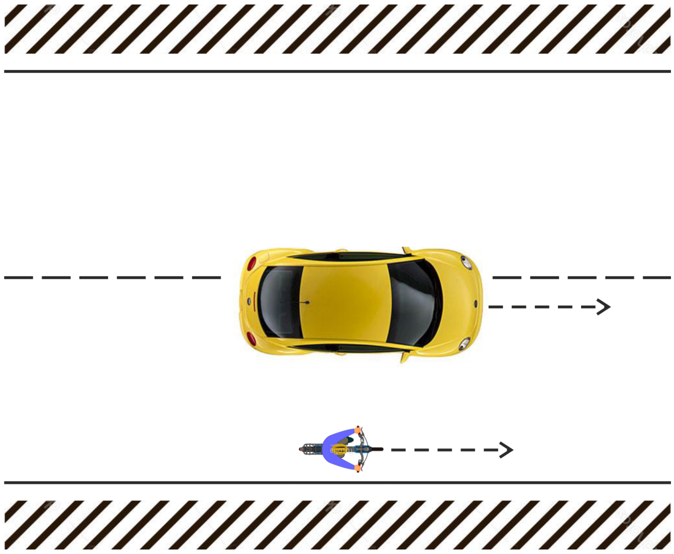


Figure 2.5: Passing phase of the overtaking maneuver.

This phase is characterized by the speed of the vehicle and its lateral distance from the cyclist. These two variables are important to define the safety of the overtaking maneuver due also to their direct correlation with the aerodynamic force at which the cyclist is exposed. The lateral distance maintained by the driver can depends on driver attitude and also on the configuration of the cross - section, as well as on oncoming vehicles.

Finally, the overtaking maneuver is completed with the "Returning phase" (Figure 2.6).

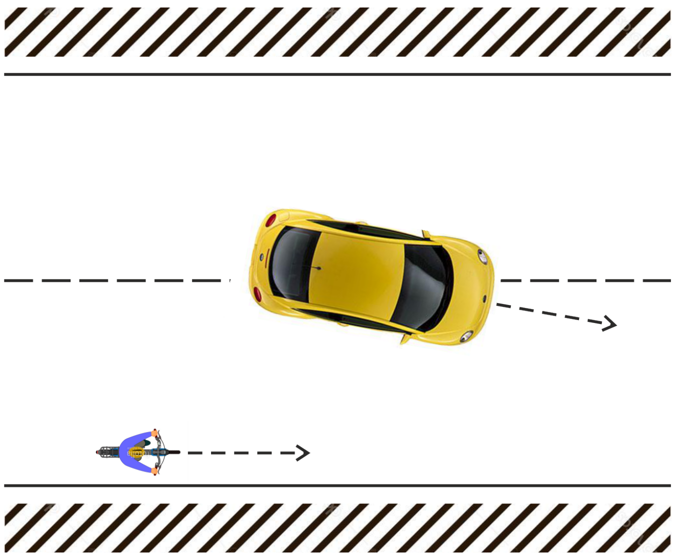


Figure 2.6: Returning phase of the overtaking maneuver.

The fourth phase begins when the back of the vehicle is over the passing zone and it's the phase in which the driver restores the speed and the lateral distance from the curb or the shoulder that were kept before the beginning of the overtaking maneuver.

It is clear that the interaction between drivers and the pedestrian or cyclist, which can occur in correspondence to crossroads or along the road, can be a dangerous situations also complex to analyze. The complexity resides in the fact that both parties involved (i.e. the driver and the VRUs) make choices and act on the basis of a series of dynamic and temporal variables. When the interaction occurs at the crossroad, the pedestrian or the cyclist is waiting for the best time gap to proceed with the crossing while the driver must similarly understand the intentions of the VRU to assess whether there is the sufficient time to cross the critical point before the pedestrian or cyclist or whether he/she must yield, letting the pedestrian or cyclist crossing first. In the rural road the interaction occurs mostly by an overtaking maneuver and the severity of crash in case of accident is much higher than in the urban context. The dynamics of the overtaking maneuver phases affect the safety of the VRU due to the forces that can be directly linked to the behavior of the driver, in the measure of the speed and the lateral distance from the cyclist (the overtake interaction can be exclusively considered only for the cyclist).

The subjective risk of the cyclist is affected by these dynamic variables whose combination determine the level of the aerodynamic forces at which the cyclist will be subjected to and that will affect the level of safety during the overtaking. Moreover, the complexity of the analysis concerning the overtaking phases increases when different geometric elements are taking into account and that can add additional effects. The infrastructure, in fact, should be designed to reduce the possibility of the driver to underestimate the distances to perform the passing maneuver and avoid as much as possible the invasion of the opposite lane.

Considering all the aspects related to the complex interaction which occurs between driver and VRUs exposed above, whose dangerousness is also supported by the accident statistics reported in the previous chapter, in the next section safety countermeasures will be presented as well as safety warning systems, aimed at improve the safety levels of the VRUs.

# Chapter 3

# VRU oriented safety countermeasures and Advanced Driving Assistance Systems: State of Art

## 3.1 Safety measures for pedestrian facilities

The increasing of the pedestrian safety during the interaction with the driver can be achieved by improving the pedestrian facilities. Several studies investigated the effects on drivers' behavior of different countermeasures that are aimed at modifying the drivers' speed behavior while approaching unsignalized pedestrian crossings [e.g. 42, 43, 44, 45]. The most often-used safety countermeasures are the following:

- advanced yield lines to improve drivers compliance;
- removal of parking to clear the line of sight to approaching vehicles;
- installation of curb extensions to improve visibility of pedestrians;
- pedestrian-activated flashing beacons to warn motorists about pedestrian presence;
- motorist signs to indicate that pedestrians have the 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 the present research.
Curb extensions are an enlargement of the edge of the sidewalk in correspondence of the crosswalk. Curb extensions are commonly made along roads equipped with parking places on the sides of the lanes. The curb extends the curb pavement up to the line that separates the lane from parking stalls that are made on the side of the roadway (Figure 3.1).

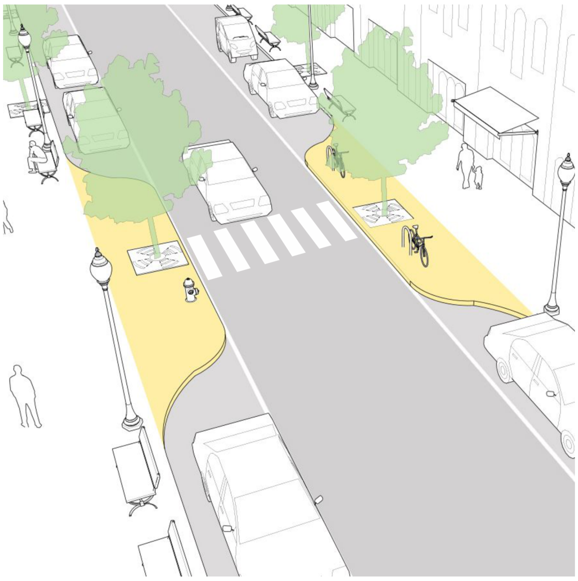


Figure 3.1: Curb extensions - *source: National Association of City Transportation Officials (NACTO).*

The reduction of the crossing distance for the pedestrian, the ability for the pedestrian and the driver to clearly see each other and reducing the time needed for the pedestrian to cross the road. are the main characteristics of this countermeasure that can improve the pedestrian safety. Moreover, the narrowing of the driving lane is expected to reduce the speed of the vehicle during the approaching at the crosswalk. Several experiences show their effectiveness in terms of operating speed reduction (up to 40%) of the vehicle [46, 47, 48] and increments in the number of drivers that yield to the pedestrian [49].

Parking restrictions are parking rules that are designed to not allow parking upstream of the zebra crossing, which is related to the improvement of the pedestrian visibility (Figure 3.2). 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 [50]. Edquist [51] found that the effect of the presence of on-street parking was 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 (Figure 3.3). A “Yield Here to Pedestrian” vertical sign is also placed at the location of the markings.

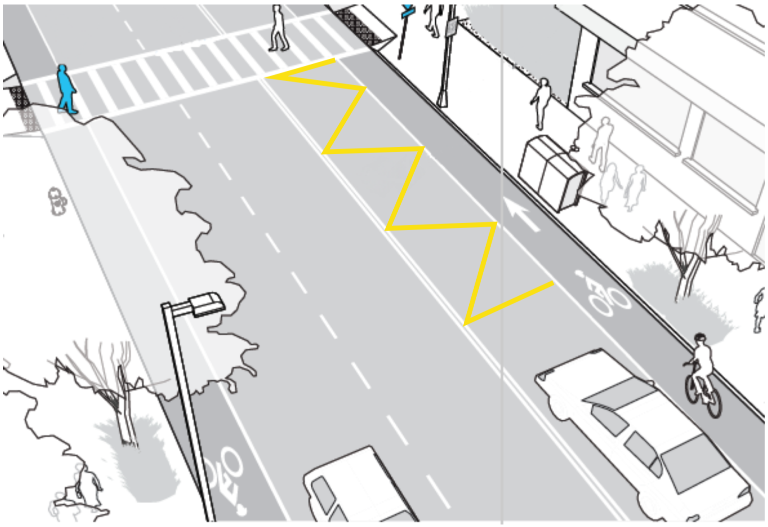


Figure 3.2: Parking restrictions upstream the zebra crossing.

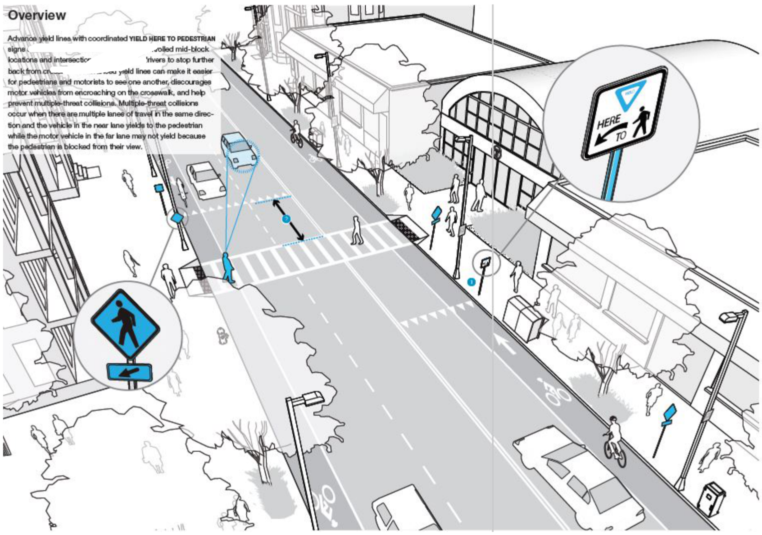



Figure 3.3: Advanced Yield Markings - *source: Boston Complete Street (BCS) - Design Guidelines.*

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 [52, 53, 54].

## 3.2 Safety measures for cyclist facilities

The interaction between driver and cyclist can occur at bicycle crossing or along urban or rural road through an overtaking maneuver. The bicycle crossroads are a crucial point along the bicycle paths and because of the importance of the speed in the driver – cyclist interaction, the countermeasures at bicycle crossroads have to induce the driver to slow down and advance the detection of the cyclist. For example, a study of Wood et al. [55] reported that both cyclist and drivers indicate the visibility as the main factor to which attribute the occurrence of a crashes involving cyclist. Moreover, Kim et al. [56] highlighted that also the speed is a key factor that affects the consequences of a vehicle – bicycle accident which are worst with the increasing of the speed. Another study [57] pointed out that higher vehicles' speed, higher traffic volumes, and the presence of heavy vehicles are detrimental to cyclist safety. Concerning the driver behavior, several studies [e.g. 58, 20] show that the drivers' yielding decision process is mainly affected by the vehicle speed while approaching the intersection. To improve the cyclist safety at bicycle crossroad, the perceptual countermeasures should induce proper driving behavior to avoid the occurrence of dangerous interactions between vehicle and cyclist. Among several treatments at bicycle crossroads, two perceptual countermeasures were analyzed:

- colored paved marking
- raised island

The colored paved marking is a textured surface and is a common traffic-calming treatments in the Europe and are often used in conjunction other traffic-calming measures to emphasize the presence of traffic-calming features. The surface color treatment is implemented on the full width of roadway and can be done with pavement markings or textured pavement (Figure 3.4).

Figure 3.4: Red painting pavement at bicycle crossroad.

The colored paved marking is a red painting of the bicycle crossroad with the principle of highlight the presence of the crossroads and focus his attention on it,

contributing at the speed reduction[59]. In a before - after field study, Hunter [60] found that the color treatment in the conflict areas between vehicle and cyclist significantly improved the driving behavior in the yield compliance, as well as more bicyclist crossed the conflict area using the designated or marked path after the installation of colored markings.
The second is a physical facility in the middle of the road based on the principle of narrowing the lane and induce the driver to adapt his speed [61] (Figure 3.5).

Figure 3.5: Example of raised island at bicycle crossroad.

The Federal Highway Administration (FHWA) reports that lane narrowing induced by the center island was effective on driver speed and on the reduction of accidents [62].

Considering the overtaking maneuver, the results of several studies in literature highlight the importance of the bicycle lane separation and width or the presence of a paved shoulder for the safety conditions of the driver - cyclist interaction and the cyclists' risk perception. An example of the reorganization of the cross - section configuration which includes the bicycle lane separated through a yellow marking is showed in the Figure 3.6.

Figure 3.6: Yellow marking for bicycle lane separation.

Parkin and Meyers [63] analyzed the effect of the bicycle lane on the passing distance the vehicles on different roads with same overall road width (about 9.50m), different posted speed limits (48km/h, 64km/h and 80km/h) and with and without cycle lane (the width was 1.45 m on roads with speed limit 64km/h and 80km/h, and 1.30 m on roads with speed limit 48km/h). Significantly wider lateral clearances were adopted by drivers in the condition without a 1.45m cycle lane, with posted speed limits of 64km/h and 80km/h. This result was not obtained for the road with a posted speed limit of 48km/h and a 1.3 m cycle lane. The authors concluded that cycle lanes do not appear to provide greater space for cyclists in all conditions. Savolainen et al. [64] carried out field studies to assess the lateral placement of motor vehicles during the overtake of a cyclists in two segments (with and without centerline rumble strips) of a high-speed (55-mph speed limit) two - lane rural road (lane width 11ft and shoulder width 4ft). The lateral position of the bicyclists (within the center of the shoulder, on the left edge of the shoulder, and on the right edge of the travel lane) affected the lateral position of the motor vehicles. Drivers were more likely to contact or cross the centerline if the bicyclists were closer to the driving lane. Kay et al. [65] analyzed the effect of the "Share the Road" sign on driver behavior during the overtaking maneuver on two segments of a high-speed rural two-lane highway (55-mph speed limit; lane width 11 ft and shoulder width 4 ft). The study highlighted that the sign contributed to shift away motor vehicles from the right edge of the lane and to reduce (on average about 4 km/h) the speed of the vehicles during the overtaking maneuver. However, no significant effects were found on the mean lateral distance between the bicyclists and passing motorists. Chapman and Noyce [66, 67] analyzed the influence of several features of rural roads on drivers' behavior during the overtaking of cyclists. They found that a significant factor influencing positively the lateral clearance distance from the bicycle was the presence and the width of the shoulder. Llorca et al. [68] analyzed the speed and the lateral clearance left by motor vehicles during the passing maneuver of a cyclist along seven rural roads segments in Spain with the aim of evaluate how these variables affect the risk perception of the cyclist. They found that lateral clearance was not the only factor that influenced rider's risk perception. On the contrary, a combined factor of lateral clearance, vehicle type and vehicle speed had a more significant correlation with it. Afterwards, Garcia et al. [69] analyzed the overtaking maneuver (a vehicle that overtakes a cyclist) on two – lane rural highways. Results showed that the passing lateral clearance between vehicle and cyclist increased with road width. Moreover, it was higher on left curve and lower on right curve, compared with the tangent elements. It was also found that, although the interaction with the cyclist lead to a speed reduction trend, in some road segments the speed was comparable to that in the condition of free-flow on the same locations. Similar results were obtained by Bella and Silvestri [70] which found that, for the same roadway width, wider bicycle lanes ensure less influence of the cyclist on drivers' overtaking and higher lateral clearance values, while on the less demanding geometric elements the drivers assume similar speed both in condition of cyclist presence and absence. Dozza et al. [37] collected data about the interaction driver-cyclist on rural roads in Sweden. The authors identified four overtaking phases and found that the presence of an oncoming vehicle was the factor that most influenced the maneuver, whereas neither vehicle speed, lane width, shoulder width nor posted speed limit significantly affected the overtaking dynamics. Although results of urban safety cannot be transferred to overtaking maneuvers of motor vehicles and bicycles on rural roads [68], useful trends can be obtained from some studies on the interaction between driver and cyclist in urban areas. Love et al. [71] measured the distance between overtaking motor vehicles and cyclists in order to assess compliance with the three-foot law (that requires motor vehicles to pass cyclists with a clearance of greater than three feet) and to examine risk factors associated with close vehicle passes. They found that vehicle passes three feet or less were common in standard lanes and lanes with a shared lane marking but not in bicycle lane streets (all the bicycle lanes were 5 ft wide). Similar results were obtained by Mehta et al. [72] and Chuang et al. [40], which also revealed that longitudinal markings (for lane separation or slow traffic separation) can encourage greater passing distances when motorized vehicles pass bicyclists.

## 3.3 Advanced Warning Systems for Pedestrian Detection

Alerting the driver in critical and unexpected situations to avoid collisions with the vulnerable road users can provide great improvements in their safety. The aim of the Advanced Driver Assistance Systems (ADAS) focused on the pedestrian detection (called also Pedestrian Protection Systems - PPSs) is to detect the pedestrian as soon as possible and then to intervene, minimizing the consequences when unavoidable [24]. The type of the intervention depends on the kind of ADAS: Collision Warning Systems (CWS) simply alert the driver about the threat by means a warning message, while Autonomous Emergency Braking (AEB) automatically stop the vehicle [73, 74]. With regard to the CWS (that will focus this study), it is very important the choice of the type and timing of the warning message: in fact, this two issues largely influence the driver's acceptance of the ADAS. A CWS can provide three kinds of message: (1) visual message, (2) auditive message and (3) haptic message. The visual warning can be provided via Head Up Display (HUD) and seems to be the most effective one (an example is reported in Figure 3.7

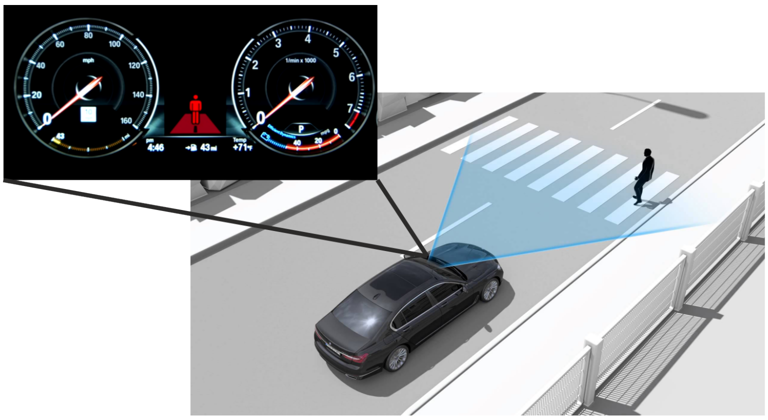


Figure 3.7: Example of visual warning for pedestrian detection.

Past studies [75, 76, 77] have shown that the drivers prefer the visual messages over acoustic signals, which should be used only for urgent warnings [78]. However, it is generally accepted that adding a non-intrusive auditive warning to a visual message could improve the efficacy of ADAS, since the evidence of a visual signal largely depends on the driver's gaze direction [78]. For the auditive warning, in fact, positive effects on driver performance in response to an unexpected situation at intersection were found [79, 80].

In addition, a visual-auditive message and an only visual one have the same effects in terms of reaction time [78, 81]. In his study, Maag et al. [78] find out that the majority of drivers even prefer visual warnings over haptic ones (that in this case consisted in an additional steering wheel angle control), which, however, have a great potential. Moreover, the combination of different kind of warning signals (e.g. audio and visual) seems to be the most efficient in terms of driving safety. Lundkvist et al. [82] carried out a simulator study in which was evident that visual warning combined with other modalities provided shortest response times. In another work, Fricke et al. [83] found that the multimodal warning (visual and auditory) led to shorter reaction times and fewer collisions compared to warning signal that gave no additional information (e.g. simple tone). Another relevant issue is the choice of the most appropriate timing of advisory. In general, drivers prefer to receive the warning message earlier rather than later. Thus, the message should be delivered as soon as possible, but the earlier the message is delivered, the more it is probably to give a wrong warning. It is important to find a tradeoff between the timing and the accuracy of warning, which must be delivered in time to allow the driver to react safely, but no too early in order to ensure the accuracy of the detection [84, 78]. The activation of an assistance system is based on a preset threshold; a too much high threshold can lead to less false positives and more false negatives; on the contrary, for a low threshold, there will be more false positives and less false negatives [84]. Moreover, an advanced warning gives to the driver more time to react, while too many false alarms (i.e. low threshold) would gradually reduce the drivers' acceptance of the warning system. Thus, the delivering time of the alarm is an important factor that can affect the effectiveness of the driving assistance system. Several studies focused on the choice of the better delivery time of warnings, for urban areas. With regard to the red-light-running events at intersections and to an audio warning, Yan et al. [85] reported out that the range between 4.0 – 4.5 s was the most appropriate choice for warning timing. Maag et al. [78] developed a driving simulator experiment in which pedestrians represented a possible threat: for urban areas, the study showed that the participants found a delivery time of a visual warning message of 3.5 s as appropriate.

# Chapter 4

# State of the art: gaps and limitations

## 4.1 Caveats about the body of knowledge

To avoid risky situations during the interaction phases between driver and VRUs, several safety measures at pedestrian crossing and bicycle crossroad, as well as advanced driving assistance systems for pedestrian detection, were developed during the last years and were described in the previous chapter. The reported results provided by literature showed positive results about changes in the driving behavior due to the reorganization of the pedestrian/cyclist crossroads and the implementation in the vehicle of warning systems aimed at improving the driving performances in critical situations. However, such results do not allow a comparative analysis of the effectiveness of the safety measures for the following reasons:

a) the improvement of safety identified for each countermeasure is provided by specific parameters (i.e., the operating speed, number of drivers that yield, distance at which the driver yields), which are different among each study, making infeasible an objective comparison about their effectiveness;

b) the results are mainly obtained from field studies with specific experimental conditions of vehicle-VRU interactions and geometrical configurations of the sites, which are different for each study, and therefore, the findings are not comparable.

Moreover, considering the driver - pedestrian interaction, the main research area involves pedestrian behavior in urban areas and focuses especially in their behavior during crossing [86, 87], the speed at which the pedestrians cross the road [88, 89] and the gap acceptance [90, 91, 92]. Interactions between pedestrians and vehicles have received notably less attention [93]. In addition, almost all of the literature research is conducted for urban areas, because of the higher frequency of the interaction between vehicle and pedestrian compared to the rural environments, as well as the assessment of warning systems for pedestrian detection, which is focused in the urban context [24, 94, 95], while no studies were focused on the effect of pedestrian collision warning systems in road environments different from the urban one, in which the crashes between vehicle and pedestrians are more serious. However, the problem of the fatal crashes involving pedestrians affects the rural areas too, in which the probability of fatality during the occurrence of an accident is much higher than in the urban areas due to the higher operating speed (see 1.2).

Furthermore, considering also the possible wrong behavior of the pedestrians, most of literature focused on the behavior of jaywalkers from the pedestrians point of view [96, 97], while the behavior and reaction of the drivers in front of illegal crossings was investigated only by Zheng et al. [98]. However, this study focused on the behavior of jaywalkers, in terms of gap acceptance and the speed adopted, and the corresponding reactions of the driver, in terms of yielding, to model the interactions between vehicle and pedestrian outside of crosswalks in a micro simulation environment. In light of this evidence, the interaction between driver and pedestrian outside of the crosswalk had received no attention, despite this kind of interaction is considerably risky for pedestrian due to the lower distance of the yielding decision point to the crossing point and the lower yielding rates [98]. In this particular context, on board detection systems can have an important impact on pedestrian safety also in situations the pedestrian crosses far from the crosswalk.

Finally, considering the interaction between driver and cyclist during the overtaking maneuver, the studies concerning this topic (with some exception [65, 69]) involve only the lateral clearance (i.e. the distance from the outside of the vehicle and the bicyclist), ignoring the speed analysis of the overtaking vehicle. It should be noted that some authors [99] highlighted, among the purposes of further studies on the driver – cyclist interaction, the analysis of the passing speed. That variable, determining important dynamic effects on the cyclist, plays, together with the space left by motorist during the overtake of a cyclist, a crucial role on the collision risk [100] and on the bicyclists' perceived level-of-service on road segments [101]. In addition, lateral clearance and overtaking speed were analyzed to compare the cyclist subjective risk perception on tangents, right and left curves [68] and not to analyze the effects of the bicycle lane widths on the driver overtaking maneuver among geometric elements. Moreover, in the study of Garcia et al. [69] the effect on lateral clearance and overtaking speed due to the shoulder width was analyzed among sites characterized by different cross - section widths; thus, the obtained results can be affected by some biases due to the additional effects produced by the cross - section dimensions, which inevitably affect the driving behavior.

Furthermore, the reported studies were conducted on field and with the use of instrumented bicycles, which had sensors and cameras that allowed the measurement of the lateral distance of the overtaking vehicles. Such field studies have the advantage of allow the tracking of the driver behavior in the real driving conditions. However, these studies are generally characterized by the impossibility of conducting controlled experiments in terms of road geometry (cross-section, features of the alignment) cyclist dynamics (different speeds or different positions of the cyclist) and interferences of the traffic (in the same lane and in the opposing lane). In other words, such field studies are generally influenced by confounding factors that can alter the analysis of the effects on the driver – cyclist interaction due to specific factors. The results of these studies, thus, must be specifically referred to the particular experimental conditions and cannot be strictly compared to those obtained in other experimental conditions.

## 4.2 Filling the gaps

Considering the gaps in literature referred to the topics concerning the complex aspects of the interaction between driver and VRUs, the present research was aimed at:

a) analyzing the driver's speed behavior while approaching a crossroad under different conditions of vehicle-pedestrian and vehicle - cyclist interaction and in the presence of several countermeasures, to provide further insights to the body of knowledge that concerns the complex process of the interaction between the driver and the VRUs;

b) comparing several countermeasures and identifying the most effective treatment for zebra crossings and bicycle crossroad, comparing the effectiveness of each countermeasure with the same parameters that describe the driver's behavior and under fixed conditions of a vehicle-VRUs interaction;

c) analyzing the driver's behavior in approach to the zebra crossing under different road environment conditions (urban, sub-urban and rural) and different conditions of driver – pedestrian interaction, to evaluate to what extent driver's behavior is influenced by such factors;

d) evaluating the effectiveness of a driver assistance system for pedestrian detection on the driver's behavior approaching a zebra crossing under different road environment conditions and different conditions of driver – pedestrian interaction;

e) examining the driver's behavior in front of a pedestrian who crosses both on the zebra crossing and outside the zebra crossing in order to provide insightful behavioral aspects of the driver and, thus, contribute to extend the knowledge framework of this particular issue in the driver – pedestrian interaction;

f) evaluating the effectiveness of on-board pedestrian detection systems, in order to understand whether the audio or the visual warning is more effective;

g) assessing the effects of several two-lane rural road configurations (three cross-section configurations with and without bicycle lane with different widths) and of four geometric elements of the road (tangents with different lengths, right curve and left curve) on driver behavior (in terms of lateral position and speed) during the overtaking maneuver.

# Chapter 5

# Research Tools

## 5.1 The driving simulator apparatus

The main tool used to achieve the aims of the present research was the driving simulator of the research laboratory located in the simulation laboratory of the Department of Engineering in the University “Roma Tre”. The driving simulator has been previously validated for speed research in road work zones and two-lane rural roads [102, 103] and the lateral dislocation of the vehicle trajectory [104] and successfully used in past studies which demonstrated its reliability [e.g. 105, 106, 107, 108, 109, 110], for the study of the driver’s behavior.

It should be noted that the present research addresses issues concerning both the rural and the urban context; for the last, a specific validation of the driving simulator was not yet developed. However, for low speed values as those adopted in urban environments, the difference between the speed recorded during the simulation tests and the real word was not significant [103]. For this reason, it can be stated that there are sufficient guarantees about the reliability of the driving simulator for the analysis of the drivers’ behavior also in the urban environment.

Within the validation studies cited above, the braking system was also properly calibrated through the procedure of trial and error, with the aim of ensure the most real experience to the participants during the braking phases. For this procedure an iterative test was conducted to observe the driver reaction and recalibrate the braking module of the driving simulator until the output is reliable.

The driving simulator is installed in a real vehicle (Figure 5.1), which allows to provide real driving sensations during the experiments.

Figure 5.1: The driving simulator of the Department of Engineering in Roma TRE University.

The image of the experimental environments is projected on three screens (a central one and two lateral ones) which allows to cover a field of view equal to 135°. The audio apparatus of the driving simulator is installed into the vehicle, with the aim of simulating its real acoustic. The resolution of the visual scene is 1024 x 768 pixels with a refresh rate of 30–60 Hz. The recording interval time of the driving simulator is under 0.5 s, for which many dynamic parameters useful to describe the driver's behavior are recorded, such as:

- elapsed time;
- longitudinal acceleration;
- transversal acceleration;
- longitudinal speed;
- transversal speed;
- distance traveled;
- distance from the center of roadway;
- vehicle curvature;
- roadway curvature;
- vehicle angulation;
- steering weel angulation;
- braking pedal pressure;

- throttle pedal pressure;
- directional indicator and acoustic signals;
- current gear.

Compared to the field study, the use of the driving simulator allows also the possibility of full repeatability of the experiments, providing to the participants the same experimental conditions. Such a characteristic is fundamental to carry out objective analysis and is guaranteed by controlled boundary conditions that are specifically designed to study only the specific factor that affect the driving behavior, avoiding also confounding factors which could, instead, influence the results of the statistical analyses. In addition, in the simulated scenario can be reconstructed also dangerous situations to be submitted to the participants without being physically exposed to real risk. Risky driving tasks, in fact, can be easily studied in the driving simulator, while are almost impossible to reproduce in field studies due to the risk at which the participants could be exposed. Moreover, the data record in the driving simulator is easy and efficient and allows time saving to set complex instruments to be installed on real vehicles. Furthermore, in the specific experimental scenario, other vehicles, pedestrians and cyclists can be part of the simulated scenario to interact with the participants during the driving. Such "interfering" elements are set to repeat predefined actions in the same specific point, time or space related, of the alignment. With this characteristic is possible to submit to the driver the same interaction conditions and objectively comparing their reactions.

## 5.2 The framework of the simulation model

The simulation process is handled by a complete dynamic model of the vehicle which works in real time. Particularly, the model is based on the VDANL (Vehicle Dynamics Analysis, Non Linear) developed for the National HighwayTrafficSafety Administration (NHTSA).

The model VDANL/RT is substantially composed by three main simulation elements interconnected each other (Figure 5.2), and that are specifically referred to:

1 The dynamic model of the vehicle, which represent the central core of the simulation process, into the which the two following elements are incorporated;

2 The power generation of the wheels (Power/Drive Train), which, based on the accelerator pedal pressure condition and the actual gear, evaluates the momentum in correspondence of each vehicle wheel;

3 The model STIREMOD for the simulation of the pneumatic-pavement contact.

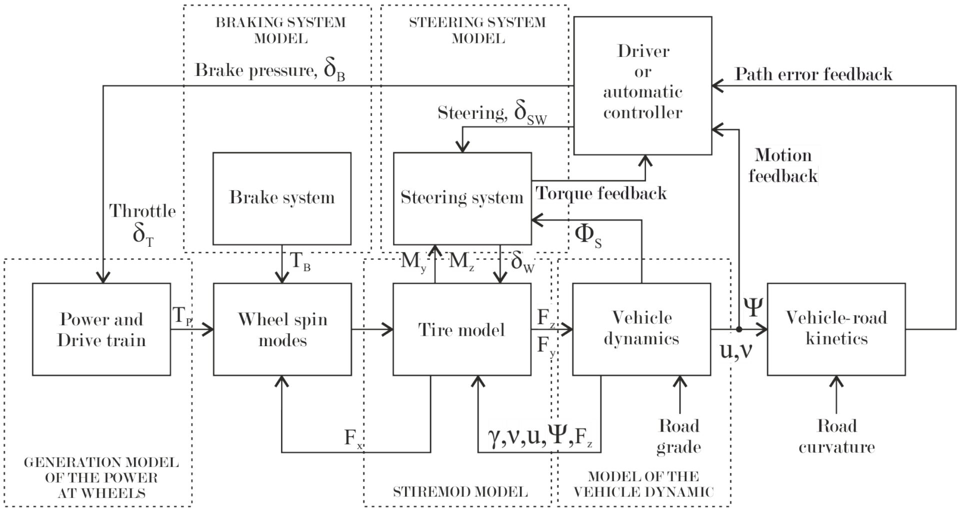



Figure 5.2: Software structure of the driving simulator.

In addition, there are other models which control the user interface, represented by the steering and braking system, which commute and quantify the size of the driving interventions on the braking and accelerator pedal (applied pressure) and on the steering wheel (degree and speed of steering)

The user control is realized by the action of four different interfaces, of which the gear can be inhibited by the execution of an automatic process. Particularly, the user can act on the following:

- pressure on the accelerator pedal ($\delta$T)
- pressure on the brake pedal ($\delta$B)
- degree of steering ($\delta$SW)
- gear ratio

In case of vehicle with automatic gear, the option on the last parameter decades.

The numeric scheme evaluates the longitudinal and transversal forces which are dependent by the steering degree and the grip coefficient considering the vertical loads distribution on the wheels, with a previous calibration of the suspension system by acting on the vehicle model.

The undertaken grip coefficients, equal to the ration between the vertical forces and the grip forces, were experimentally verified and showed a good fit.

The transversal sliding is determined by the lateral displacements of the vehicle and by the drift phenomenon. The actual force strictly depends on the instantaneous conditions of the rolling motion and of advancement, in addition to the vehicle pitch. Such solicitations are determined by the loads distribution of the vehicle, which instantly varies due to the effect of the mobility of some vehicle masses.

The degree of steering is dependent by the suspensions characteristics and the rolling degree. The effects of the vertical load are schematized on the basis of the pneumatic-pavement interaction, in terms of pick skid coefficient and stiffness of steering, considering that these parameters generally decrease with the increasing of the load.

The steering system of the simulator is realized by a steering wheel connected to an engine that returns a torque resistant momentum which depends by the moving conditions, the local road geometry (slopes, curvatures, etc...) and by the physical properties of the tyre-pavement contact (grip, tyre pressure, deformations, etc...). The simulation model of the braking system evaluates, on the basis of the pressure acted by the driver on the braking pedal, the braking momentums at the rotating axes of the wheels. The software allows to calibrate the parameters which are used to evaluate the resistant response that the engine, connected to the steering wheel, provides to the user.

In addition to the possibility of modulating the resistance provided by the rotation of the steering wheel during the driving, it is possible provide to the user also solicitations that make more real the simulation.

## 5.3 Self-reported questionnaire

For each of the experiment a specific questionnaire was developed and submitted to the participants. The first part of each questionnaire aimed at collecting data about age, gender and driving experience of each participants to characterize the driving sample. The second part was about the discomfort perceived during driving, to eliminate from the sample driving performed under anomalous conditions, which could cause biases in the interpretation results. 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. Then, for each specific experiment, the driver could provide the indication about the perceived effectiveness of the countermeasures or the driving assistance systems. First, the driver could indicate if the there was a real effect in the behavior adopted during the test; for those who perceived effectiveness, we asked also to indicate how the countermeasure or the driving assistance system affected their driving behavior (slowing down, more willingness to yield, more visibility, speed reduction, higher attention, etc.). Finally, participants were asked also to indicate suggestions and modifications which could further improve the effectiveness of countermeasures, as well as the driving assistance systems.

# Chapter 6

# Experiments on driver - pedestrian interaction

## 6.1 Safety measure at pedestrian crossing: effects on drivers' behavior

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.

To obtain the three different conditions of driver - pedestrian interaction the pedestrian was set to start to cross from the right side of the driver, defining three different triggering points with respect of the distance of the vehicle from the pedestrian crossing: 13.9 m, 34.7 m and 55.6 m. 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.

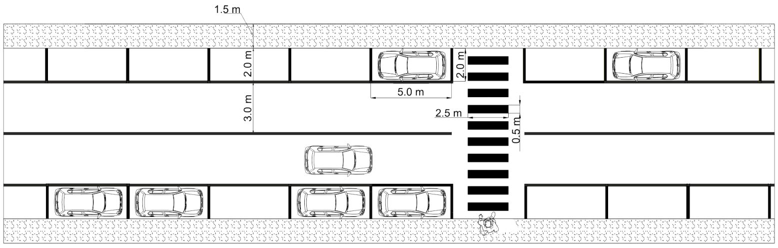
### 6.1.1 Experiment design

The road scenario submitted to participants was a two-lane urban road approximately 15 km long within which the vehicle test had its own driving lane without other vehicle in the same lane. In the other driving lane, a slight amount of traffic was distributed to induce the driver to not invade the other lane. The simulated vehicle was a standard medium-class car with automatic gears. Into the road alignment were placed the 16 zebra crossing/pedestrian combinations; the pedestrian crossing was the mid - block type, with parking lanes on the right-side and the left-side of the roadway. 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 [111], the crosswalk strips 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 (Figure 6.1a). 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 [112] (Figure 6.1b). Parking restrictions were designed following the Italian road design guidelines [113] and the Italian Highway Code [111]. 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 (Figure 6.1c). The reference for the advanced yield markings was the Manual on Uniform Traffic Control Devices [114]. 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 (Figure 6.1d). 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.

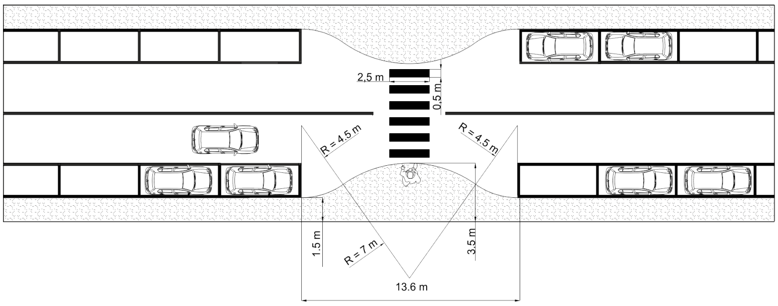
Concerning the vehicle-pedestrian interaction, in addition to the pedestrian absence condition, 3 conditions of the vehicle-pedestrian interaction (i.e. 3 theoretical values of $TTZ_{arr}$, equal to 1 s, 2.5 s and 4 s) were considered. Pedestrian crossing from the right side of the vehicle was simulated.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

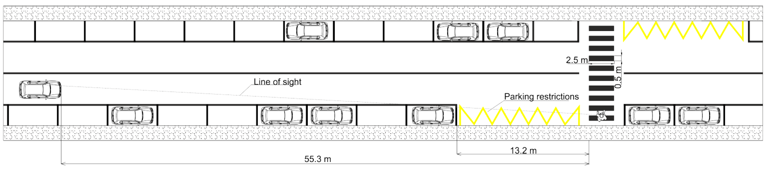
The condition of a pedestrian from the right should emphasize the effect of the safety measures on the driver behavior; such an effect is determined by comparing the behavior that was adopted when the safety measures were present and the behavior that was adopted for the baseline condition. The pedestrian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




(a)




(b)

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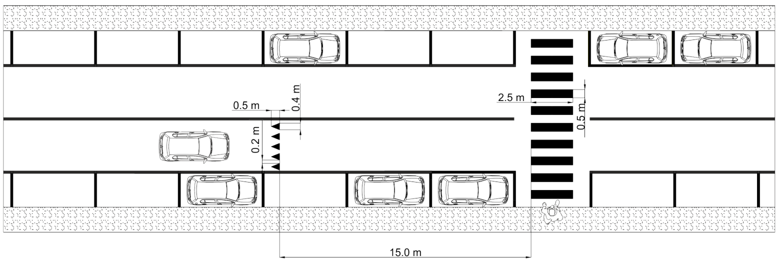


(d)

Figure 6.1: Safety measures at pedestrian crossings: *a) baseline condition b) curb extension c) parking restrictions d) advanced yield markings*

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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 behavior (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.

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 2.500 km. The average number of years of driving experience was approximately 9. The driving sample were then divided in 3 groups; the 3 groups drove different scenarios, which were differentiated by a specific encountering sequence of zebra crossing treatment/pedestrian.

All the participants of the experiment filled also a specific questionnaire about the discomfort perceived during the driving simulation with the aim of exclude data of participants which drove in physiological discomfort and, thus, which could affect the reliability of the analysis. Furthermore, a questionnaire about the perceived effectiveness of the countermeasure was submitted to the driving sample. In particular 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. Finally, drivers were instructed to drive as they normally would in the real world.

### 6.1.2 Data analysis

With the aim of investigate the driver - pedestrian interaction and the corresponding driver 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.

Three theoretical conditions of vehicle - pedestrian interaction were implemented in the simulated drive, corresponding to three theoretical values of $TTZ_{arr}$ equal to 1 second, 2.5 seconds and 4 seconds. However, the tests carried out at 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. Thus, many conditions of vehicle-pedestrian interaction, considering the actual speeds of the drivers and their distances from the pedestrian crossings at the moment when they perceived the pedestrian presence, were recorded. 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 TTZarr x 4 countermeasures x 42 drivers). Afterward, from each speed profile, the following variables were determined (Figure 6.2):

- $V_i$: 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 with the equation (2), which represents the time left for the vehicle to arrive at the zebra crossing at the moment he/she 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 6.1 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.

Table 6.1: Actual driver - pedestrian interactions recorded during the tests.

| **Safety measure** | **N° of vehicle-pedestrian interaction** | **$TTZ^*_{arrive}$** | | | | | | | **Non yield events** |
|---|---|---|---|---|---|---|---|---|---|
| | | Mean [s] | Max [s] | Min [s] | $TTZ^*_{arr} \leq 3s$ | $3s < TTZ^*_{arr} \leq 4s$ | $4s < TTZ^*_{arr} \leq 5s$ | $TTZ^*_{arr} > 5s$ | |
| Baseline condition | 115 | 4.1 | 9.1 | 1.4 | 31 | 28 | 28 | 28 | 11 |
| Curb extension | 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 |

In addition to the already mentioned variables $V_i$ and $L_{Vi}$, several other variables were collected from the drivers' speed profiles to analyze the driving behavior while approaching the pedestrian crossing from all of the 672 drivers' speed profiles (42 drivers x 16 combinations of zebra crossing/pedestrian)(Figure 6.2):

- $V_{min}$ 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 $V_{min}$;
- SRT: Speed Reduction Time, the time required to the driver to pass from the $V_i$ and the $V_{min}$.

The variable $d_m$ is given by the following equation:

$$d_m = \frac{V_i^2 - V_{min}^2}{2 \cdot S} \tag{3}$$

where S is the longitudinal distance needed to pass from $V_i$ and $V_{min}$.

The variable SRT represents the width of the interval time taken by the driver to pass from the initial speed to the minimum speed and highlights if the driver receives an information that is more or less clear about the pedestrian crossing and, therefore, if he can yield to the pedestrian with a gradual maneuver. In other words, a small speed reduction time reveals an inappropriate driver's braking behavior indicating that the driver needs to modify his speed in a short time in response to a crossing pedestrian and, therefore, he adopts abrupt maneuver.

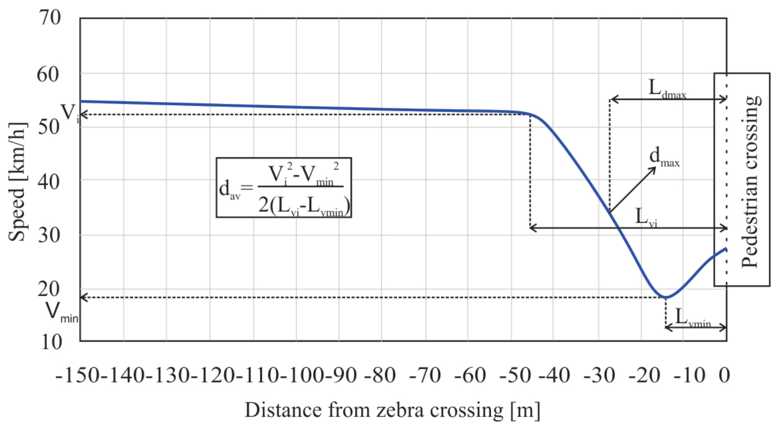


Figure 6.2: Explicative variables of the driving behavior during the interaction with VRUs.

It should be noted that the obtaining of variables related to spatial measures and deceleration rates is based on the drivers' speed behavior recorded during the tests. For this purpose the driving simulator has been validated for the speed research on highways and two-lane rural roads. However, it has been demonstrated that for low speed values, the speed adopted by the drivers in the real word are not significantly different from those recorded on driving simulator [103], ensuring the reliability about the use of these variables to assess the effectiveness of the safety measures and analysis of the drivers' behavior in the urban context too.

### 6.1.3 Results

Three analyses were performed. The first analysis focused 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 identified the willingness to give way to the pedestrians linked to 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 cautious 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. Table 6.2 shows the number of interactions for different groups of $TTZ*_{arr}$ that were obtained from the three theoretical values of $TTZ_{arr}$.

Table 6.2: Actual driver - pedestrian interaction obtained from the three theoretical values of $TTZ_{arr}$

| Actual driver-pedestrian interaction | Theoretical driver-pedestrian interaction | | | Total nº of interactions |
|---|---|---|---|---|
| | $TTZ_{arr}$=1s | $TTZ_{arr}$=2.5s | $TTZ_{arr}$=4s | |
| $TTZ^*_{arr} \leq 3s$ | 21 | 30 | 54 | 105 |
| 3s<$TTZ^*_{arr} \leq 4s$ | 46 | 51 | 34 | 131 |
| 4s<$TTZ^*_{arr} \leq 5s$ | 35 | 30 | 31 | 96 |
| $TTZ^*_{arr} > 5s$ | 40 | 43 | 47 | 130 |

The main aim of this analysis was to investigate how the driving speed behavior while approaching the pedestrian crossing was affected by the interaction conditions of vehicle-pedestrian (and therefore implicitly by the driver's characteristic) and how the drivers' modify the approaching behavior at pedestrian crossing among the several countermeasures. The second and more in-depth analysis that was performed was based on variables 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 6.1). 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). The last analysis was performed on the variable SRT and was conducted by means of the survival analysis (see Appendix A), which allows to highlight the relationship between the covariates of the model (i.e. the independent variables) and the time variable. The use of the survival analysis in this context is justified by the fact that the modeling of the dependent variable (SRT) ensure only positive values, consistently with the nature of the variable. Other statistical methods, such as mixed linear models are restricted in the field of the duration data due to some model assumptions and the unique character of the empirical data (i.e. empirical duration data are limited to have positive values because negative values of time do not exist for definition) [115].

**Drivers' mean speed profiles** Mean speed profiles were plotted for each countermeasure, for 4 groups of $TTZ*_{arr}$ values and for the pedestrian absence condition (Figure 6.3).

For all of the countermeasures and for $TTZ^*_{arr} \leq 3s$, 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 to avoid a potential conflict. The minimum

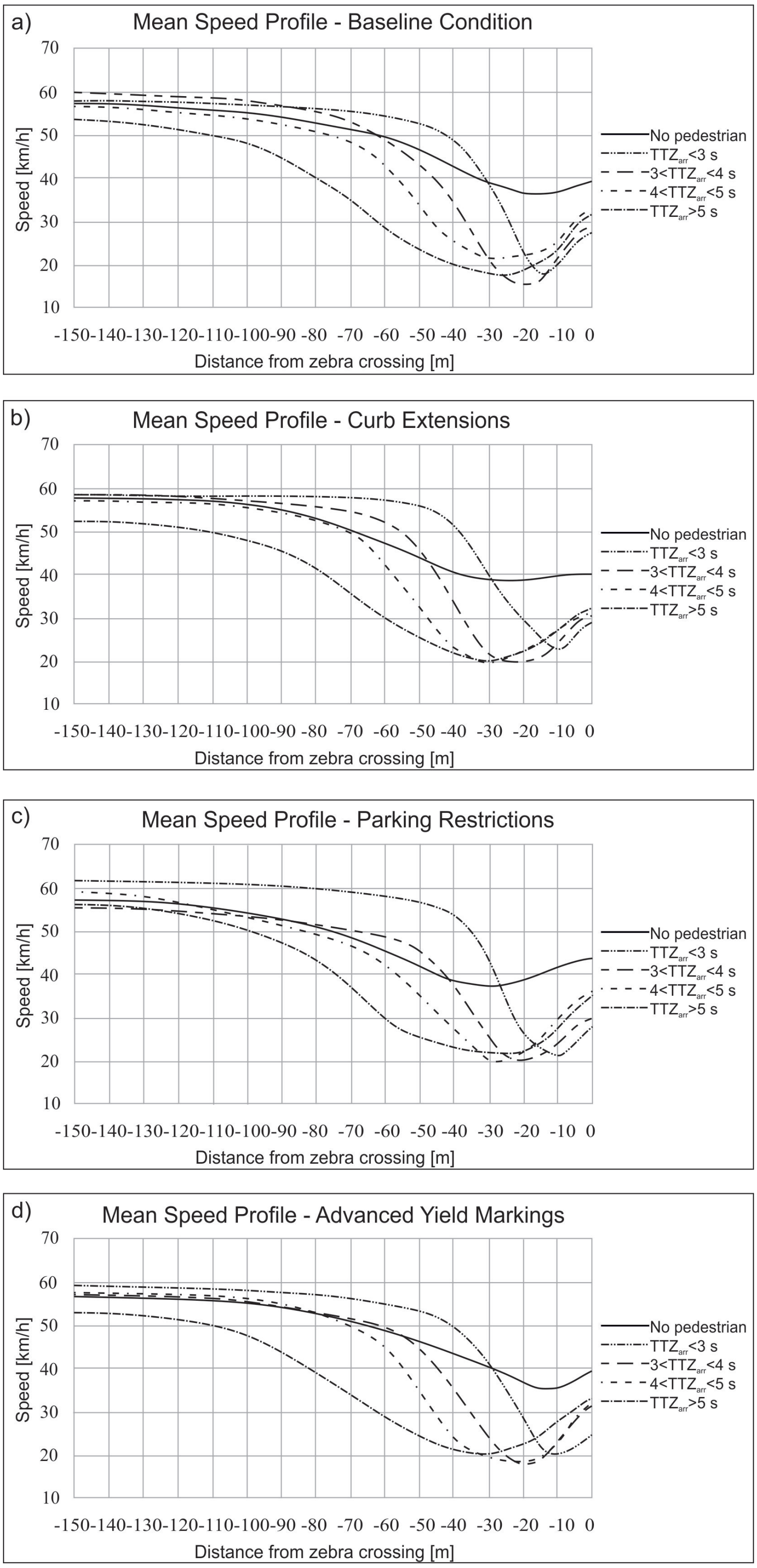


Figure 6.3: Drivers' mean speed profiles: *a) baseline condition b) curb extensions c) parking restrictions d) advanced yield markings*

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speed was reached at 15 m from the zebra crossing for the baseline condition and 10 m for the other countermeasures. The corresponding values of minimum speed were 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.

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

The lower mean speed profile was recorded for $TTZ^*{}_{\mathrm{arr}} > 5s$ for all the countermeasures. The speed reduction occurs gradually and begins at a point that is more than 100 m away from the pedestrian crossing. The corresponding mean 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 $TTZ^*_{\mathrm{arr}}$.

**Drivers' speed behavior** The Table 6.3 shows the descriptive statistics of the explicative driving behavior variables. 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. The Bonferroni correction was used for multiple comparisons.

Table 6.3: Descriptive statistics of the dependent variables during the driver-pedestrian interaction.

| **Safety measure** | **Pedestrian condition** | $V_i$[Km/h] | | $L_{Vi}$[m] | | $V_{min}$[Km/h] | | $L_{Vmin}$ [m] | | $d_m$[m/s$^2$] | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Mean | SD | Mean | SD | Mean | SD | Mean | SD | Mean | 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 |

The results of MANOVA about the main effects of safety measures and pedestrian conditions are reported in Table 6.4 and tablename 6.5

Table 6.4: Significantly main effects of safety measures and pedestrian condition factors.

| **Indipendent variables** | **F** | **P** | **Wilk's Λ** | **Partial Eta Squared** | **Observed Power** |
|---|---|---|---|---|---|
| Safety measure | $F_{(15,1607)} = 2.660$ | 0.001 | 0.935 | 0.022 | 0.990 |
| Pedestrian condition | $F_{(5,582)}$=125.401 | <0.000 | 0.481 | 0.519 | 1 |

Table 6.5: Effects of safety measures and pedestrian conditions on dependent variables.

| **Indipendent variable** | **Dependent variable** | **F** | **P** |
|---|---|---|---|
| Safety measure | $V_i$ | F(3,586)=0.861 | 0.461 |
| | $L_{Vi}$ | F(3,586)=7.936 | <0.000 |
| | $V_{min}$ | F(3,586)=4.494 | 0.004 |
| | $L_{Vmin}$ | F(3,586)=2.648 | 0.048 |
| | $d_m$ | F(3,586)=1.540 | 0.203 |
| Pedestrian condition | $V_i$ | F(1,586)=9.361 | 0.002 |
| | $L_{Vi}$ | F(1,586)=27.157 | <0.000 |
| | $V_{min}$ | F(1,586)=297.238 | <0.000 |
| | $L_{Vmin}$ | F(1,586)=14.672 | <0.000 |
| | $d_m$ | F(1,586)=101.285 | <0.000 |

The effect of safety measures on variable $V_i$ was not 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. On the contrary, for the pedestrian condition, the statistical analysis showed a significant main effect ($F_{(1,586)}= 9.361$, $P = 0.002$). As expected, the outcomes of the pairwise comparison showed 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), highlighting that the pedestrian actually affected the drivers during the approaching of the zebra crossing.

The results indicated that there was a main effect for the safety measures on the corresponding distance at the beginning point of the yielding maneuver ($F_{(3,586)}$=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 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) (Figure 6.4).

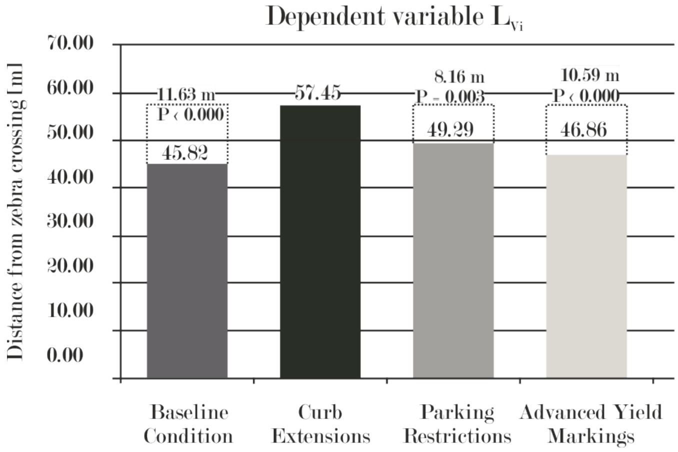



Figure 6.4: Main effect of countermeasures on drivers' $L_{Vi}$.

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).

A significant main effect for the safety measure was also found for the minimum speed value ($V_{min}$) that was reached during the braking maneuver ($F_{(3,586)}$ = 4.494, P=0.004). Post-hoc analysis indicated that the minimum speed value for the curb extensions condition (23.13 Km/h) was 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 significant (Figure 6.5).

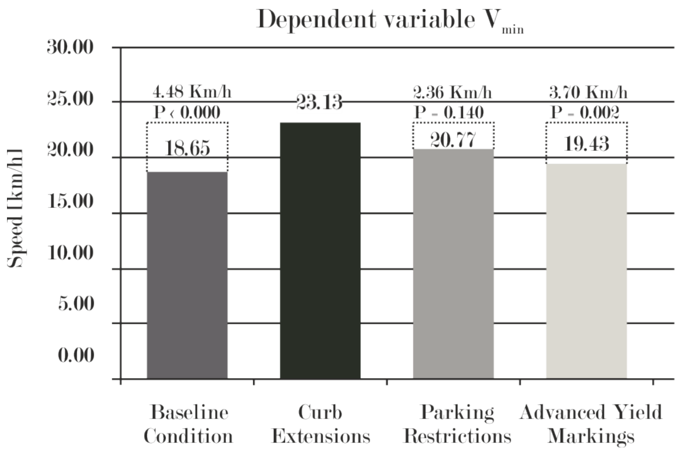



Figure 6.5: Main effect of countermeasures on drivers' minimum speed.

The results also showed a main effect for the pedestrian conditions ($F_{(1,586)} = 297.238$, $P < 0.000$). Pairwise comparison indicated that the absence of pedestrian induce the driver to reach a significantly higher minimum speed (28.35 Km/h) compared to the condition of pedestrian presence (mean difference = 15.19 Km/h; P=0.000).

Statistical analysis showed also a significant main effect on the corresponding distance of the yielding maneuver ending point 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 ($L_{Vmin}$) was 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 significant (Figure 6.6).

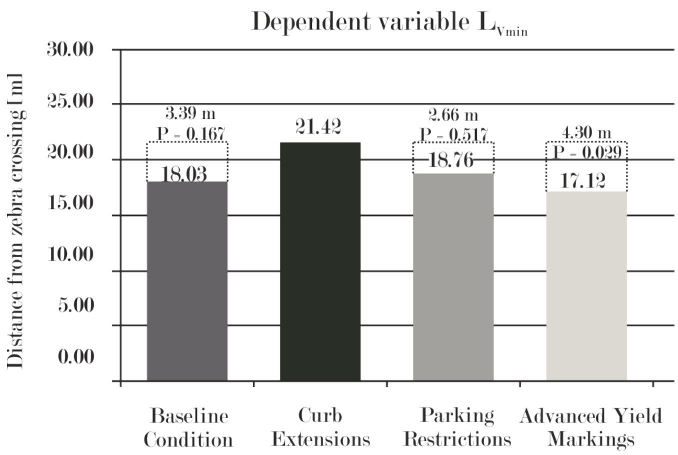



Figure 6.6: Main effect of countermeasures on drivers' $L_{Vmin}$.

The results also showed a main effect for the pedestrian conditions ($F_{(1,586)} = 14.672$, $P < 0.000$). Pairwise comparison indicated that the driver ended the deceleration maneuver farther from the crosswalk when the pedestrian was present (21.21 m), which was significantly higher than that when the pedestrian was absent (mean difference = 5.05 m; P<0.000).

Finally the results indicated that the effect of the safety measures for the average deceleration rate ($d_m$) was not 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 $m/s^2$) (Figure 6.7).

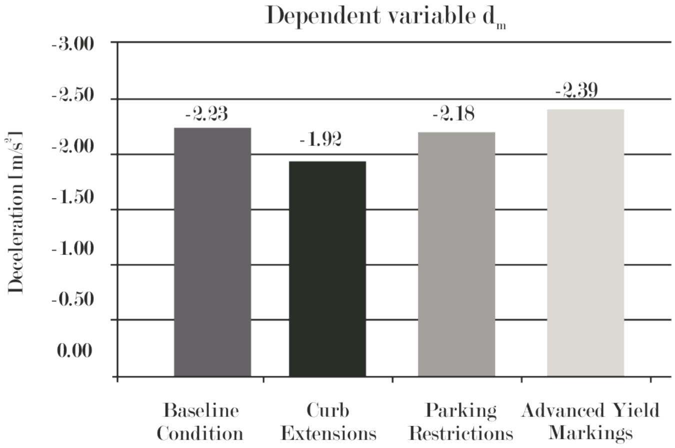



Figure 6.7: Main effect of countermeasures on drivers' average deceleration

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).

**Hazard-Based duration model of Speed Reduction Time** The time to reduce the speed from the initial value to the minimum value preliminary tested and compared across the countermeasures by using the ANOVA test, to asses if the safety measures affect the driver's braking behavior while yielding to the pedestrian under different pedestrian crossing conditions. Bonferroni correction was used for multiple comparisons. Table 6.6 shows the descriptive statistics of the continuous variables used to model the speed reduction time.

Table 6.6: Descriptive statistics of the set of variables used for modeling drivers' SRT in the interaction with pedestrian.

| Variable | Mean value | Standard deviation |
|---|---|---|
| $V_i$[m/s] | 13.35 | 3.09 |
| $L_{Vi}$ [m] | 54.79 | 21.27 |
| $V_{min}$[m/s] | 3.66 | 2.14 |
| $L_{Vmin}$[m] | 21.22 | 13.97 |
| $d_m$[$m/s^2$] | 2.99 | 1.75 |
| SRT [s] | 4.23 | 1.75 |

ANOVA revealed that there was a significant main effect across the countermeasures ($F_{(3,458)} = 7.52$, $P = 0.000$). The longer speed reduction time was reached when the curb extensions were present (4.34 s), which was significantly longer than that in baseline condition (mean difference = 1.40 s, P = 0.000), in parking restrictions (mean difference = 0.93 s, P = 0.020) and in advanced yield markings (mean difference = 1.08 s, P = 0.003) (Figure 6.8). No other mean difference was significant. Therefore, braking behavior is affected by the countermeasures; thus, to gain insight into the driver's braking behavior, the survival time of speed changes from the initial speed to the minimum speed was modeled using hazard-based duration models.

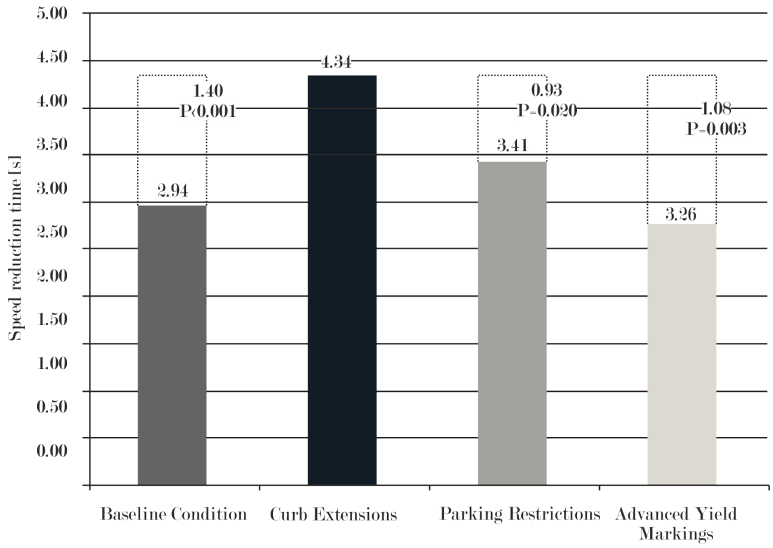
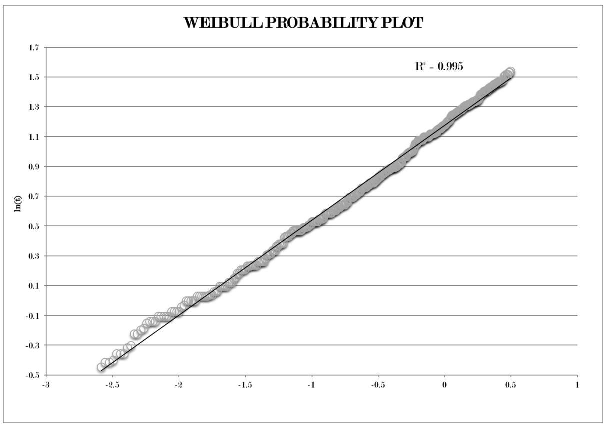
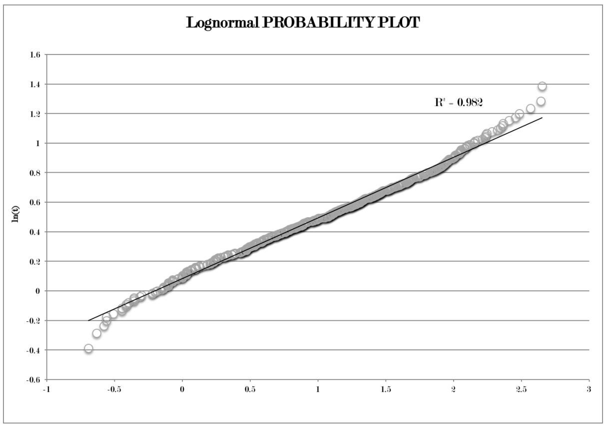



Figure 6.8: Main effect of countermeasures on SRT

The distribution function to model the SRT was carried out with the probability plot method, which assesses whether or not a data set follows a given distribution; in particular, the Weibull (Figure 6.9a), the lognormal (Figure 6.9b) and log-logistic (Figure 6.9c) distributions were compared. The data were plotted against the theoretical distributions in such a way that the points should form approximately a straight line. Departures from this straight line indicate departures from the specified distribution. For this purpose, the value of $R^2$ against a reference straight line was reported. As showed in Figure 6.9, the best fitting distribution was the Weibull one.




(a)

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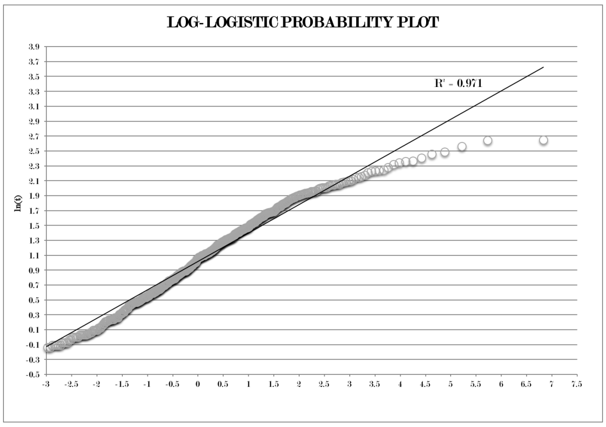


(c)

Figure 6.9: Assessment of the best fitting distribution to model SRT in driver-pedestrian interaction: *a) Weibull b) Lognormal c) Log-logistic*

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Thus, the speed reduction times from the initial speed to the minimum speed were modeled with the Weibull accelerated failure time (AFT) (see Appendix A) and, in addition, two extensions of this model were tested; the Weibull AFT model with inverse – Gaussian shared frailty and the Weibull AFT model with clustered heterogeneity. The two models were compared with their likelihood ratio statistics, with the AIC and BIC tests. The likelihood ratio statistics of the Weibull AFT model with shared frailty and with clustered heterogeneity was -216.83 and -222.23 respectively, highlighting that the first was preferable. The AIC and BIC test also confirmed the previous result; for the shared frailty model the AIC was 455.66 while for the clustered heterogeneity model was 466.47, while the BIC was 501.16 and 511.96, respectively (the model with the lower AIC and BIC is preferable). Thus, based on both likelihood ratio statistics, the AIC and BIC tests, the Weibull AFT model with shared frailty was the preferable for the speed reduction time of drivers in response to a crossing pedestrian, under different conditions of the zebra crossing.

The Table 6.7 shows the significant parameter estimates for the Weibull AFT model with shared frailty for the speed reduction times of drivers. As expected, the scale parameter P has an estimate value equal to 3.155, which implies that the survival probability of the speed reduction times decreased with the elapsed time. This implies that the probability of the driver response to a crossing pedestrian was increased with the elapsed time; in other words, the probability that the driver ends the braking maneuver, decreasing his speed from the initial value to the minimum value (this occurs in the speed reduction time), increases with the elapsed time. On average, in fact, the probability of decreasing the speed from $V_i$to $V_{min}$ after 4 s was approximately 4.4 times higher than that after 2 s (i.e., $(4/2)^{3.155\text{-}1}$). The effect on the probability of the scale parameter P higher than 1 ensures that the hypotheses concerning the speed reduction times (i.e., monotone hazard function and positive duration dependence) were consistent with the applied model. Concerning the appropriateness of inclusion of inverse – Gaussian shared frailty specification, the likelihood ratio test on the frailty parameter $\Theta$, showed that effectively in the observation group the unobserved heterogeneity was present ($\chi^2 = 11.00$, p = 0.000).

Table 6.7: Estimated parameters for the survival model of drivers' SRT in response to a crossing pedestrian.

| Variable | Estimate | SE | z-Statistic | p-value | Exp($\beta$) | 95% Conf. interval | |
|---|---|---|---|---|---|---|---|
| $V_i$[m/s] | 0.049 | 0.009 | 5.55 | 0.000 | 1.05 | 0.032 | 0.067 |
| $L_{Vi}$[m] | 0.001 | 0.001 | 7.06 | 0.000 | 1.01 | 0.007 | 0.012 |
| $V_{min}$[m/s] | -0.099 | 0.009 | -11.27 | 0.000 | 0.91 | -0.116 | -0.082 |
| $L_{Vmin}$[m] | -0.009 | 0.001 | -6.65 | 0.000 | 0.99 | -0.012 | -0.007 |
| $d_m$[m/s$^2$] | -0.274 | 0.016 | 16.87 | 0.000 | 0.76 | 0.242 | 0.306 |
| *Safety measure* | | | | | | | |
| **Baseline condition** | - | - | - | - | - | - | |
| **Curb extensions** | 0.236 | 0.044 | 5.36 | 0.000 | 1.27 | 0.150 | 0.323 |
| **Parking restrictions** | 0.103 | 0.045 | 2.31 | 0.127 | 1.108 | 0.015 | 0.191 |
| **Advanced yield markings** | 0.107 | 0.043 | 2.48 | 0.079 | 1.113 | 0.022 | 0.191 |
| Constant | 1.250 | 0.087 | 14.27 | 0.000 | | 1.078 | 1.421 |
| P | 3.155 | 0.134 | | | | 2.903 | 3.429 |
| Variance of inverse - Gaussian frailty, $\Theta^a$ | 0.130 | 0.064 | | | | 0.049 | 0.339 |
| Log-likelihood at convergence | -216.83 | | | | | | |
| Log-likelihood at zero | -496.24 | | | | | | |
| AIC | 455.66 | | | | | | |
| BIC | 501.16 | | | | | | |
| N° of observations | 462 | | | | | | |
| N° of groups | 42 | | | | | | |

[a]Likelihood ratio test of Θ: $\chi^2$ = 11.00, p-value < 0.000

All the set of variables was significant to model the time required for the driver to pass from $V_i$ to $V_{min}$ in order to yield to the pedestrian; the sign of all the coefficients was consistent with the effect on the speed reduction time. The coefficient of the initial speed was positive, which means that when the value of this variable increased, the time to reach the minimum speed (i.e. the speed reduction time) value also increased, due to the wider speed gradient. More specifically, for 1 m/s increase in the driver's initial speed, the time required to reach the minimum speed value was 5% longer (Exp ($\beta$)=1.05). Also the distance where the Vi is located ($L_{Vi}$) was positively associated with the speed reduction time; if the driver starts to brake farther from zebra crossing, in fact, he covers a greater distance to pass from the initial speed to the minimum speed, needing more time. With an increase of 1 m in $L_{Vi}$, the speed reduction time was 1% longer (Exp ($\beta$)=1.01). The minimum speed value had a negative coefficient, meaning that with an increase of the Vmin, the speed reduction time decreased; this is consistent because if the minimum speed increases, the speed gradient is smaller, requiring less time. More specifically, for 1 m/s increase in the driver's minimum speed, the speed reduction time was 9% lower (Exp ($\beta$)=0.91). The distance where the $V_{min}$ is located ($L_{Vmin}$) also had a negative coefficient; if the braking maneuver ends farther from zebra crossing, the distance to pass from the initial speed to the minimum speed is smaller, requiring less time. For 1 m increase in $L_{Vmin}$, the speed reduction time was 1% lower (Exp ($\beta$)=0.99). As expected, the average deceleration rate was negatively associated with the survival speed reduction time; this is consistent because if the drive brakes abruptly to yield to the pedestrian, the passage from the initial speed to the minimum speed occurs in a shorter interval time. With an increase of 1 m/s$^2$ in the average deceleration rate, in fact, the speed reduction time was 24% lower (Exp ($\beta$)=0.76). Among the pedestrian crossing conditions only the curb extensions were significant and positively associated with the speed reduction time (mean difference = 1.62 s, P=0.000). Compared with the baseline condition (6.06 s), the time to pass from the initial speed to the minimum speed (7.68 s) was 27% longer (Exp ($\beta$)=1.27, see also Figure 6.10).

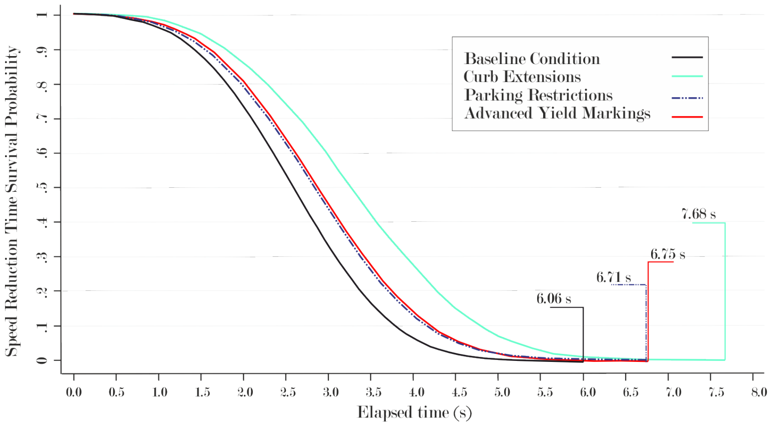



Figure 6.10: Survival curves of SRT for the different countermeasure condition in driver-pedestrian interaction.

Parking restrictions and advanced yield markings were also positively associated with the speed reduction time but the differences with the baseline condition were not significant (mean difference = 0.65 s, P=0.127; mean difference = 0.69 s, P=0.079 respectively). It should be noted that for the baseline condition a coefficient was not provided because it was the reference condition (i.e., the baseline condition had the shorter speed reduction time). A pairwise comparison with Bonferroni's correction among the safety measures was also performed; the results indicated that the speed reduction time for curb extensions (7.68 s) was significantly longer than that for parking restrictions (mean difference = 0.97 s, P =0.014) and for advanced yield markings (mean difference = 0.93 s, P=0.016) (Figure 6.10). No other difference was significant.

The estimation of the survival curves was provided by the equation 17, where the vector **X** was represented by the driver's braking behavior variables, while the vector $\beta$ was represented by the related coefficients. The survival curves for the several countermeasures were plotted by using the mean values of the continuous variable (Table 6.6) and the coefficients in Table 6.7.

For example, a comparison of the SRT survival probability among the safety countermeasures can be carried out by evaluating the survival function after a specific elapsed time (e.g. t = 3s):

$$S(t = 3s) = exp\{-[exp(-3.155(1.250 + (0.049 \cdot 13.35) + (0.001 \cdot 54.79) + (-0.099 \cdot 3.66) + (-0.009 \cdot 21.22) + (-0.274 \cdot 2.99) + \mathit{0.103}))] \cdot 3^{3.155}\} \quad (4)$$

$$S(t = 3s) = exp\{-[exp(-3.155(1.250 + (0.049 \cdot 13.35) + (0.001 \cdot 54.79) + (-0.099 \cdot 3.66) + (-0.009 \cdot 21.22) + (-0.274 \cdot 2.99) + \mathit{0.236}))] \cdot 3^{3.155}\} \quad (5)$$

Using this method, the survival curve for each countermeasure was plotted (Figure 6.10).

### 6.1.4 Conclusions

The analyses of the mean speed profiles and of the dependent variables related to the drivers' speed behavior provide 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. This finding confirms the results of the field study conducted by Johnson et al. [49] who found that after the installation of the curb extensions, the site with this pedestrian crossing treatment registered a lower number of vehicle that passed before the pedestrian. Moreover, also for the advanced yield markings an increasing trend of the drivers that yielded to the pedestrian was recorded. However, the effect was less evident (7%), compared to the curb extensions. The worst result was obtained for the parking restrictions and it was unexpected. The large number of drivers who did not yield to a pedestrian (12%) 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 induces 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.

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 [18] and with the "Threat Avoidance Model" developed by Fuller [27], according to which the driver could choose to 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. These behaviors were evident through the different classes of the $TTZ^*_{arr}$; in particular, 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. With the increasing of the $TTZ^*_{arr}$ values, especially for the class of $TTZ^*_{arr}$>6s, the driver realizes that is not possible to reach the zebra crossing before the pedestrian and, thus, he/she adopts an advanced yielding maneuver which is more gradual with respect of the lower values of $TTZ^*_{arr}$, highlighting an accentuated cautious driving behavior.

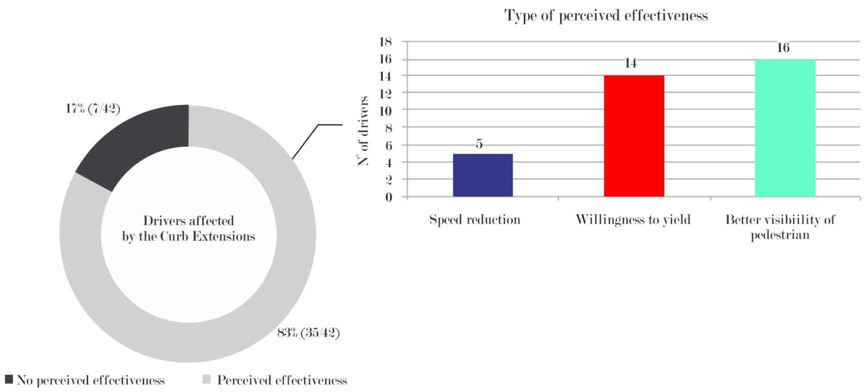
It should be noted that these drivers' behaviors are completely consistent with the "Threat Avoidance Model" developed by Fuller. In particular, the behavior observed for $TTZ^*_{arr}$<3s can be related to the "non-avoidance response". The driver, in fact, maintains the same speed because he considers 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 $3s<TTZ^*_{arr} \leq 4s$ and $4s<TTZ^*_{arr} \leq 5s$) 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.

More evident differences between the countermeasures were observed for the pedestrian absence condition. In particular, similar outcomes were observed for the advanced yield markings and baseline condition. In both of these conditions, 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.

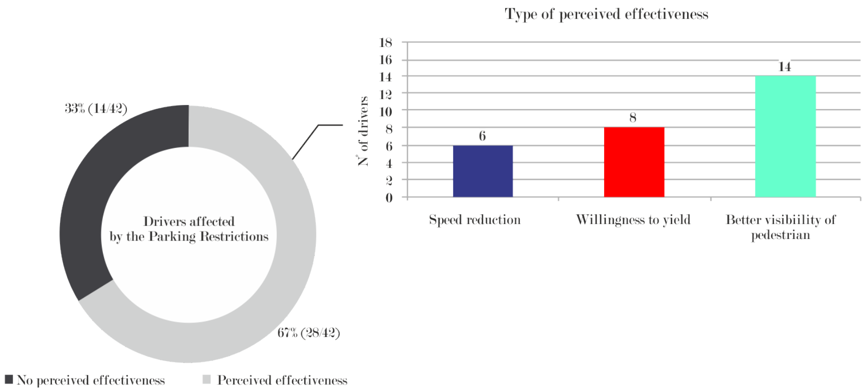
The statistical analysis for the assessment of the effectiveness of the safety countermeasures, indicated that the higher (significantly) values of the distance at which the driver started to yield to the pedestrian was recorded for the curb extensions. This distance gives an indication of how clear the information perceived by the driver is. Higher values of this variable indicate that the driver advances the yielding maneuver and the point where the speed adaptation begins. 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 completely stop because the beginning of the braking maneuver is 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 variable $L_{Vmin}$ 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.

Consistently with the outcomes reported above, the survival analysis of the drivers’ speed reduction time confirmed that the curb extensions allows the driver to adopt a smoother maneuver to yield to the pedestrian, given the possibility of advance the yielding maneuver (the higher value of $L_{Vi}$ was recorded for the curb extensions). On average, in fact, the time required to pass from the $V_i$ to the $V_{min}$ was of 26.7% longer (significantly) than that the baseline condition, 14.4% longer (significantly) than that parking restrictions and 13.7% longer (significantly) than that the advanced yield markings. This finding suggest that in this condition of pedestrian crossing, the drivers are able to start earlier the braking maneuver to yield to the pedestrian and the consequence is that they undertake less deceleration rates. The improvement of the pedestrian visibility provided by the curb extensions, in fact, allows the driver to advance the detection of the pedestrian and, thus, he has more time to brake and give way.

The findings provided with the statistical analyses were also consistent and confirmed by the outcomes of the self-reported questionnaire about the perceived effects of the countermeasures. The results are shown in Figure 6.11. 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.




(a)

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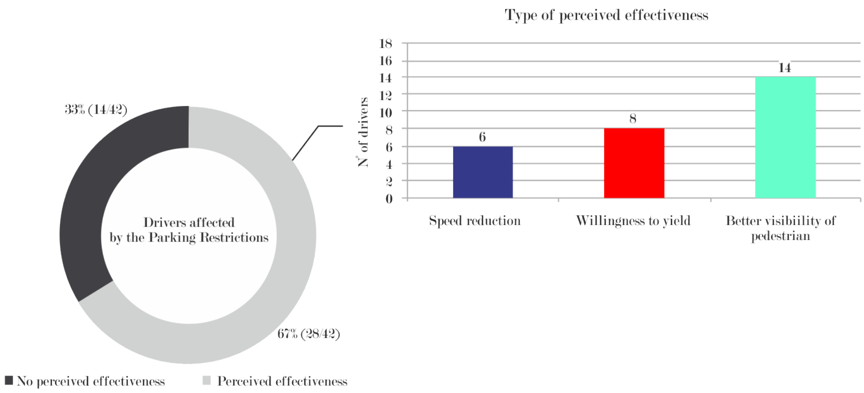


(c)

Figure 6.11: Outcomes of the questionnaire about the perceived effectiveness of the safety measures at pedestrian crossings

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The last result is related to the self-reported distance from the zebra crossing where the driver modified his speed (Figure 6.12). 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.

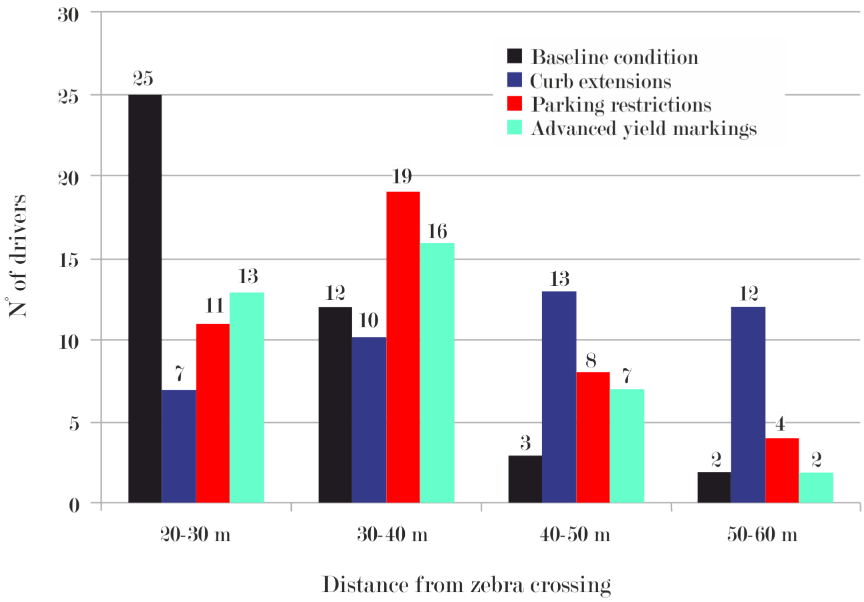


Figure 6.12: Self-reported distances at which drivers modified their behavior while approaching pedestrian crossing

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## 6.2 Jaywalking pedestrian - driver interaction

The aspects regarding the illegal pedestrian crossing (i.e. pedestrians that cross outside the crosswalk) is a topic that has received not so much attention by the researchers, although it can significantly affect the drivers' behavior due to unexpected situations at which the driver is subjected to. For this reason, the specific design of the experiment aimed at analyzing the interaction between drivers and pedestrian that crosses onto and outside crosswalks, had the following purposes:

- analyze the effects of the illegal crossing on drivers' behavior compared to the interaction between driver and pedestrian that crosses onto the crosswalk;
- assess the potential benefits of pedestrian detection system that could help the driver to avoid conflicts under unexpected situations;

To simulate the pedestrian that crosses the road, the triggering point of its movement was set when the vehicle was at 55.6 m from the conflict point (both in case of legal and illegal crossing) at a speed equal to 1.4 m/s. The legal crossing is defined for pedestrian that crosses onto the zebra crossing, while the illegal crossing is defined for a pedestrian that crosses outside the zebra crossing. The triggering point of the warning system was also set at 55.6 m from the conflict point: considering a theoretical vehicle speed of 50 Km/h this condition represents a theoretical TTC equal to 4s.

### 6.2.1 Experiment design

The pedestrian crossroads along the road scenario were designed according to the Italian Highway Code [111]. The cross – section of the simulated urban road was consistent with the Italian road design guidelines [113], characterized by two 3.0 m wide driving lanes, 2.00 m wide parking lanes and 1.50 m wide curbs. (Figure 6.13).

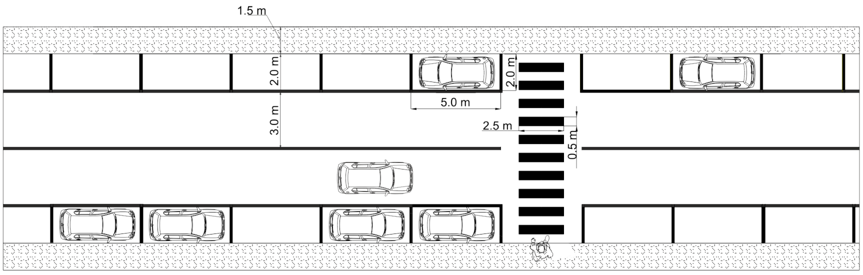


Figure 6.13: Pedestrian crosswalk layout for legal crossing

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To simulate the illegal crossing (i.e. pedestrian that crosses outside of the zebra crossing), simulated pedestrian crossed in a section where no vertical and horizontal signs were present (Figure 6.14).


Figure 6.14: Output in the driving simulator for driver-jaywalking pedestrian interaction

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In the simulated scenario 8 conditions of driver – pedestrian interaction were presented: presence of PPS (audio and video) with presence of pedestrian for legal/illegal crossing, absence of PPS with presence of pedestrian and legal/illegal crossing, and absence of PPS with absence of pedestrian and legal/illegal crossing. To ensure the same approaching condition, intersection with traffic lights that turned red was placed 400 m before each legal and illegal crossing, forcing the vehicle stop and allowing the drivers to adopt a consistent speed for the simulated urban scenario. The posted speed limit was 50 km/h.

A visual and audio PPS for pedestrian detection were also simulated. The first system provides a visual warning displayed on the central screen (simulating a Head-Up Display), while the second provide an auditive non-directional message ("attention, crossing pedestrian") which informs the driver of a pedestrian who is crossing. In addition to the 8 studied interaction conditions described above, along the alignment other pedestrian crossing situations, within and outside of the zebra crossing, were presented. These are defined as 'distracting conditions', aimed at avoiding that drivers understood where their behavior was actually recorded. Two scenarios were implemented in the driving simulator each one 5 km long in which half interaction conditions of interest (4 of 8) were implemented in the first scenario and half conditions in the second scenario. To avoid the order effect, 4 different sequences of the interaction conditions were also implement for each road scenario.

The experiment was conducted with the free vehicle in its own driving. The original sample was composed by 42 participants; however, 2 of the 42 users did not complete the test simulation for reasons related to an excessive level of psycho - physical discomfort. Thus, the actual sample was reduced to 40 users composed by 20 males and 20 females.

### 6.2.2 Data analysis

The set of variables selected to study the driving behavior was the same of that used in the previous experiment; $V_i$: the driver's initial speed, when the driver perceives the zebra crossing and decreases his speed, releasing the acceleration pedal; $L_{Vi}$: the distance from the conflict point at which $V_i$ is registered; $V_{min}$: the minimum speed during the deceleration phase; $L_{Vmin}$: the distance from the conflict point where $V_{min}$ is located; $d_m$: the average deceleration to pass from $V_i$ to $V_{min}$, evaluated with the equation 3; SRT: speed reduction time, defined as the time to pass from $V_i$ to $V_{min}$.

In addition, also the drivers' reaction time (RT) was recorded, which represents the time needed for the driver to react in response to the warning signal which alerts the driver about the presence of the pedestrian which is crossing. It is a parameter of drivers' behavior that has concrete implication for road safety [e.g. 116, 117] and it is an important variable that affects traffic accidents. It is believed that a lower reaction time is better for driving safety, as indicated by Evans [118].

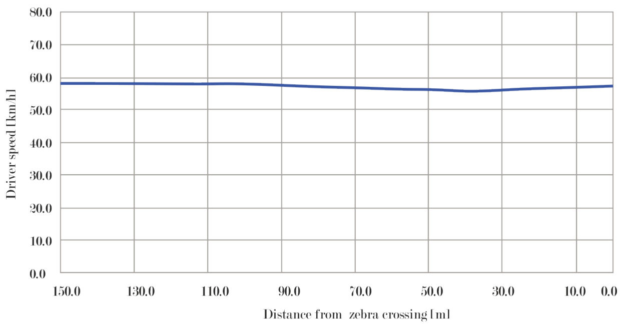
The first step towards the analysis of the results was the plotting of the speed profiles based on the speed data obtained by the driving simulator. Each speed profile shows the driver's speed values 150 m in advance the crosswalk and allows to obtain all the parameters (the dependent variables) describing the driver's speed behavior in approach to the zebra crossing and his willingness to yield.

A total of 320 speed profiles were plotted (40 participants x 8 interaction conditions). However, in 7 cases the driver collided with the pedestrian and specifically: 2 cases for the illegal pedestrian crossing with the audio warning, 3 cases for the illegal pedestrian crossing with no PPS, 1 case for the legal pedestrian crossing and no PPS and 1 case for the legal crossing with PPS (Table 6.8), as reported in the following table:

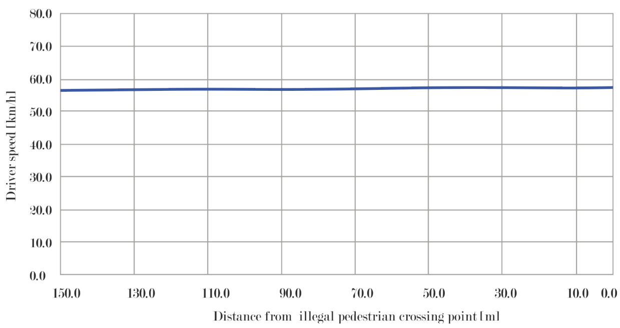
Table 6.8: Summary of collision for each PPS condition.

| | Visual warning | | Audio warning | | No PPS | | Total |
|---|---|---|---|---|---|---|---|
| | Legal crossing | Illegal crossing | Legal crossing | Illegal crossing | Legal crossing | Illegal crossing | |
| n° of obsesrv.(a) | 40 | 40 | 40 | 40 | 40 | 40 | 240 |
| Collisions (b) | 0 | 0 | 1 | 2 | 1 | 3 | 7 |
| % of collision [b/a] | 0 | 0 | 2.5 | 5.0 | 2.5 | 7.5 | 2.9 |
| Remaining [a-b] | 40 | 40 | 39 | 38 | 39 | 37 | 223 |

It should be noted that these variables can be obtained from the speed profiles representing the interaction between driver and pedestrian. Thus, 223 driver speed profiles (see Table 6.8) for the condition of pedestrian presence were considered for the following analysis. On the contrary, these variables cannot be obtained from the condition of pedestrian absence. For such condition, therefore, the average speed profile was analyzed. Both profiles (Figure 6.15) (i.e. marked crosswalk without pedestrian and cross-section without pedestrian with same characteristics of that in which the illegal pedestrian crossing was recorded) show, along the last 150 m, a trend of almost constant speed, which is approximately around 57 km/h.




(a)




(b)

Figure 6.15: Example of drivers' mean speed profiles in pedestrian absence condition: *a) marked crosswalk b) outside of crosswalk*

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In the case of marked crosswalk there is a slight decrease of the speed just before the pedestrian crossing, while in the case of absence of markings the profile, as expected, follows a situation in which the driver does not expect any interference. Therefore, only the condition of pedestrian presence was considered for the statistical analysis.

### 6.2.3 Results

A set of ANOVAs was performed with the crossing condition (two levels: legal and illegal crossing) and PPS condition (three levels: No PPS, Audio warning and Visual warning) to investigate the main effects and the interaction effects of the independent factors on the variables obtained from the drivers' speed behavior. The main and interaction effects of the investigate factors on dependent variables are reported in Table 6.9

Table 6.9: Main and interaction effects of crossing condition and PPS condition.

| **Indipendent variable** | **Dependent variable** | **F** | **P** |
|---|---|---|---|
| Crossing condition | $V_i$ | $F_{(1,217)}$=0.409 | 0.523 |
| | $L_{Vi}$ | $F_{(1,217)}$=27.436 | 0.000 |
| | $V_{min}$ | $F_{(1,217)}$=4.948 | 0.027 |
| | $L_{vmin}$ | $F_{(1,217)}$=1.698 | 0.197 |
| | $d_m$ | $F_{(1,217)}$=8.901 | 0.004 |
| | SRT | $F_{(1,217)}$=1.080 | 0.302 |
| | RT | $F_{(1,217)}$=0.359 | 0.550 |
| PPS condition | $V_i$ | $F_{(2,217)}$=0.005 | 0.995 |
| | $L_{Vi}$ | $F_{(2,217)}$=0.815 | 0.910 |
| | $V_{min}$ | $F_{(2,217)}$=4.491 | 0.012 |
| | $L_{Vmin}$ | $F_{(2,217)}$=0.004 | 0.996 |
| | $d_m$ | $F_{(2,217)}$=1.610 | 0.202 |
| | SRT | $F_{(2,217)}$=1.128 | 0.326 |
| | RT | $F_{(2,217)}$=1.980 | 0.141 |
| Crossing condition by PPS condition | RT | $F_{(2,217)}$=4.150 | 0.017 |

The effects of the crossing condition on drivers' initial speed was not significant; Pairwise comparison showed that the mean value of the initial speed for the legal crossing (57.70 km/h) was almost the same for the illegal crossing (56.71 km/h). As expected the driver approached both the sections in which the pedestrian crossed the road with same speed value, depending only on the urban road environment. Also the effect of the PPS condition was not significant.

ANOVA showed a significant main effect of the crossing condition on the variable $L_{Vi}$; the mean value of the variable $L_{Vi}$ for the legal crossing (58.04 m) was significantly higher than that for condition in which the pedestrian crossed outside of the crosswalk (mean difference = 13.75 m) highlighting that the driver delayed the braking maneuver when the pedestrian crossed outside the crosswalk (Figure 6.16).

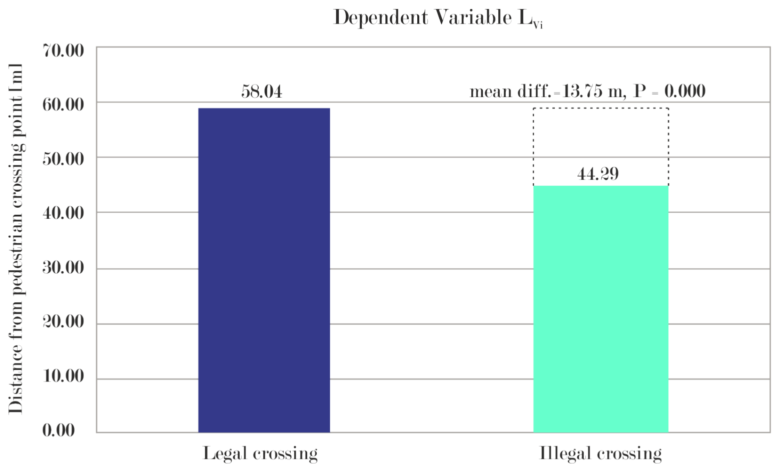


Figure 6.16: Effect of crossing condition on the variable $L_{Vi}$.

Results showed that the effect of PPS was not significant. However, it should be noted that ,on average, when the vehicle was equipped with the PPS, the driver advanced the braking maneuver. The mean value for the No PPS condition was 49.08 m, while for the audio warning and the visual warning was 51.24 m and 53.18 m, respectively.

The results on the variable $V_{min}$ showed that the value for the legal crossing (20.84 km/h) was significantly higher than that for the illegal crossing (mean difference = 3.62 km/h, P = 0.027) (Figure 6.17). The driver, when the pedestrian crossed outside of the crosswalk, was forced to an almost complete stop to avoid the conflict due to the delayed response.

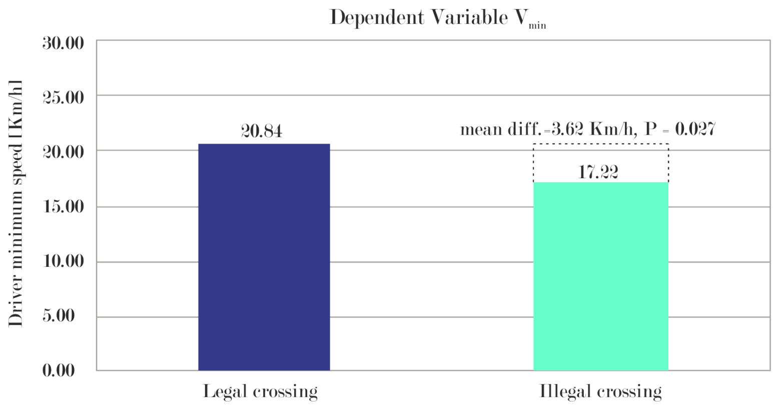


Figure 6.17: Main effect of the crossing condition on the variable $V_{min}$.

Furthermore, the effect of the PPS condition was also significant. In particular, for the audio warning the minimum speed (16.05 km/h) was significantly lower than that the No PPS condition (mean difference = -5.88 km/h, P = 0.021) (Figure 6.18). Also for the video warning the $V_{min}$ was lower than that the No PPS condition, but the difference was not significant (mean difference = -3.05 km/h, P = 0.689).

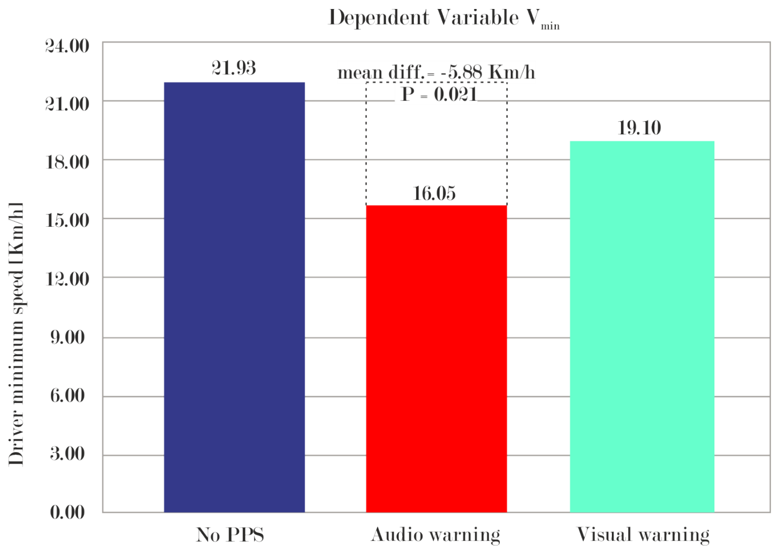


Figure 6.18: Main effect of the PPS condition on the variable $V_{min}$.

The statistical analysis on the variable $L_{Vmin}$ showed that the effect of the crossing condition was not significant. However, results showed that the driver completed the yielding maneuver at higher (not significant) distance from the crossing point in the legal crossing condition (17.23 m) than that in the illegal crossing condition (14.34 m). The effect of the PPS was not significant ($F_{(2,217)} = 0.004$, $P = 0.996$).

ANOVA showed that the crossing condition affected in a significant way the average deceleration adopted by the driver. Results highlight that $d_m$ in the legal crossing condition (3.03 $m/s^2$) was significantly lower than that in the illegal crossing condition (mean difference = -1.22 $m/s^2$) (Figure 6.19). This means that the unexpected situation of a crossing pedestrian outside of the crosswalk forced the driver to adopt a more aggressive braking to avoid the conflict.

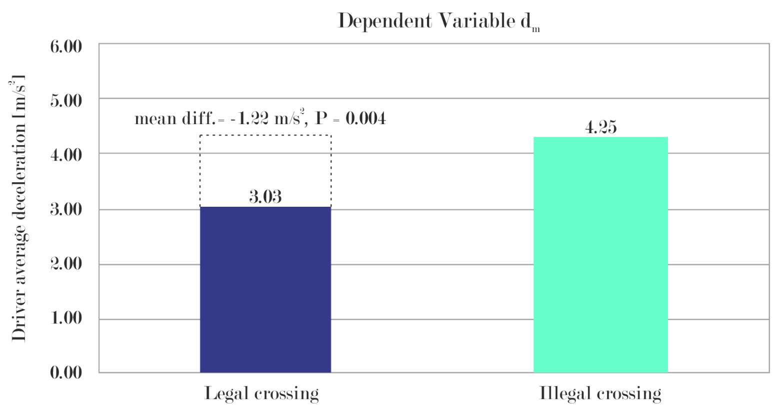


Figure 6.19: Effect of crossing condition on the variable $d_m$.

The effect of PPS was not significant ($F_{(2,217)} = 1.610$, $P = 0.202$).

The statistical analysis showed that the effect of the crossing condition in the speed reduction time was not significant. This results shows that the driver took similar time to pass from the initial speed to the minimum speed both in the legal and illegal crossing condition (3.43 s and 3.14 s, respectively). Also the effect of the PPS was not significant. However, a longer (not significant) SRT was recorded for the visual warning (3.88 s) and the audio warning (3.83 s) compared to the no PPS condition (3.50 s).

Finally, for the variable reaction time, the results highlighted a significant interaction effect crossing condition by PPS condition. In particular, results highlighted that in the condition in which the pedestrian crossed outside the zebra crossing, the drivers' reaction time was similar among the PPS conditions, highlighting that the driver, despite the alarm, had the tendency to want the priority when there was not a marked pedestrian crossing by delaying the reaction toward the pedestrian (Figure 6.20).

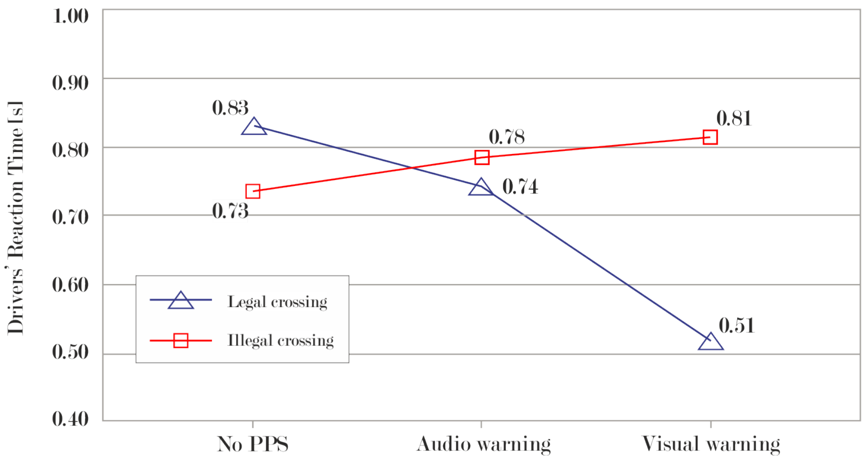


Figure 6.20: Interaction effects of crossing condition by PPS condition on the variable RT.

In those situations, in fact, the reaction time was longer than that when the pedestrian was crossing on the marked crossroad. On the contrary, in the condition of legal crossing, the shortest reaction time was recorded for the video warning (0.51 s), while for the audio warning and the no PPS condition was 0.74 s and 0.83 s, respectively, highlighting that the driver reacted earlier when the vehicle had the video warning.

### 6.2.4 Conclusions

The results of the statistical analysis showed that the crossing conditions affected the drivers' speed behavior and the outcomes of the analysis showed that the interaction between driver and jaywalking pedestrian can be a critical situation. In particular, the crossing condition affected the approaching behavior of the driver towards the pedestrian. Specifically, the point in which the driver started to slow down was farther from the collision point for the condition of legal crossing compared to the condition of illegal crossing, highlighting that the unexpected situation induced the driver to react later towards the jaywalker. This finding confirms the results of Zheng et al. [98] in which it was found that the drivers' yield choice for the jaywalkers was clearly nearer to the crossing point. Moreover, the results highlight that the later driver reaction for illegal crossing condition induced the driver to reach a lower speed value to avoid the conflict, compared to the legal crossing condition in which the driver had much time to slow down before reaching the collision point. The later reaction to the unexpected situation forced also the driver to undertake higher deceleration rates to avoid the conflict. This driving behavior is also fully consistent with the behavioral model of Fuller [27]; in the case of illegal crossing, the driver did not expect a "threat" and, thus, he adopted the delayed braking response to avoid the conflict. As consequence of the delayed braking response in the condition of illegal crossing, the driver adopted a more aggressive braking which led to higher values of the average deceleration. Finally, the average speed profiles in the condition of pedestrian absence show that the driver behaves differently compared to the condition in which the pedestrian is crossing; in particular, the driver did not experience a "threat" and, thus, maintained the same speed, which is consistent with the theoretical framework of driver – pedestrian interaction of Fuller [27].

Surprisingly, the PPS affected only the drivers' minimum speed. Results highlighted that in presence of PPS (both for audio and visual warning) the driver reached a lower minim speed compared with the condition of no PPS; moreover, the lower (significant) minimum speed was reached for the audio warning compared to the no PPS condition. This outcome highlighted that when the vehicle was equipped with the driving assistance system the driver completed the yielding maneuver with lower speed values. This is a remarkable improvement of the pedestrian risk fatality since the speed of vehicle has a positive correlation with the pedestrian probability of death in case of accident.

Furthermore, the analysis showed that for the illegal crossing condition the driver had almost the same RT among the PPS condition. However, the collision rates reported in Table 6.8 highlight the improvement of the pedestrian safety when the PPS was present, showing a reduction of the number of collisions between driver and pedestrian. Moreover, when the pedestrian crossed into the zebra crossing the PPS produced an improvement of the driving performance by reducing the RT, which is significant of an improvement of the driving safety [118] and of the pedestrian safety during the interaction with the drivers.

## 6.3 Driver-pedestrian interaction: effects of road environment and PPSs

The analysis of the driver - pedestrian interaction, as reported in the previous chapters, is focused almost all in the urban context. However, the consequences of an accident in road environments characterized by higher speeds than the urban roads are sensibly worst. The fatality rate, in fact, is almost six-time higher for the rural road compared to the urban environment. Moreover, the previous experiment, highlighted that during the legal crossing, the presence of a PPS improved the pedestrian safety by reducing the vehicle-pedestrian conflicts. Therefore, the experiment aims at the following:

- analyzing the driver's behavior in approach to the zebra crossing under different road environment conditions (urban, sub-urban and rural) and different conditions of driver – pedestrian interaction, to evaluate to what extent driver's behavior is influenced by such factors;
- evaluating the effectiveness of a driver assistance system for pedestrian detection on the driver's behavior approaching a zebra crossing under different

road environment conditions and different conditions of driver – pedestrian interaction.

With this aim, a driving simulation study was conducted by implementing in the driving simulator three road environments (urban, sub-urban and rural) and analyzing the behavior of a driver sample during different driver – pedestrian interactions, in presence and absence of the pedestrian protection system. Considering the literature review (see [85] and [78]) in the present experiment a combined visual-auditive pedestrian protection system was simulated with a warning time of 3.5 s and a duration of 3.5 s after the triggering.

Two analyses were performed: the first analysis focused of the drivers' mean speed profiles to describe the driver approaching behavior to the zebra crossing and his willingness to yield, while the second analysis was more insight and considered numerous independent variables which describe the driving behavior.

### 6.3.1 Experiment design

To accomplish the aims of the experiment, three road scenarios were designed and implemented in the driving simulator to simulate the driving condition in the urban, sub – urban and rural environments. An output of the different road environment and the PPS is reported in the figure Figure 6.21.

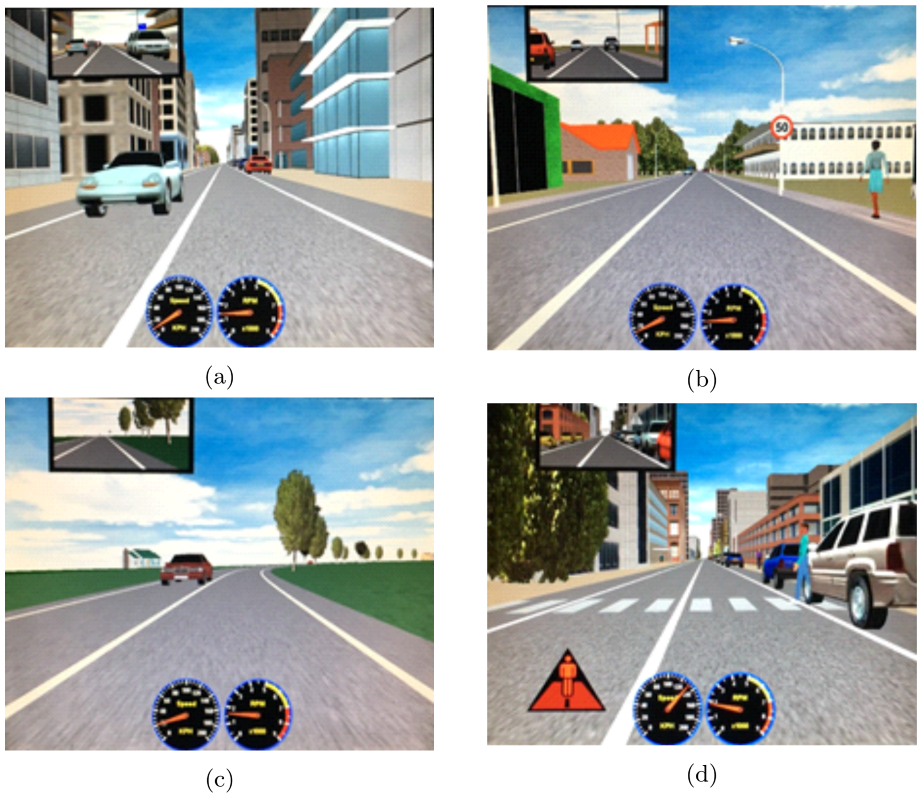


Figure 6.21: Output of the driving simulator: *a) urban road b) suburban road c)rural road d) visual PPS*

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All the simulated scenarios were characterized by the cross-section of a two-lane road with a driving lane width equal to 3.00 m for the urban and suburban road and 3.50 m for the rural road. The urban and suburban roads had a shoulder width equal to 2.00 m in which the parking was allowed and a curb 1.50 m wide. For the rural road the shoulder was 1.25 m wide without parked cars and curb. These cross-section configurations were designed according to Italian Highway Code [111] and are typical of the Italian urban, sub – urban and the urban roads. In urban and suburban scenario, the stripes of the zebra crossings are 2.5 m long and 0.5 width, in the rural scenario they are 4.0 m long and 0.5 m. On urban and suburban scenarios, in advance of the pedestrian crosswalk, a parking restriction 13.2 m long was located by horizontal marking. The speed limit was 50 km/h for the urban and sub-urban roads, while it was equal to 90 Km/h for the rural road. It should be noted that the cross sections of the urban and sub – urban road are identical; the only difference is in the building environment around the alignment

For each road scenarios, two interaction conditions with the pedestrian crossing from right with a speed equal to 1.4m/s were presented: one case in which the driver was helped by the pedestrian protection system and one case in which the driving assistance system was absent (in total three conditions of driver - pedestrian interaction). The triggering point of the pedestrian movement was set at different vehicle distances from the crosswalk, which was different for each road scenario: 55.6 m for urban scenario, 66.6 m for sub - urban scenario and 88.8 m for rural scenario. Considering a driver's speed of 50 km/h on urban scenario, of 60 km/h on sub - urban scenario and 80 km/h on rural road, these distances represent the theoretical value of $TTZ_{arr}$ (the time left for the vehicle to arrive at the zebra crossing) equal to 4 s.

The simulated vehicle was equipped with a visual-auditive pedestrian protection system; this system provides a visual warning (Figure 6.21d) displayed on the central projection screen (simulating a Head-Up Display), accompanied by an auditive non-directional message (a "beep" sound) which informs the driver of a pedestrian who is crossing, provided by the audio system of the vehicle. The warning was activated when the driver reached a point that was 49 m, 59 m and 78 m in advance of the crosswalk for the urban, suburban and the rural road, respectively. Considering the same speed values for the evaluation of the theoretical $TTZ_{arr}$, these values represent a time to collision (TTC) equal to 3.5 s. It should be noted that this value of TTC is theoretical because it depends on the actual approaching speed of the driver at the pedestrian crossing during the simulated driving. In other words, if the driver reaches the triggering point of the warning at a speed higher or lower than that hypostasized (i.e. 50 km/h, 60 km/h and 80 km/h for the urban, suburban and rural roads, respectively), the value of the TTC will be lower or higher than 3.5 s, respectively. It should be also noted that this value of TTC is fully consistent with those used in previous driving simulator studies [119, 120]. The visual warning was displayed for a duration of 3.5 s.

The initial sample of participants used in this experiment included forty-five volunteers, but three of them did not end the driving due to sickness. According to the results of the questionnaire about participants' physical disease, almost all the volunteers felt a null level of sickness. However, one of them stated a high level of disease: this test was excluded from the sample. Therefore, the sample used for the analysis was composed by 41 participants, balanced in gender and (21 males and 20 females), aged from 20 to 74 (average 33).

Between each scenario the driver waited about 10 min to restore his/her psychophysical conditions and filled in of a questionnaire about the effectiveness of the driver assistance system; participants were asked if PPS was useful for an easier pedestrian detection, and if this PPS had annoyed them. Each question could be answered “Yes” or “No”. In the case of positive answer, participants could indicate why PPS was useful (speed reduction, higher attention, easier detection) or why PPS was annoying (late warning, distracting). The fourth question asked participants to give some advices in order to improving PPS.

### 6.3.2 Data analysis

The first step towards the analysis of the drivers’ behavior was the plotting of the speed profiles based on the speed data recorded during the simulated drives. Each speed profile shows the driver’s speed values 150 m in advance the crosswalk and allows to obtain all the parameters (the dependent variables) describing the driver’s speed behavior in approach to the zebra crossing and his willingness to yield. A total of 369 speed profiles were plotted (41 participants x 3 scenarios x 3 crosswalk conditions). The dependent variables taken into account in this study were the following:

- $V_i$: the driver’s initial speed, when he perceive the zebra crossing and decrease his speed, releasing the acceleration pedal
- $L_{Vi}$: the distance from the zebra crossing at which $V_i$ is registered;
- $V_{min}$: the minimum speed registered at the end of the deceleration phase;
- $L_{Vmin}$: the distance from the zebra crossing at which $V_{min}$ is registered;
- $d_m$: the mean deceleration value during the deceleration phase;

as reported also in the Figure 6.2.

For three of the participants, the speed profiles did not allow to obtain the values of these variables, so the related data were excluded from the sample. For the condition of pedestrian presence, 228 left speed profiles (38 participants x 3 scenarios x 2 crosswalk conditions) were classified referring to their $TTZ*_{arr}$ value, calculated with the equation 2. It should be noted that $TTZ*_{arr}$ represents the actual interaction condition between driver and pedestrian (determined with the actual values of $L_{Vi}$ and $V_i$ obtained from the driver speed profiles). Three ranges of $TTZ*_{arr}$ were considered: a) $TTZ*_{arr} \leq 4s$; b) 4 s $< TTZ*_{arr} \leq 6s$; c) $TTZ*_{arr}$ $>$ 6 s. The numerousness of each group is reported in Table 6.10

Table 6.10: N° of driver-pedestrian interactions recorded at the driving simulator.

| Interaction condition | PPS | | | No PPS | | |
|---|---|---|---|---|---|---|
| | Urban | Suburban | Rural | Urban | Suburban | Rural |
| $TTZ*_{arr} \leq 4s$ | 16 | 10 | 10 | 15 | 13 | 17 |
| $4s < TTZ*_{arr} \leq 6s$ | 11 | 18 | 20 | 12 | 11 | 18 |
| TTZ*arr>6s | 11 | 10 | 8 | 11 | 12 | 5 |

### 6.3.3 Results

The first analysis was focused on the effects of PPS on the driver’s speed behavior for different groups of $TTZ*_{arr}$ and regardless of the road environment. For each group of TTZ*$_{arr}$ two mean speed profiles were plotted using the data obtained on the three road scenarios in conditions of absence and presence of PPS. For PPS absence, the mean speed profile in condition of absence of pedestrian was also reported. The statistical significance of the difference was calculated at every 2 m along the last 150 m in advance of pedestrian crossing with t – test on the $p<0.05$ level of the significance.

The second more in-depth analysis was focused on the explicative variables of the drivers' behavior and a set of analyses of variance (ANOVA) were performed. The objective was to study the influence of three within – subject factors (road environment, PPS and TTZ*$_{arr}$ group) on the dependent variables describing the driver behavior. More specifically, the three factors were manipulated as in the following:

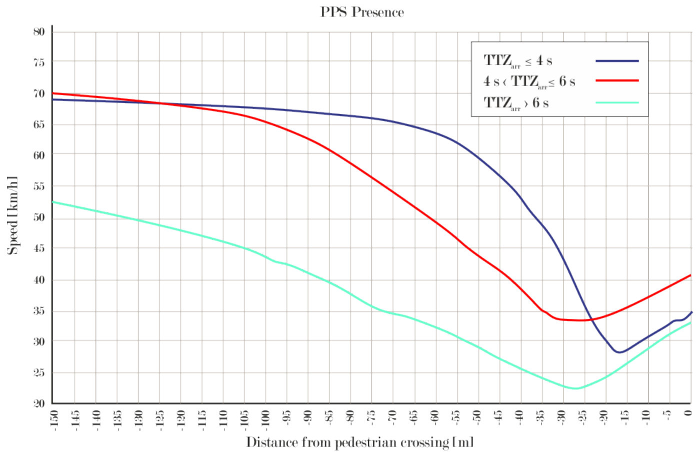
- Road environment: urban, suburban and rural (3 levels):
- PPS: presence and absence (2 levels)
- TTZ*$_{arr}$ group: $TTZ*_{\text{arr}} \leq 4s$, 4 s $< TTZ*_{\text{arr}} \leq 6s$, TTZarr* $>$ 6 s (3 levels)

In the Table 6.11 a summary of the main and interaction effects due to the three factors investigated in the present experiment is reported.

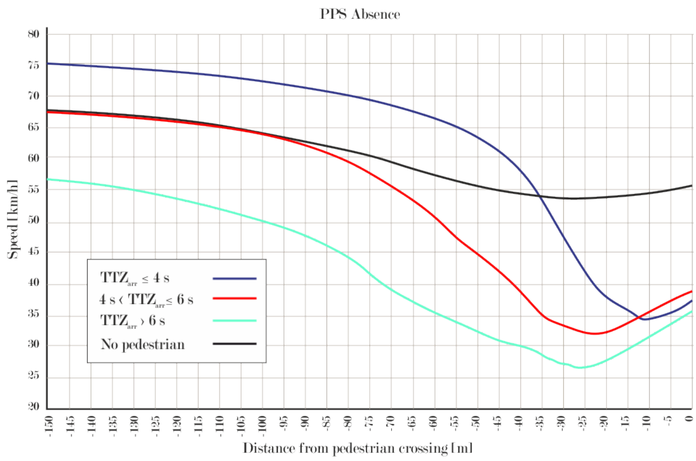
Table 6.11: Summary of main and interaction effects on dependent variables.

| Independent variable | Dependent variable | **F** | **P** |
|---|---|---|---|
| Road environment | $V_i$ | $F_{(2,291)} = 9.250$ | 0.000 |
| | $L_{Vi}$ | $F_{(2,291)} = 10.062$ | 0.000 |
| | $V_{min}$ | $F_{(2,291)} = 4.021$ | 0.019 |
| | $L_{Vmin}$ | $F_{(2,291)} = 7.470$ | 0.001 |
| PPS | $L_{Vi}$ | $F_{(1,291)} = 3.575$ | 0.060 |
| | $V_{min}$ | $F_{(1,291)} = 8.210$ | 0.004 |
| TTZ*$_{arr}$ group | $V_i$ | $F_{(2,291)} = 5.688$ | 0.018 |
| | $L_{Vi}$ | $F_{(2,291)} = 60.634$ | 0.000 |
| | $V_{min}$ | $F_{(2,291)} = 4.098$ | 0.018 |
| | $L_{Vmin}$ | $F_{(2,291)} = 29.006$ | 0.000 |
| | $d_m$ | $F_{(2,291)} = 33.112$ | 0.000 |
| Road environment by TTZ*$_{arr}$ group | $V_i$ | $F_{(4,291)} = 3.431$ | 0.009 |
| Road environment by PPS | $L_{Vmin}$ | $F_{(2,291)} = 3.315$ | 0.038 |

**Drivers' mean speed profiles** The mean speed profiles for the different categories of TTZ*$_{arr}$, both for the conditions of presence/absence of PPS and regardless of the road environment are reported in Figure 6.22.




(a)




(b)

Figure 6.22: Drivers' mean speed profiles: *a) presence of PPS b) absence of PPS*
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Results on drivers' mean speed profile highlight a similar trend. Generally, lower values of TTZ*$_{\text{arr}}$ correspond to higher speed profiles. More specifically, is possible observe the following. For $TTZ*_{\text{arr}} \leq 4s$ and for presence and absence of PPS, the speed profile is higher (significantly) than those under higher values of TTZ*$_{\text{arr}}$ (except 10-30 m in advance of the pedestrian crossing). In the last section (about 55-70 m from the zebra crossing), the drivers change abruptly their speed from approximately 65 km/h to approximately 30 km/h because they must yield to the pedestrian that started crossing. It is interesting observe that PPS presence induces drivers to anticipate the decelerating phase: the distance from the zebra crossing at which the drivers start decelerating is about 55 m without PPS, which is significantly lower than that with PPS (mean value 70 m). In addition, when the warning message is provided, drivers reach the minimum speed value farther (not significant) from the crosswalk: the distance from the zebra crossing at which the minimum speed is registered is 12 m without PPS and 18 m with PPS. For

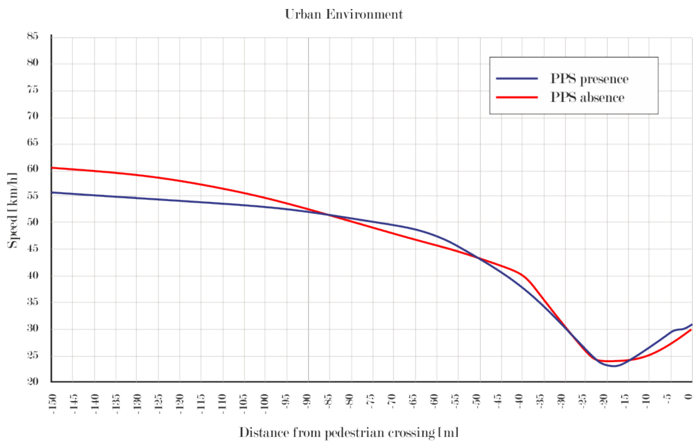
4 s $< TTZ*_{\text{arr}} \leq 6s$ and for presence and absence of PPS the speed profiles show that the speed values were lower (significant) than those for $TTZ*_{\text{arr}} \leq 4s$ (except between 150 and 80 m in the condition of PPS presence). The speed at which the driver starts the speed reduction is about 65 km/h, which is similar to that observed for $TTZ*_{\text{arr}} \leq 4s$ but the speed reduction is less abrupt than that for $TTZ*_{\text{arr}} \leq 4s$ condition. The beginning of such reduction occurs farther from the zebra crossing (at approximately 100 m for both the PPS presence and absence) and the minimum speed is approximately 32 km/h reached at about 25 m from the pedestrian crossroad. Therefore, for 4 s $< TTZ*_{\text{arr}} \leq 6s$; no relevant effects due to PPS presence were observed compared to those obtained for PPS absence condition. For $\text{TTZ*}_{\text{arr}} > 6$ s, and for presence and absence of PPS, the speed profile is the lower (significantly). The speed reduction occurs gradually and already begins in the entry point of the section object of the study, where the driver has a speed approximately of 55 km/h. The minimum speed is approximately 25 km/h and is reached at about 25 m from the pedestrian crossroad. Therefore, also for $\text{TTZ*}_{\text{arr}} > 6$ s no evident effects were observed due to the presence of PPS.

Finally, the effect of PPS for each road environment was also studied (Figure 6.23).

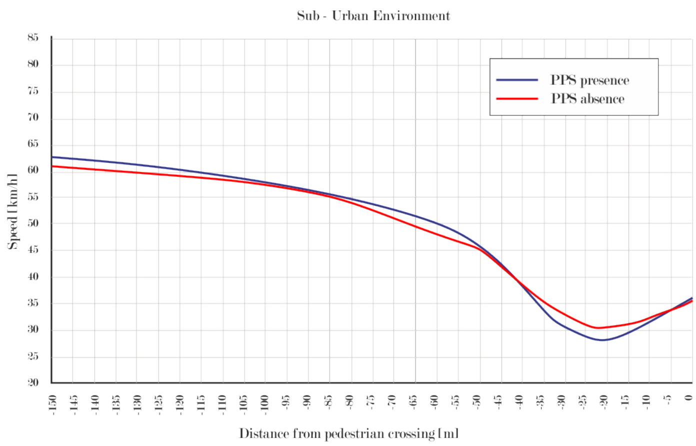
The mean speed profiles highlighted that for the urban road, when PPS was present the driver started the speed reduction immediately after the warning (between 55 and 50 m) while in the condition of PPS absence the speed reduction began 10 m after (at approximately 40 m from the pedestrian crossroad, not significant) and was more abrupt. No other effect of PPS was observed compared to the condition of PPS absence.

Similar effects were recorded also for the sub − urban environment. Results showed that when the vehicle was equipped with PPS the driver started to slow down most significantly immediately after the warning (between 60 e 55 m; the warning was provided at 66.6 m from the pedestrian crossroad), while in the condition of PPS absence the driver started a significant speed reduction approximately 10 m after (not significant).

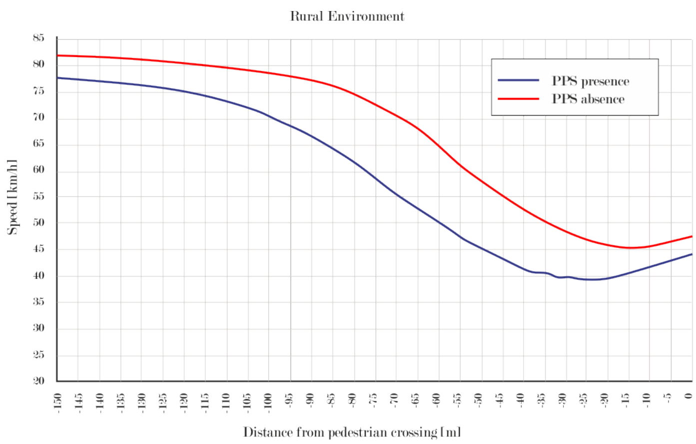
On the rural road, the main effect induced by the PPS seems to be the reaching of a lower (significantly) minimum speed (40 km/h, less of approximately 5 km/h compared to the minimum speed for the condition of PPS absence) at higher (significantly) distance from the pedestrian crossroad (mean value 30.9 m for PPS presence and 16.2 m for PPS absence condition). However, such outcomes could not be due to only the provided warning to the drivers, but also to the lower speed adopted by the driver in the point in which the warning was triggered (at approximately 78 m from the pedestrian crossroad, where the mean speed in the condition of PPS presence is approximately 13 km/h lower than that recorded for PPS absence condition).




(a)




(b)




(c)

Figure 6.23: Drivers' mean speed profiles for PPS conditions: *a) urban road b) suburban road c)rural road*

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**Drivers' speed behavior** The analysis on drivers' speed behavior was carried out through a set of ANOVAs on the explicative variables of the driving behavior. Results showed that the effects of the road environment on drivers' initial speed was significant ($F_{(2,291)} = 9.250$, $P = 0.000$); the mean value of the initial speed for the rural road (64.56 km/h) was significantly higher than that for the urban road (mean difference = 24.91 Km/h; P = 0.000) and for the for the sub – urban road (mean difference = 20.36 km/h ; P = 0.000). No other difference was significant. Also the effect of the pedestrian interaction condition on the initial speed was significant ($F_{(2,291)} = 5.688$, $P = 0.018$). The mean value for $TTZ*_{\mathrm{arr}} \leq 4s$ was 66.78 km/h, which was significantly higher than that for 4 s $< TTZ*_{\mathrm{arr}} \leq 6s$ (mean difference = 9.27 Km/h; P = 0.018) and for $TTZ^*_{arr} > 6$ s (mean difference = 25.67 km/h; P = 0.000). The effect of PPS was not significant ($F_{(1,291)} = 1.258$, $P = 0.263$). ANOVA showed that the interaction effect road environment by pedestrian interaction condition was significant ($F_{(4,291)} = 3.431$, $P = 0.009$). More specifically, for $TTZ^*_{arr} > 6$ s, which highlight a cautious driver behavior, the initial speed is almost the same among the road environments (from 40 to 43 km/h), showing the tendency of the driver to approach the zebra crossing with the same low speed, regardless of the road characteristics (Figure 6.24).

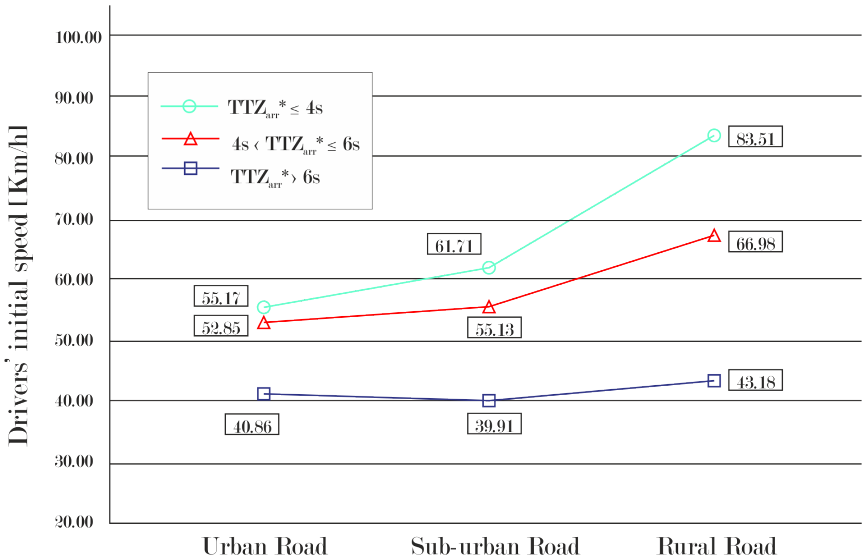


Figure 6.24: Interaction effects of road environment by pedestrian interaction condition on drivers' initial speed.

For the group 4 s $< TTZ*_{\mathrm{arr}} \leq 6s$ the driver adopted the same speeds only for the urban and suburban environment (the difference of the speed was approximately 2 km/h), while a higher initial speed was recorded on the rural road (approximately 67 km/h, higher than that recorded on suburban road of approximately 12 km/h). The speed values difference are much evident for the class $TTZ*_{\mathrm{arr}} \leq 4s$ (more aggressive driving behavior): the difference of the speed among urban and suburban road was approximately 6.5 km/h, while it was 22 km/h among sub-urban a rural environment. Such results highlight that the road environment affected the initial speed of the drivers in a significantly increasing way with the decreasing of the class of $TTZ^*_{arr}$. (i.e. progressively aggressive drivers).

Results on the variable $L_{Vi}$ showed a significant effect of the road environment

($F_{(2,291)}$ = 10.062, P = 0.000); the mean value of the variable $L_{Vi}$ for the rural road (112.09 m) was significantly higher than that for the urban road (mean difference = 24.28 m; P = 0.000) and the sub − urban road (mean difference = 15.94; P = 0.000). Moreover, for the sub − urban environment (96.15 m), the mean value of $L_{Vi}$ was significantly higher than that for the urban road (mean difference = 8.34 m; P =0.038). The effect of PPS was significant at the level of 94% ($F_{(1,291)}$ = 3.575, P = 0.060); results showed that the higher value of the variable $L_{Vi}$ was recorded for PPS presence condition (100.50 m), while for PPS absence condition the recorded value was 92.00 m. The effect of the pedestrian interaction condition was significant ($F_{(2,291)}$ = 60.634, P = 0.000). The mean value for $TTZ*_{\text{arr}} \leq 4s$ was 71.48 m, which was significantly lower than that for 4 s $< TTZ*_{\text{arr}} \leq 6s$ (mean difference = -32.43 m; P = 0.000) and for $TTZ^*_{arr} > 6$ s (mean difference = -38.70 m; P = 0.000). No other difference was significant.

The effect of the road of the road environment was significant also for the variable $V_{min}$ ($F_{(2,291)}$ = 4.021, P = 0.019); the minimum speed for the rural road (32.35 km/h) was significantly higher than that for the urban road (mean difference = 18.36 km/h; P = 0.000) and for the sub – urban road (mean difference = 14.90 km/h; P = 0.000). No other difference was significant. Also the effect of PPS condition was significant ($F_{(1,291)}$ = 8.210, P = 0.004). More specifically, the recorded minimum speed for the condition of PPS presence (20.87 km/h) was significantly lower than that for PPS presence condition (mean difference = -9.20 km/h; P = 0.004). Results showed a significant effect of the pedestrian interaction condition ($F_{(2,291)}$ = 4.098, P = 0.018); the mean value for $TTZ*_{\text{arr}} \leq 4s$ was 30.47 km/h, which was significantly higher than that for 4 s $< TTZ*_{\text{arr}} \leq 6s$ (mean difference = 6.58 km/h; P = 0.011) and for $TTZ^*_{arr} > 6$ s (mean difference = 12.68 km/h; P = 0.002). No other difference was significant.

The effect of the road environment on the distance from the zebra crossing where the braking maneuver ends was significant ($F_{(2,291)}$ = 7.470, P = 0.001). The mean value of the $L_{Vmin}$ for the urban road (25.56 m) was significantly lower than that for the rural road (mean difference = - 5.65 m; P = 0.017) and for the sub – urban road (mean difference = -5.81 m; P = 0.010). No other difference was significant. Results showed that the effect of PPS condition was not significant ($F_{(1,291)}$ = 0.976, P = 0.324). However, the interaction effect road environment by PPS condition was significant ($F_{(2,291)}$ = 3.315, P = 0.038). The results showed that the benefits of PPS were remarkable in the rural road environment, where the driver significantly increased the distance from the zebra crossing in which he ended the yielding maneuver (45.7 m) compared to the condition of PPS absence (32.03 m) (Figure 6.25).

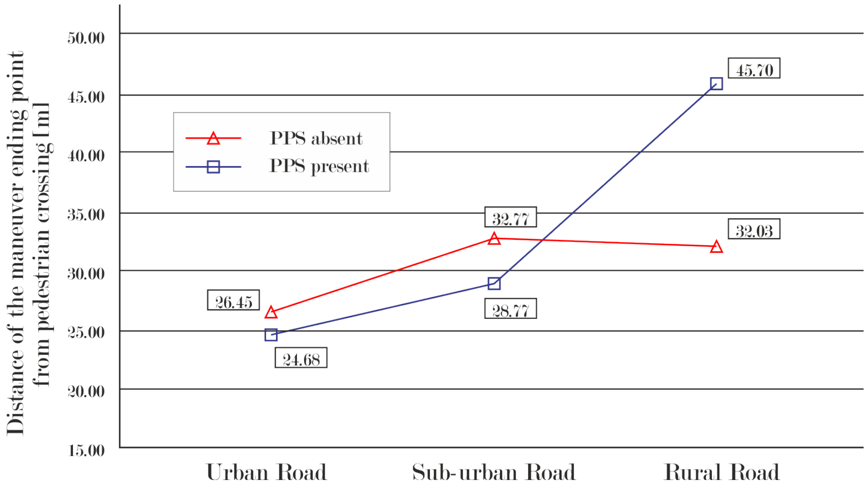


Figure 6.25: Interaction effects of road environment by pedestrian interaction condition on the variable $L_{Vmin}$.

ANOVA showed also a significant effect of the pedestrian interaction condition ($F_{(2,291)} = 29.006$, $P = 0.000$). The mean value for $TTZ*_{arr} \leq 4s$ was 21.76 m, which was significantly lower than that for 4 s $< TTZ*_{arr} \leq 6s$ (mean difference = -13.76 m; P = 0.000) and for $TTZ*_{arr} > 6$ s (mean difference = -16.89 m; P = 0.000). No other difference was significant.

The analysis on the average deceleration showed that the effects of the road environment and PPS condition were not significant ($F_{(2,291)} = 0.197$, $P = 0.821$; $F_{(1,291)} = 1.689$, $P = 0.195$, respectively), while the effect of the pedestrian interaction condition was significant ($F_{(2,291)} = 33.112$, $P = 0.000$). The average deceleration for $TTZ*_{arr} \leq 4s$ was 2.88 m/s$^2$, which was significantly higher than that for 4 s $< TTZ*_{arr} \leq 6s$ (mean difference = 1.27 m/s$^2$; P = 0.000) and for $TTZ*_{arr} > 6$ s (mean difference = 2.02 m/s$^2$; P = 0.000). No other difference was significant.

### 6.3.4 Conclusion

The objectives of the present experiment were the assessment of the effects induced on drivers' behavior by the road environment and the warning systems for pedestrian detection in different driver - pedestrian interaction conditions. The analysis of the mean speed profiles and the more in-depth analysis on the dependent variables of the driving speed behavior provided interesting findings.

As expected, the mean speed profiles showed that the driver behavior was affected both by the pedestrian interaction condition (i.e. the different $TTZ*_{arr}$) (Figure 6.22) and by the road environment (Figure 6.23). Among the different values of $TTZ*_{arr}$, regardless of the PPS condition the results confirm the outcomes obtained in literature [18] and are consistent with the behavioral model of Fuller [27]. For lower value of $TTZ*_{arr}$, the speed profiles highlight that the driver adopts higher speed and more abrupt speed reduction due to a delayed braking maneuver, highlighting a certain aggressiveness. In those cases, the driver experiences the discriminative stimulus but he wants the priority at the zebra crossing. However, the pedestrian behavior is comparable to the "competitive behavior" because he crosses the road regardless of the driver behavior and, thus, he forces the driver to a delayed response to avoid the conflict. For higher value of $TTZ^*_{arr}$, which belongs to cautious drivers, it was highlighted that the driver experiences the discriminative stimulus but he adopts the "anticipatory avoidance response". In these cases, in fact, less abrupt speed reductions were observed. When the pedestrian was absent the driver did not experienced any interaction with the pedestrian and he maintained the same speed. Comparing the speed profiles for presence/absence of PPS and for different groups of $TTZ^*_{arr}$ showed that the presence of the driving assistance system influenced only the driver behavior recorded in the condition of low value of $TTZ^*_{arr}$ ($TTZ*_{arr} \leq 4s$), which is proper of an aggressive driving behavior. For such interaction conditions, PPS presence induced drivers to anticipate the decelerating phase and to reach the minimum speed value farther from the crosswalk. As expected, the positive effects of PPS observed for $TTZ*_{arr} \leq 4s$ (i.e. aggressive driver behavior) were not so evident for the averagely cautious (4 s $< TTZ*_{arr} \leq 6s$) and very cautious drivers ($TTZ^*_{arr} > 6$ s). Such outcome is consistent with the cautious drivers' behavior that during the approaching phase to the pedestrian crosswalk were inclined to respect the priority if the pedestrian was present. Thus, the speed behavior in the presence of PPS was similar to that for PPS absence condition because the averagely cautious and cautious drivers were already breaking to give way to the pedestrian in the moment in which PPS was triggered. However, it should be noted that the important result on the aggressive drivers is remarkable, because highlight that PPS effectively influenced the behavior of those drivers whose driving style can seriously affect the pedestrian safety. The effect of PPS, among the several road environments, was similar for the urban and sub - urban roads, causing the beginning of the breaking maneuver in advance and less abrupt compared to that adopted when PPS was absent. These results highlight that PPS allows the driver to anticipate the braking maneuver to yield to the pedestrian, providing the improvement of the pedestrian safety. On the rural road PPS allowed the driver to end the yielding maneuver farther from the pedestrian crossroad with lower speed values. These results highlight that in road environments with high speed limits, in which in the case of collision with the pedestrian the consequences are worst due to the higher speeds, the presence of driving assistance systems can affect effectively the ability of the driver to complete a safer yielding maneuver, implying a remarkable improvement of the safety conditions of the pedestrian that crosses the road.

The statistical analysis on the drivers' speed behavior variables confirmed and provided more detailed outcomes due to the main factors. On overall, the driving behavior was significantly different in the rural road compared to the urban and sub – urban one in which, instead, the driving behavior is comparable. In the rural road, the drivers adopted higher speeds compared to the urban and sub – urban road ($V_i$); this outcome was expected because of the wider cross – section of the rural road and the absence of obstacles at the sides which make easier the detection of the pedestrian which is about to cross. The higher speeds induced the driver to compensate the risk by moving back the beginning point of the braking maneuver increasing the distances from the pedestrian crossings ($L_{Vi}$). In the urban and sub – urban road, the lower driver speed induced to slow down at distances nearer to the crosswalk. Consistently with the outcomes on $V_i$ and $L_{Vi}$, for the rural road the higher minimum speed ($V_{min}$) was recorded. The adoption of higher approaching speeds and the advanced beginning of the braking maneuver induced the driver to adopt higher minimum speed compared to the urban and sub – urban roads. The driver has more space to decelerate and, thus, does not need to reach an almost complete stop to give way to the pedestrian. Moreover, the driver reached the minimum speed at a distance from the crosswalk ($L_{Vmin}$) that was higher compared to the urban and sub – urban roads.

Considering the effectiveness of the PPS, the analysis showed significant effects on the variable $L_{Vi}$ (at 94%) and $V_{min}$. When the vehicle was equipped with PPS the driver was able to advance the braking maneuver due to the timely advice provided by the driving assistance system. In this condition, the driver started to decrease the speed, on average, up to 8.50 m in advance compared to the condition of absence of PPS. This means that the timely information about the presence of the pedestrian that is crossing allowed the driver to react early and effectively decrease the speed to yield to the pedestrian, improving in this way the pedestrian safety. Furthermore, when PPS was present the driver reached the lower minimum speed ($V_{min}$ = 20.87 km/h); this outcome is consistent with the findings about the effectiveness of the PPS during the interaction between drivers and jaywalking pedestrian. Similarly, also in this situation, the presence of PPS induced the driver to reach lower speed values while approaching the pedestrian crossing. The speed management is an important key factor in the improvement of the pedestrian safety; such a result, thus, is fully consistent with decreasing the probability of death in case of accident due to the less energy released by the vehicle if an impact with the pedestrian occurs.

Considering the different types of driver – pedestrian interaction (i.e. different $TTZ^*_{arr}$), the results of the statistical analysis are consistent with the outcomes of the mean speed profiles and, again, with behavioral model of Fuller [27]. On overall, results highlighted that lower values of $TTZ^*_{arr}$, related to aggressive driving behaviors, produced more abrupt maneuvers characterized by higher speed values (significantly) reached nearer (significantly) the zebra crossing, highlighting the drivers' will to obtain the priority. The delayed response to the pedestrian that was crossing, the driver ended the braking maneuver nearer to the zebra crossing with lower minimum speed (i.e. almost a complete stop) and adopted higher deceleration rates (significantly). On the contrary, for higher values of $TTZ^*_{arr}$ (i.e. more cautious driving behavior) results showed that the driver had more willingness to yield; in particular it was found that cautious drivers adopted a smoother yielding maneuver, which started at higher distances from the pedestrian crossing at lower speed values and ended farther from the pedestrian crossing with higher speed values. This yielding behavior returned also lower average deceleration rates, typical of less aggressive braking maneuvers. These findings were consistent with the literature [18] in which the kind of driving propensity (e.g. willingness to yield, aggressiveness) was different among the different types of driving - pedestrian interactions classified as in the present research.

Finally, the statistical analysis showed significant interaction effects, reported in Figure 6.24 and Figure 6.25. Specifically, the results showed that among the road environments, for the higher value of $TTZ^*_{arr}$ (i.e. more cautious drivers) the approaching speed was comparable (40.86 km/h for the urban road, 39.91 km/h for the sub – urban road and 43.17 km/h for the rural road). This outcome highlights that the cautious drivers approach in the same way the zebra crossing regardless of the road environment. On the contrary, for the other classes of $TTZ^*_{arr}$ results showed differences of the drivers' initial speed adopted on the three different road environments, which were higher with the decreasing of the $TTZ^*_{arr}$ class highlighting that the road environment affected the drivers' behavior in a significantly increasing way with the decreasing of the $TTZ^*_{arr}$ class (progressively aggressive drivers).

A significant interaction effect of the road environment by PPS condition was found for the variable $L_{Vmin}$. Results showed that the effectiveness of PPS was recorded for the rural road environment, in which the difference between the $L_{Vmin}$ values of the PPS presence and absence conditions was higher (13.67 m). This outcome highlights that in the road environment with higher speed limit, the PPS contributed to help the driver to end the braking maneuver farther from the zebra crossing. Considering the higher probability of fatal accident in case of collision at higher speeds, the contribute on the pedestrian safety highlighted in this case is remarkable.

The potential benefits of the presence of PPS were also outlined by the results of the questionnaire submitted to the participants, aimed at collecting driver's opinion on the efficacy and/or annoyance of PPS. With regard to the rural and suburban scenarios (Figure 6.26), nearly half of the participants (21 of 41 in rural environment and 22 of 41 in suburban environment) considered PPS as a useful tool for an easier pedestrian detection; meanwhile, nearly half of the drivers did not think it is an effective instrument. In the urban environment, this percentage is slightly higher: 59% of the drivers (25 of 41) perceived PPS as a useful tool, probably because of the major complexity and elements of distraction of the city environment.

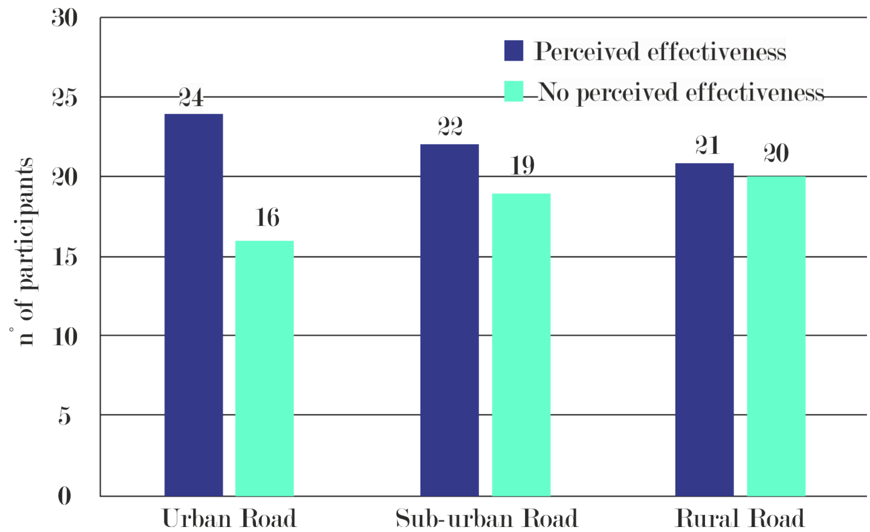


Figure 6.26: smallOutcomes of the questionnaire about PPS efficacy rates among road environments.

In all scenarios, drivers who have found PPS useful (participants could answer with more than one choice regarding the kind of perceived effectiveness and annoyance) stated that a warning message led to an increase of attention. In urban and sub-urban scenario participants stated that PPS facilitates the pedestrian detection (8 and 9 participants, respectively), while in the rural environment, the lower number of drivers (7) stated that PPS make pedestrian detection easier: it is probably due to the simplicity of this environment, which lacks of elements that can occlude pedestrians (Figure 6.27).

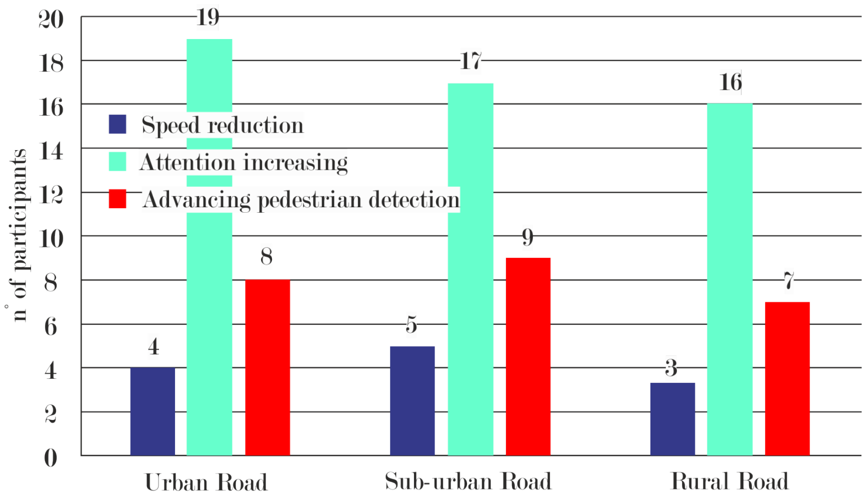


Figure 6.27: Outcomes of the questionnaire about perceived effectiveness of PPS.

Only three participants found the warning system to be annoying in urban and suburban scenario, 4 in the rural one (Figure 6.28a). The causes of this annoyance are variously distributed between “distraction caused” and “late timing of the warning” (Figure 6.28b).

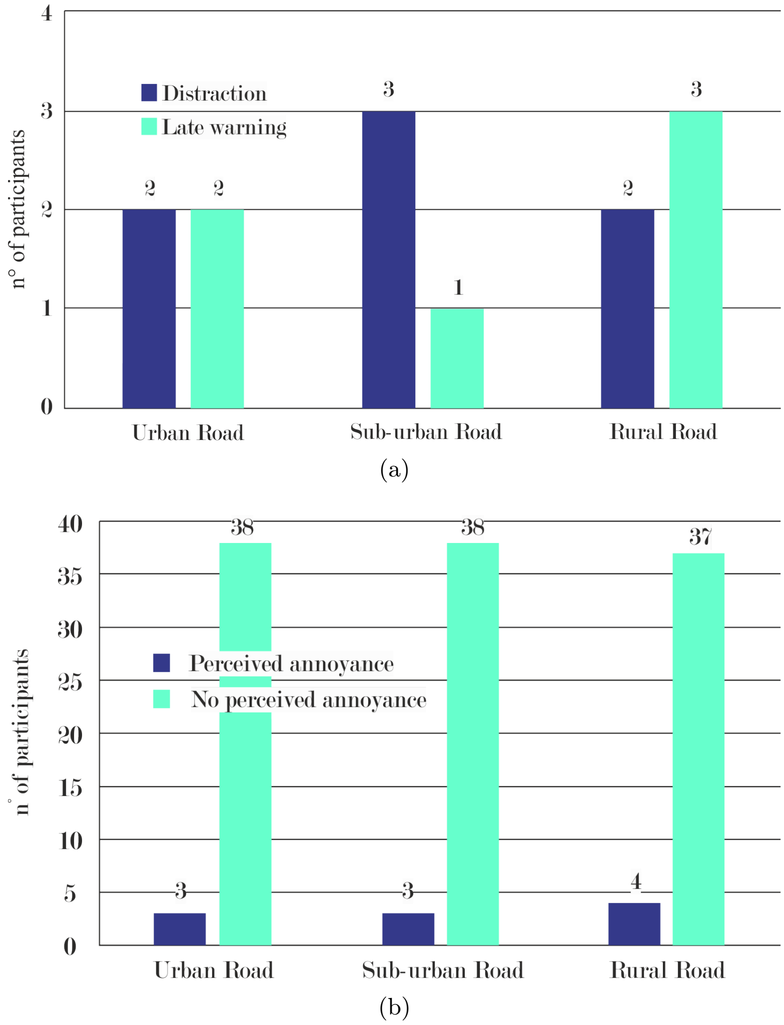


Figure 6.28: Outcomes of the questionnaire about the perceived annoyance of PPS.
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According to the questionnaire results, it is clear that this warning system do not generally annoy drivers. However, while nearly half of the participants believe it to be an effective tool for pedestrian detection, the other half of them do not perceive it as a useful tool. In this questionnaire, participants were also asked to give some advice for a better run of the system: 11 participants suggest to anticipate the warning message, 3 of them state that the warning symbol should be clearer, and 3 left drivers suggest that PPS should provide a directional warning, which indicates where the threat is. On overall, the outcomes of the questionnaire highlight that this kind of PPS has a great potential, but it must be improved in order to increase its efficacy. To accomplish this aim, useful indications provided by the participants should be considered (anticipate the warning message, warning symbol should be clearer, PPS should provide a directional warning).

# Chapter 7

# Experiments on driver - cyclist interaction

## 7.1 Safety measure at cyclist crossroads: effects on drivers' behavior

The aim of the experiment was to analyze the driving behavior while approaching the bicycle crossroad under different crossroad configuration and driver - cyclist interaction. To achieve the objective, the following main factors were implemented in the simulated scenarios:

- three bicycle crossroad configurations: two countermeasures (colored paved markings and raised island) and the condition of no treatment (baseline condition);
- two conditions of vehicle-cyclist interaction: in addition to the cyclist absence, another condition of vehicle-cyclist interaction was implemented in the driving simulator.

In particular, the condition of cyclist presence was represented by a cyclist which started the movement at 20 m from the collision point when the driver was at 50 m from it. The speed of the cyclist was set at 20 Km/h. Assuming the driver speed equal to 50 Km/h, in such conditions the driver and cyclist have the same Time To arrive ($TT_{arr}$) to the collision point, equals to 3.6 s.

### 7.1.1 Experiment design

For the analysis of the driving behavior towards the cyclist that crosses the road, an experimental road scenario of two – lane suburban road about 7.6 Km long was designed. To ensure the same approaching condition for each participant, 9 signalized intersections were placed in advance of each bicycle crossroad. 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 bicycle crossroad was equal to 400 m, which allowed the drivers to reach a congruous speed for the simulated scenario. The posted speed limit was 50 Km/h while the cross-section was 10 m wide, formed by two 3.00 m wide lanes, two paved shoulders 0.50 m wide and two curbs 1.50 m wide, according the Italian road design guidelines [113]. According to the Italian Highway Code [111] the bicycle crossroad was 1.50 m wide and three vertical signs were posted: one at 150 m in advance of the bicycle crossroad to signal the presence of it. One at 10 m, to advice the driver to yield if the cyclist was present and one in correspondence of the bicycle crossroad. This configuration represents the baseline condition (Figure 7.1a). In addition to the baseline condition, two types of countermeasures were placed in the scenario: colored paved markings and raised island. The first was the red painting of the bicycle crossroad (Figure 7.1b), while the second was a physical facility 40 m long, 0.50 m wide and 0.05 m height (Figure 7.1c), implying the narrowing of the vehicle lane to 2.75m.

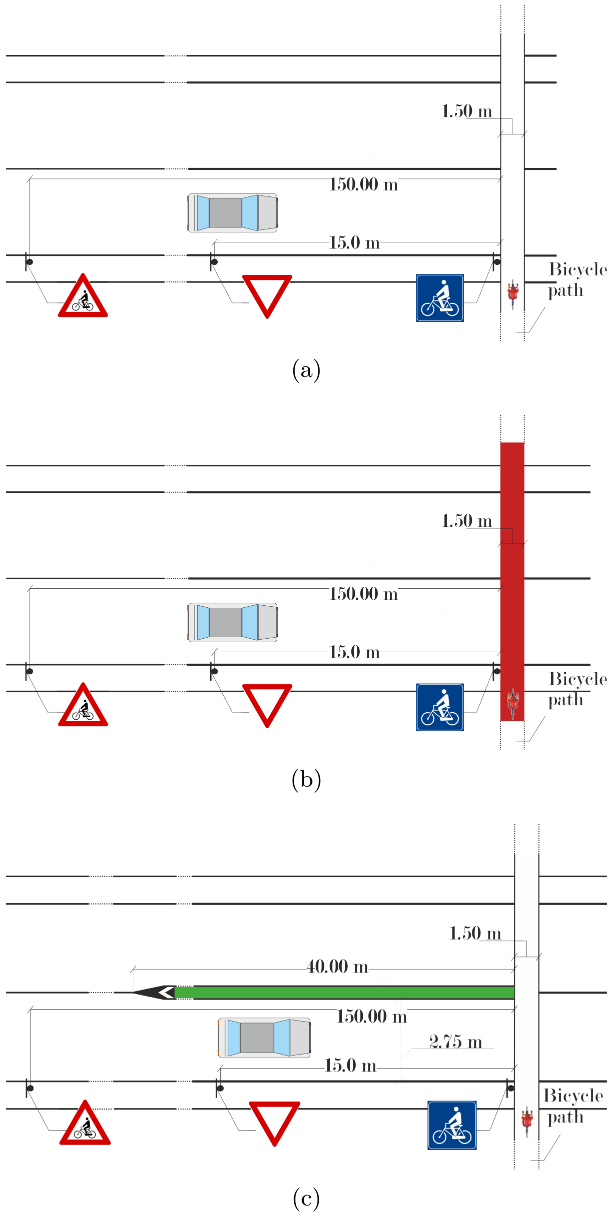


Figure 7.1: Safety measures at bicycle crossings: *a) baseline condition b) colored paved markings c) raised island*

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At six bicycle crossroads (2 for the baseline condition, 2 for the colored paved markings and 2 for the raised island) a cyclist coming from driver right side crossed the road. The cyclist was set to start the crossing at 20 m from the collision point when the driver was at 50 m from it. The speed of the cyclist was 20 Km/h. Assuming the driver speed equal to 50 Km/h, in such condition the driver and cyclist have the same time to arrive (3.6 s) to the collision point. It should be noted that this condition is representative of a theoretical driver – cyclist interaction, which occurs only if the driver adopts the hypothesized speed value. Forty-two drivers (24 men and 18 women), whose ages ranged from 24 to 59 (mean = 29.3; SD = 8.5) and who had regular European driving licenses for at least three years (mean = 11.0; SD = 8.0) were selected to perform the driving in the simulator. According to the questionnaire on perceived discomfort, no participant was excluded from the analysis due to the perceived discomfort. Thus, the sample used for the analysis consisted of all 42 drivers. To avoid a potential effect of the order on the driver's behavior, 3 road scenarios that have a different sequence of the 9 combinations of bicycle crossroad (baseline condition, colored paved markings and raised island) x cyclist (cyclist absence and two conditions in which the cyclist was crossing the road) were implemented in the driving simulator. The participants were divided into 3 groups and each group was assigned to only one road scenario. Thus, each group experienced a different presentation sequence of the 9 combinations of crossroad layout x cyclist condition. After the driving simulation the participants filled a questionnaire about the perceived effectiveness of the safety measures; in particular, the participants could select a score from null (zero) to high (three) about the effects of driving aid and obstacle of each countermeasure.

### 7.1.2 Data analysis

In order to analyze the driving behavior during the interaction with the cyclist at the bicycle crossroad the speed profiles of the last 150 m in advance of each one of the 9 bicycle crossroads along the alignment were plotted. Overall, 378 speed profiles were plotted (42 drivers x 9 bicycle crossroads), from which the dependent variables explicative of the driving behavior were obtained similarly to those obtained from the drivers' speed profiles concerning the driver-pedestrian interaction. In particular the following variables were analyzed:

- $V_i$: initial speed, is the speed identified at the moment when the driver starts to decrease his speed, in response to the cyclist that is crossing;
- $L_{Vi}$: initial speed distance, is the distance from the bicycle crossroad where $V_i$ is recorded;
- $V_{min}$: minimum speed, is the minimum value of the speed during the driver braking maneuver;
- $L_{Vmin}$: minimum speed distance, is the distance from the bicycle crossroad where $V_{min}$ is recorded;
- $d_m$: average deceleration, is the average deceleration adopted by the driver during the entire braking maneuver obtained from the equation (3)
- SRT: speed reduction time, is the elapsed time to pass from the initial speed to the minimum speed.

### 7.1.3 Results

Four analyses were performed. The first analysis was focused on the drivers mean speed profiles which were plotted for different groups of $TT_{arr}$, determined with the equation (2). $TT_{arr}$ which is the time left for the driver to arrive at the bicycle crossroad in the moment in which he started to decelerate, regardless of the cyclist position. It should be noted that the $TT_{arrive}$ implicitly determined a classification of the interactions based on the driver's characteristics. Drivers with low "availability" to yield determined low $TT_{arrive}$, because they tended to start to slow down when they were close to the bicycle crossroad and/or from high initial speeds. Drivers with high "availability" to yield, instead, determined high values of $TT_{arrive}$ because they tended to start to reduce the speed when they were far from bicycle crossroad and/or from low initial speeds. Speed profiles also showed several events when drivers did not yield because they accelerated to pass the conflict point before the cyclist. However, no case of collision was recorded.

In the Table 7.1, for the 3 configurations of bicycle crossroad, the number of driver-cyclist interactions, the mean, maximum and minimum values of $TT_{arrive}$, the number of driver-cyclist interactions for several groups of values of $TT_{arrive}$ are reported.

Table 7.1: Actual driver - cyclist interaction recorded at the driving simulator.

| **Safety measure** | **N° of vehicle-cyclist interaction (a)** | | | **$TT_{arrive}$** | | | | **N° of failed yields (b)** |
|---|---|---|---|---|---|---|---|---|
| | | Mean [s] | Max [s] | Min [s] | $TT_{arr} \leq 3s$ | 3s<$TT_{arr} \leq 4s$ | $TT_{arr}$ >4s | |
| Baseline condition | 72 | 4.1 | 9.1 | 1.4 | 31 | 28 | 28 | 12 |
| Raised island | 79 | 4.6 | 10.7 | 1.2 | 13 | 43 | 38 | 5 |
| Colored paved markings | 78 | 4.2 | 9.0 | 1.1 | 24 | 29 | 34 | 6 |
| Total (a+b) | | | | | 252 | | | |

The Table 7.2 reports the mean values and the standard deviation of the variables obtained from the speed profiles. The speed profiles also highlighted several events in which the driver did not yield to the cyclist, reported also in Table 7.1. More specifically, 12 failed yields were recorded for the baseline condition, 6 for the colored paved markings and 5 for the raised island. These cases were excluded from the analysis due to the missed driver – cyclist interaction at the bicycle crossroad. This event was due to the high speed adopted by the driver which passed, thus, the conflict point before the cyclist.

The main aim of this analysis was to investigate the drivers' behavior while approaching the bicycle crossroad under different bicycle crossroad safety measures and under different interaction conditions of vehicle-cyclist (and therefore implicitly by the driver's characteristic) determined by the actual values of speed recorded at the driving simulator during the tests. This first analysis was then deepened considering the points at 60m, 40m and 20m in advance of the bicyclist crossroad, which are the section where a major change in the drivers behavior is expected due to the proximity with the cyclist to the collision point. In particular, the drivers' speed was analyzed with the ANOVA analysis to assess the speed adaptation of the driver among the several safety measures, the driver-cyclist interaction conditions and the distance from the bicycle crossroad.

A further in-depth analysis was performed on the dependent variables obtained from each driver speed profiles. This analysis was not performed for different values of $TT_{arr}$ (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 cyclist in the common conditions of vehicle-cyclist interaction that occur at bicycle crossroad. As explained for the analysis of the driver-pedestrian interaction, the cyclist presence condition implicitly includes a wide range of vehicle-pedestrian interactions.

Table 7.2: Descriptive statistics of the driver-cyclist interaction dependent variables

| Dependent variable | Countermeasure | Cyclist condition | Mean | SD |
|---|---|---|---|---|
| $V_i$ [km/h] | Baseline | Cyclist absent | 44.46 | 8.03 |
| | | Cyclist present | 42.77 | 10.90 |
| | Colored paved markings | Cyclist absent | 43.81 | 14.36 |
| | | Cyclist present | 41.00 | 9.47 |
| | Raised island | Cyclist absent | 11.86 | 2.58 |
| | | Cyclist present | 42.48 | 9.79 |
| $L_{Vi}$ [m] | Baseline | Cyclist absent | 61.16 | 15.61 |
| | | Cyclist present | 40.23 | 10.40 |
| | Colored paved markings | Cyclist absent | 58.72 | 15.50 |
| | | Cyclist present | 45.69 | 10.25 |
| | Raised island | Cyclist absent | 55.62 | 18.75 |
| | | Cyclist present | 41.47 | 11.33 |
| $V_{min}$ [km/h] | Baseline | Cyclist absent | 30.71 | 11.92 |
| | | Cyclist present | 17.14 | 11.56 |
| | Colored paved markings | Cyclist absent | 29.09 | 13.75 |
| | | Cyclist present | 17.57 | 10.15 |
| | Raised island | Cyclist absent | 27.07 | 13.32 |
| | | Cyclist present | 17.60 | 10.98 |
| $L_{Vmin}$ [m] | Baseline | Cyclist absent | 25.33 | 11.09 |
| | | Cyclist present | 20.64 | 9.91 |
| | Colored paved markings | Cyclist absent | 28.29 | 17.02 |
| | | Cyclist present | 26.07 | 10.93 |
| | Raised island | Cyclist absent | 26.39 | 15.22 |
| | | Cyclist present | 20.84 | 11.23 |
| $d_m$ [m/s$^2$] | Baseline | Cyclist absent | 1.20 | 1.06 |
| | | Cyclist present | 2.75 | 1.56 |
| | Colored paved markings | Cyclist absent | 1.37 | 1.00 |
| | | Cyclist present | 2.58 | 1.58 |
| | Raised island | Cyclist absent | 1.59 | 1.60 |
| | | Cyclist present | 2.64 | 1.70 |

The analysis was conducted by means of a analysis of variance (ANOVA) 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: safety measures (with 3 levels: baseline condition, colored paved markings and raised island) and cyclist conditions (with 2 levels: presence and absence of a cyclist). The last analysis was performed on the variable SRT and was conducted by means of the survival analysis (see Appendix A), which allows to highlight the relationship between the covariates of the model (i.e. the independent variables) and the time variable. The use of the survival analysis in this context is justified by the fact that the modeling of the dependent variable (SRT) ensure only positive values, consistently with the nature of the variable. Other statistical methods, such as mixed linear models are restricted in the field of the duration data due to some model assumptions and the unique character of the empirical data (i.e. empirical duration data are limited to have positive values because negative values of time do not exist for definition) [115].

**Mean speed profiles** The drivers' mean speed profiles were plotted for each countermeasure, for 3 groups of $\mathrm{TT}_{\mathrm{arr}}$ values and for the cyclist absence condition Figure 7.2. It should be noted that the speed profiles for the "no cyclist" condition were obtained from all the cases (3 countermeasures x 42 drivers) in which the driver, while approaching the bicycle crossroad, did not encounter the cyclist. For all the countermeasures and for $TT_{\mathrm{arr}} \leq 3s$, the speed profile is higher than those for higher values of $\mathrm{TT}_{\mathrm{arr}}$. However, in the last section in advance of the bicycle crossroad, approximately 40 m in advance of the bicycle crossroad, an abrupt speed reduction is observed starting from approximately 52.2 km/h to 25.2 km/h because the driver is forced to yield to the cyclist that is crossing.

Among the safety measures, the minimum speed value was reached at 20 m from the bicycle crossing for the raised island and the colored paved markings, while for the baseline condition is located is located nearer to the bicycle crossing, at approximately 15 m in advance of it. Moreover, the minimum speed values are approximately 23.4 km/h for the raised island and the colored paved markings, while for the baseline conditions is 28.1 km/h. For all the countermeasures and for $3s < TT_{\mathrm{arr}} \leq 4s$, the speed profiles show that the speed values were lower than those for the condition of $TT_{\mathrm{arr}} \leq 3s$. The beginning point of the abrupt speed reduction is located farther from the bicycle crossroad; for the baseline condition is approximately at 50 m from the bicycle crossroad, while for the raised island and the colored paved markings is located at approximately 40 m. However, the speed value at which the deceleration begins is higher for the baseline condition (approximately 49.3 km/h) than that for the raised island and the colored paved markings (approximately 43.2 km/h and 46.8 km/h, respectively). The minimum speed values are located at approximately 30 m from the bicycle crossing for the baseline condition and the colored paved markings, while is located at approximately 25 m from the bicycle crossing for the raised island. However, the minimum speed values are higher for the baseline condition and the colored paved markings (approximately 28.8 km/h) than that for the raised island (approximately 25.2 km/h). For all the countermeasures and for $\mathrm{TT}_{\mathrm{arr}} > 4$ s, the speed profiles are lower than those for the other $\mathrm{TT}_{\mathrm{arr}}$ values. The speed reduction occurs gradually, starting from more than 90 m away from the bicycle crossroad. The corresponding speed value is approximately 46.8 km/h. The minimum speed is located at approximately 35 m from the bicycle crossing and the values are approximately 25.2 km/h. For the condition of no cyclist and for all the countermeasures a gradual speed reduction was observed, starting from a speed value approximately of 50.4 km/h until the minimum speed value. The minimum speed is reached at approximately 30 m from the colored paved markings and the baseline condition, while is located at approximately 25 m for the raised island.

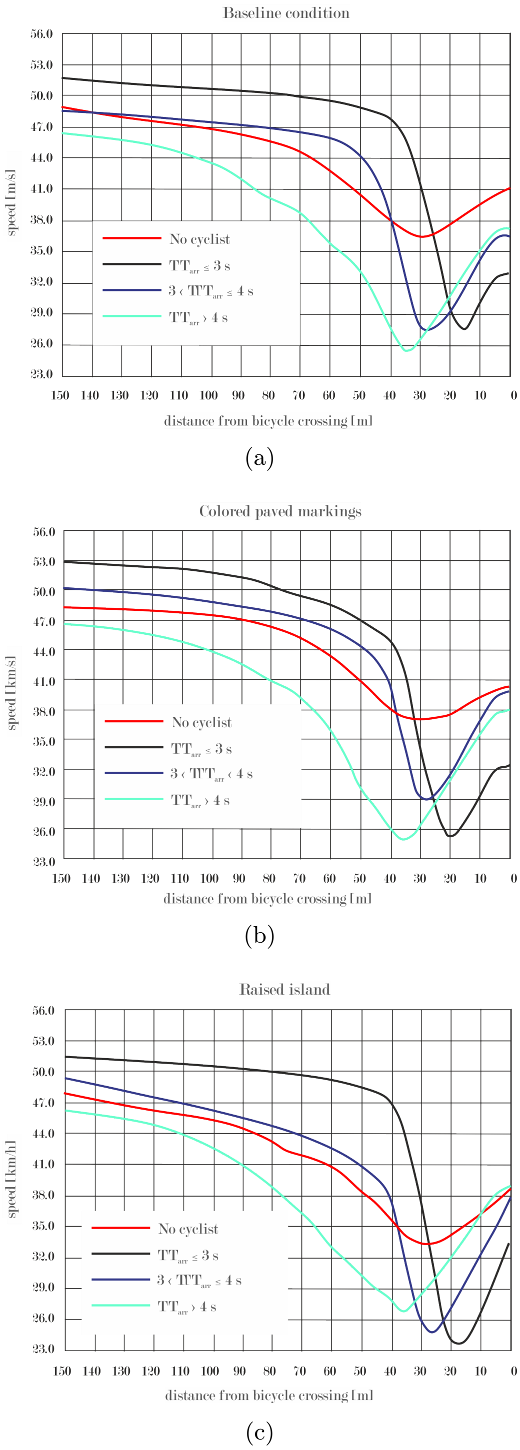


Figure 7.2: Drivers' mean speed profile at bicycle crossroad: *a) baseline condition b) colored paved markings c) raised island*

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However, the minimum speed value is lower for the raised island (approximately 34.6 km/h) than those for the baseline condition and colored paved markings (38.5 km/h and 39.2 km/h, approximately). This result, together with the results on the minimum speed for the average cautious and cautious drivers (i.e. $3s < TT_{\text{arr}} \leq 4s$ and $\text{TT}_{\text{arr}} > 4$ s) is reasonably due to characteristic of the physical facility which reduces the lane width, inducing the driver to pass the crossroad with a lower speed.

After the analysis on the mean speed profiles, a more in-depth analysis on the drivers' speed profiles was carried out by means of ANOVA, focusing on the last 60 m in advance of the bicycle crossroad, which are the sections where the more evident changes in the driving behavior were observed. ANOVA showed that there was a significant (al level of 5.2%) main effect of the countermeasures ($F_{2,1116} = 2.919$, $P = 0.052$, partial Eta squared = 0.005, observed power = 0.570). Pairwise comparison showed that the driver speeds for the colored paved markings and the raised island (39.2 km/h and 38.9 km/h, respectively) were less than that for the baseline condition (41.4 km/h). This outcome is consistent with the aim of the countermeasures, which provide a better information about the presence of the bicycle crossroad helping him to adapt the speed. Statistical analysis showed that there was a significant main effect of the distance from the bicycle crossroad ($F_{2,1116} = 73.731$, $P = 0.000$, partial Eta squared = 0.117, observed power = 1.000). Pairwise comparison showed that the speed at 60 m from bicycle crossroad (46. 4 km/h) was significantly higher than that at 40 m from bicycle crossroad (mean difference = 5.7 km/h; $P = 0.000$) and at 20 m from bicycle crossroad (mean difference = 13.7 km/h). Moreover, the speed at 40 m from bicycle crossroad was significantly higher than that at 20 m from bicycle crossroad (mean difference = 7.9 km/h; $P = 0.000$). This result was expected because the driver, while approaching the bicycle crossroad, reduced his speed in order to detect the presence of the cyclist. ANOVA showed that there was a significant main effect for the cyclist conditions ($F_{1,1116} = 9.950$, $P = 0.002$, partial Eta squared = 0.009, observed power = 0.883). Moreover, the speed for the condition of cyclist presence (38.9 km/h) was lower than that for the condition of cyclist absence (mean difference = 2.9 km/h; $P = 0.002$). This result showed that the driver was affected by the presence of the cyclist and, thus, reduced the speed to give way.

A significant interaction effect was found for distance from the bicycle crossroad by driver – cyclist interaction ($F_{2,1116} = 13.038$, $P = 0.000$, partial Eta squared = 0.023, observed power = 0.997). No other significant interaction effect was found. Results showed that the driver's behavior was affected by the presence of the cyclist in the section between 40 m to 20 m from the bicycle crossroad. At 60 m and at 40 m from bicycle crossroad, in fact, the driver's speed is almost the same among the cyclist conditions (Figure 7.3a), which is reasonably due to the fact that at high distance from the collision point the driver does not perceive yet the possible presence of the cyclist. Therefore, in the section nearest the bicycle crossroad the cyclist condition influenced the driver's behavior. In the section between 40 m to 20 m from the bicycle crossroad the speed reduction was 10.8 km/h when the cyclist was present, while for the condition of cyclist absence was 1.8 km/h. Thus, when the cyclist was present the driver decreased the speed in order to yield to the cyclist. For the condition of no cyclist the driver did not perceived the presence of the cyclist and, thus, maintained approximately the same speed.

It should be noted that, even if not significant, the interaction effect distance from bicycle crossroad by countermeasure ($F_{4,1116} = 1.551$; $P = 0.208$) provided interesting results (Figure 7.3b).

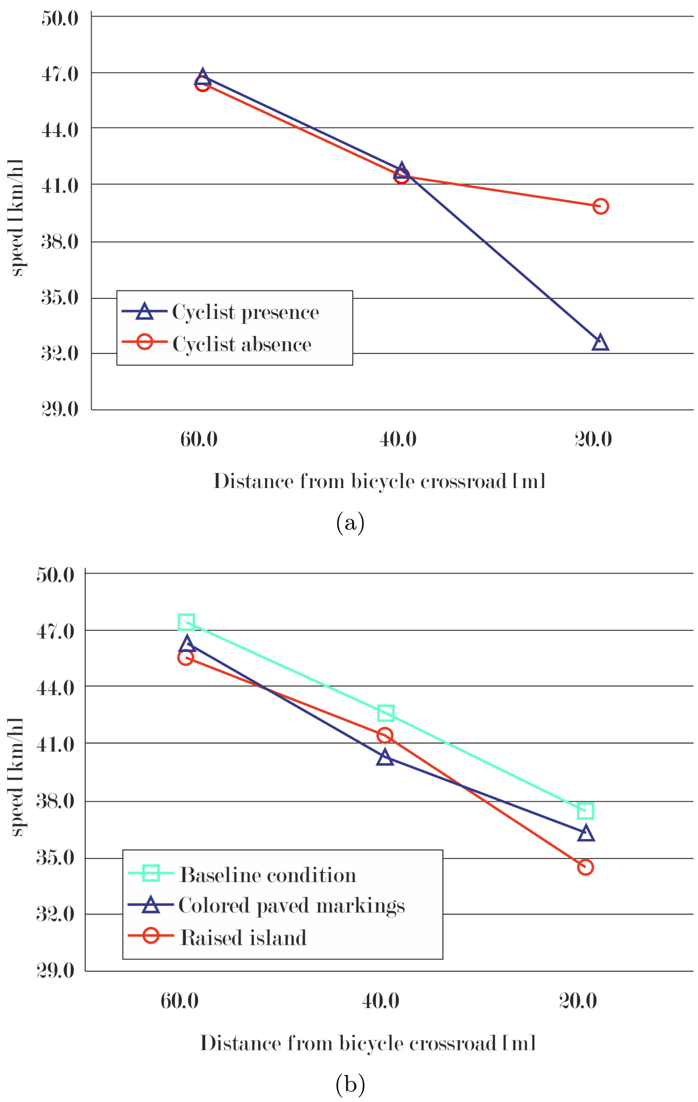


Figure 7.3: Interaction effects on drivers' behavior: *a) distance from bicycle crossroad by driver - cyclist condition b) distance from bicycle crossroad by safety measure*

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When the driver was at 60 m from bicycle crossroad, the driver was not influenced by the colored paved markings and raised island (mean driver speed of 46.4 and 45.4 km/h, respectively) because he was far from the bicycle crossroad. Passing from 60 m to 40 m in advance of the bicycle crossroad, the driver reduced the speed more for the colored paved markings (7.2 km/h) than the raised island (5.0 km/h). From 40 m to 20 m in advance of the bicycle crossroad, the driver continued to decrease the speed but to a lesser extent for colored paved markings. This points out that:

- the colored paved markings provides an advanced information to the driver about the presence of a bicycle crossroad, allowing him to decrease (with higher rates) the speed since 60 m in advance the bicycle crossroad;

- the raised island, instead, induces a driver speed reduction that is more pronounced in the section between 40 m and 20 m, where it is physically present; in this section, the countermeasure determines a reduction of the lane width, which produces a greater influence in terms of speed reduction.

In other terms, it seems that the driver's behavior is actually affected by the specific peculiarities of the two countermeasures (better visibility and information to the driver for the colored paved markings and greater "physical" influence for the raised island in the section nearest to the bicycle crossing).

**Drivers' speed behavior** With the aim of analyze the driver speed behavior in response to a cyclist that crosses the road under different bicycle crossroad safety treatments, a set of Analysis of Variance (ANOVA) was carried out to verify the effects due to the countermeasure condition (baseline condition, raised island and colored paved markings) and the cyclist condition (presence/absence) on the dependent variables obtained from the drivers' speed profiles ($V_i$, $L_{Vi}$, $V_{min}$, $L_{Vmin}$, $d_m$).

The effects of the countermeasures on drivers' initial speed was not significant ($F_{(2,349)} = 0.335$, $P = 0.715$); the mean value of the initial speed was 43.59 km/h under the baseline conditions, 42.41 km/h for the colored paved markings and 42.59 km/h for the raised island. Also the effect of the cyclist condition on the initial speed was not significant ($F(1,349) = 1.517$, $P = 0.219$). The mean value under the cyclist absence condition was 43.63 km/h while for the cyclist presence condition was 42.08 km/h.

Results showed a non-significant effect of the countermeasures on the variable $L_{Vi}$ ($F_{(2,349)} = 1.775$, $P = 0.171$). For the baseline condition the mean value was 50.63 m, while for the colored paved markings and the raised island the mean values were 52.20 m and 48.75 m, respectively (Fig. 2.b). Conversely, the effect of the cyclist condition was significant ($F_{(1,349)} = 97.854$, $P = 0.000$). The pairwise comparison showed that the point in which the driver started to decrease the speed was significantly further from the bicycle crossroad when the cyclist was present (mean value = 58.50 m) than that for the cyclist absence condition (mean difference = 16.04 m; P = 0.000) (Figure 7.4).

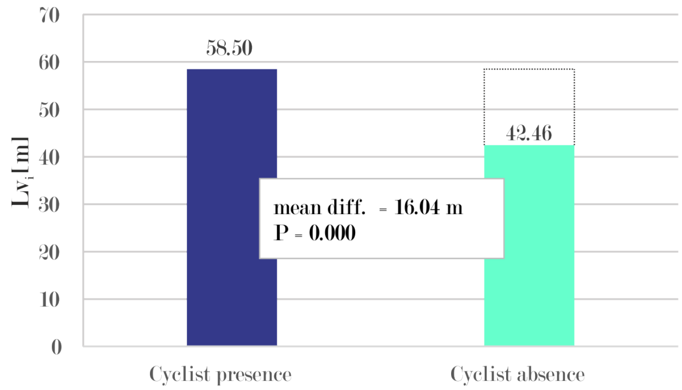



Figure 7.4: Main effects of cyclist condition on drivers' initial speed.

The analysis showed that the effect of the countermeasures on drivers' minimum speed was not significant ($F_{(2,349)} = 0.406$, $P = 0.667$). For the baseline condition the mean value was 23.33 km/h, while for the colored paved markings and the raised island the mean values of the variable $V_{min}$ were 23.90 km/h and 22.36 km/h, respectively. The effect of the cyclist condition affected the drivers' minimum speed in a significantly way ($F_{(1,349)} = 61.108$, $P = 0.000$); the pairwise comparison showed that for the cyclist present condition (mean value = 17.42 km/h) the minimum speed was significantly lower than that for the cyclist absent condition (mean difference = 11.52 km/h, P = 0.000) (Figure 7.5).

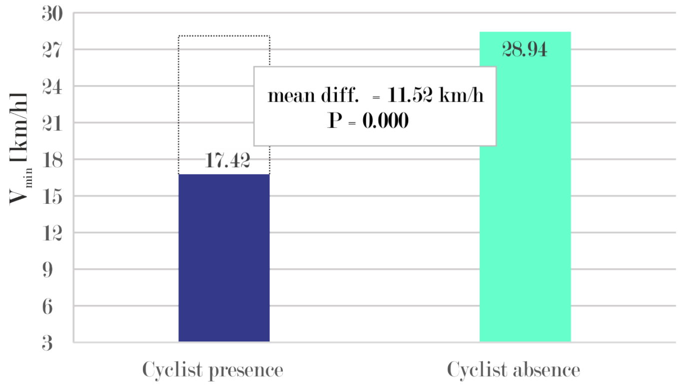
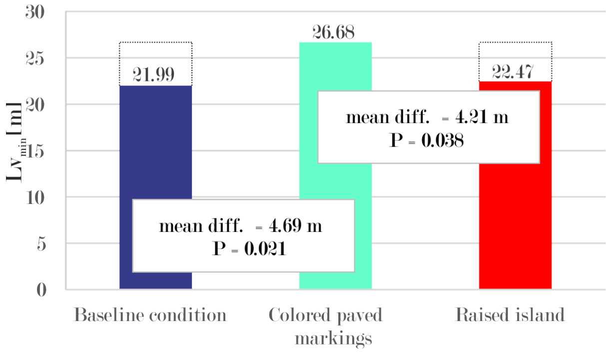


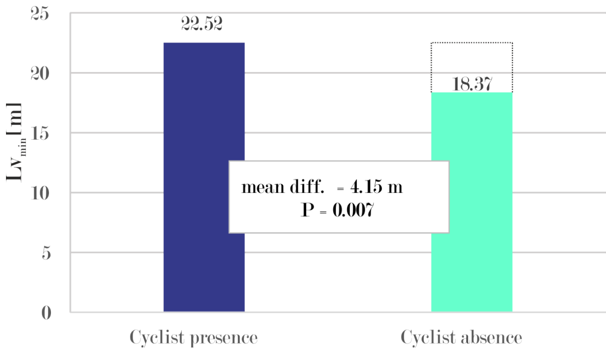

Figure 7.5: Main effect of cyclist condition on drivers' initial speed.

The effect of the countermeasure condition on the variable $L_{Vmin}$ was significant ($F_{(2,349)} = 4.586$, $P = 0.011$); post – hoc analysis revealed that the drivers ended the yielding maneuver farther from the bicyclist crossroad under the condition of colored paved markings (mean value = 26.68 m), while for the baseline condition and the raised island the mean values were significantly less (mean difference = 4.69 m, P = 0.021; mean difference = 4.21, P = 0.038). No other difference was significant (Figure 7.6a). The effect due to the cyclist condition was also significant ($F_{(1,349)} = 7.366$, $P = 0.007$). Results showed that for the cyclist present condition (mean value = 22.52 m) the variable $L_{Vmin}$ was significantly higher than that for the cyclist absence condition (mean difference = 4.15 m, P = 0.007) (Figure 7.6b).

markings




(a)




(b)

Figure 7.6: Main effects on drivers' distance at which the braking maneuver ends: *a) safety measure b) cyclist condition*

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Finally, the statistical analysis revealed that the effect of the countermeasure on drivers' average deceleration rate was not significant ($F_{(2,349)} = 0.220$, $P = 0.802$); however it should be noted that the lower mean value was obtained for the colored paved markings (1.81 $m/s^2$); higher mean values were recorded for the baseline condition (1.98 $m/s^2$) and for the raised island (2.11 $m/s^2$). Conversely, the effect of the cyclist condition was significant ($F_{(1,349)} = 42.675$, $P = 0.000$). The pairwise comparison showed that the average deceleration rate when the cyclist was present (mean value = 2.66 m/s2) was significantly higher than that for the cyclist absence condition (mean difference = 1.27 $m/s^2$, $P = 0.000$) (Figure 7.7).

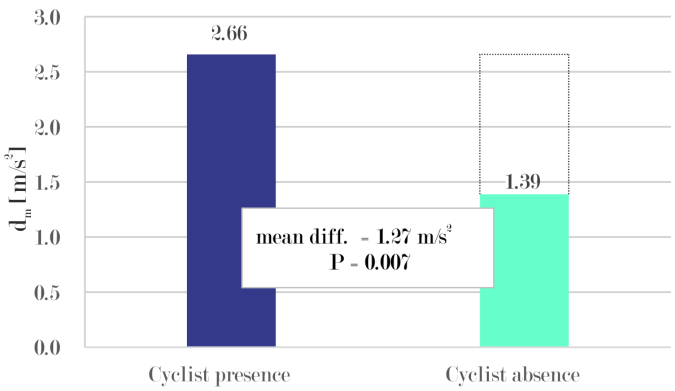



Figure 7.7: Main effect of cyclist condition on drivers' average deceleration.

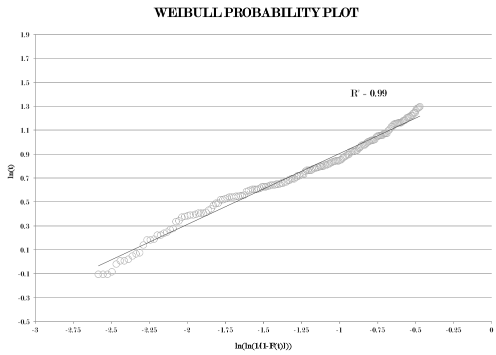
**Hazard-based duration model of the Speed Reduction Time** The time to reduce the speed from the initial value to the minimum value preliminary tested and compared across the countermeasures by using the ANOVA test, to asses if the safety measures affect the driver's braking behavior while yielding to the cyclist under different treatments of bicycle crossroad. Bonferroni correction was used for multiple comparisons. In the Table 7.3 the descriptive statistics of the continuous variables used to model the speed reduction time are reported.

Table 7.3: Descriptive statistics of the set of variables used for modeling SRT during the driver-cyclist interaction.

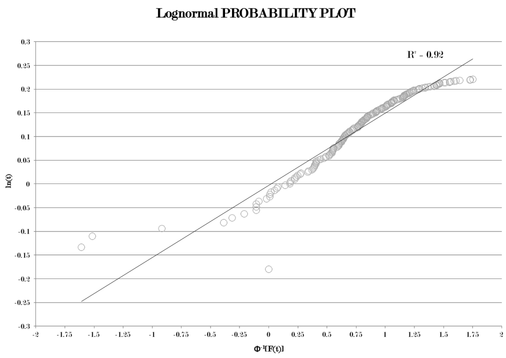
| Variable | Mean value | Standard deviation |
|---|---|---|
| $V_i$[km/h] | 42.05 | 10.04 |
| $L_{Vi}$ [m] | 42.58 | 10.89 |
| $V_{min}$[km/h] | 18.11 | 11.02 |
| $L_{Vmin}$[m] | 21.57 | 11.00 |
| $d_m$[m/s$^2$] | 2.67 | 1.60 |
| SRT [s] | 2.44 | 1.07 |

ANOVA revealed that there was a significant main effect across the countermeasures ($F_{(2,227)} = 6.22$, P = 0.002). The longer speed reduction time was reached when the colored paved markings (2.37 s), which was significantly longer than that in baseline condition (mean difference = 0.61 s, P = 0.002), while it was not significantly longer than that in the raised island condition (mean difference = 0.38 s, P = 0.079). Therefore, braking behavior is affected by the countermeasures; thus, to gain insight into the driver's braking behavior, the survival time of speed changes from the initial speed to the minimum speed was modeled using hazard-based duration models.

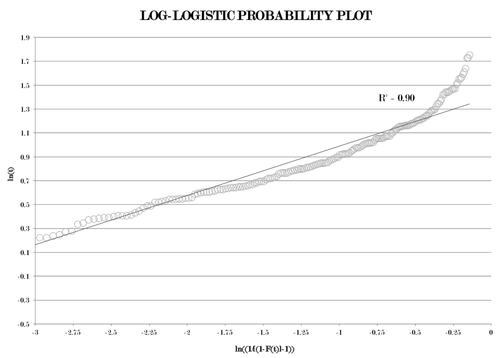
The distribution function to model the SRT was carried out with the probability plot method, which assesses whether or not a data set follows a given distribution; in particular, the Weibull (Figure 7.8a), the lognormal (Figure 7.8b) and log-logistic (Figure 7.8c) distributions were compared. The data were plotted against the theoretical distributions in such a way that the points should form approximately a straight line. Departures from this straight line indicate departures from the specified distribution. For this purpose, the value of $R^2$ against a reference straight line was reported. As showed in Figure 7.8, the best fitting distribution was the Weibull one.




(a)




(b)




(c)

Figure 7.8: Assessment of the best fitting distribution to model SRT in driver-cyclist interaction: *a) Weibull b) Lognormal c) Log-logistic*

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Based on the outcomes of the probability plot method, the Weibull function was selected to model the accelerated failure time (AFT) (see Appendix A) of the present analysis, which was the speed reduction times from the initial speed to the minimum speed. Moreover, two extensions of this model were also tested; the Weibull AFT model with inverse – Gaussian shared frailty and the Weibull AFT model with clustered heterogeneity. The frailty was gamma distributed and the two models were compared with their likelihood ratio statistics, with the AIC and BIC tests. The likelihood ratio statistic of the Weibull AFT model with clustered heterogeneity was -104.04 while that for the shared frailty model was -104.54, highlighting that the first was preferable. The AIC and BIC tests also confirmed the better fit of the model; for the clustered heterogeneity model and for the shared frailty model the AICs were 222.07 and 223.08, while the BICs were 245.63 and 246.65, respectively. Thus, comparing the likelihood ratio statistics, the AIC and the BIC, the Weibull AFT model with clustered heterogeneity was the preferable for modeling the speed reduction times of the drivers in response to a cyclist that is crossing at the bicycle crossroad, under different conditions safety measures.

For modeling the speed reduction time, in addition to the drivers' age (mean value was equal to 28.85 years and the standard deviation was 8.19 years), only the dynamic variable average deceleration $d_m$ (the mean value and standard deviation was 2.67 $m/s^2$ and 1.60 $m/s^2$, respectively) was used as explanatory variable due to the high representativeness of the driver's braking behavior provided by this variable.

On the Table 7.4 the significant parameter estimates for the Weibull AFT model with clustered heterogeneity for SRT are reported. The value of the scale parameter P is equal to 3.166, meaning that the survival probability of SRT decreased with the elapsed time. For example, on average the probability of complete the yielding maneuver after 5 s was 7.3 times higher than that after 2 s (i.e., $(5/2)^{(3166\text{-}1)}$). The scale parameter P higher than 1 implies that the hazard function of the speed reduction times was monotone and with positive duration dependence; this is consistent with the hypothesis of the applied model. The model identified that the driver average deceleration ($d_m$) was significant (P= 0.000) for the drivers' speed reduction times. The coefficient of the average deceleration was negative, which implies that when the value of this variable increased, the SRT value decreased. More specifically, for a 1 $m/s^2$ increase of the driver's average deceleration, the time required to complete the yielding maneuver was approximately 13% lower (Exp ($\beta$)=0.867). Moreover, the model identified the drivers' age as significant explanatory variable (P =0.031): more specifically, for an increase of one year in driver's age, the SRT was approximately 1% longer (Exp ($\beta$)=1.006). Among the countermeasure conditions, the model identified significant coefficient estimates for the colored paved markings (P= 0.000) while for the raised island the effect on the survival model was not significant (P=0.349). For the coefficient estimate of the baseline condition the model did not provide a coefficient estimate, because this condition was set by the model as the reference one.

Table 7.4: Estimated parameters for the survival model of drivers' SRT in response to a crossing cyclist.

| Variable | Estimate | SE | z-Statistic | p-value | Exp($\beta$) | 95% Conf. interval | |
|---|---|---|---|---|---|---|---|
| Drivers' age [yr] | 0.006 | 0.003 | -2.15 | 0.031 | 1.006 | 0.001 | 0.012 |
| $d_m$[m/s$^2$] | -0.142 | 0.018 | -7.85 | 0.000 | 0.867 | -0.176 | -0.107 |
| *Safety measure* | | | | | | | |
| **Baseline condition** | - | - | - | - | - | - | |
| **Raised Island** | 0.052 | 0.061 | 0.85 | 0.349 | 1.053 | -0.067 | 0.171 |
| **Colored Paved Markings** | 0.211 | 0.059 | 3.53 | 0.000 | 1.235 | 0.094 | 0.328 |
| Constant | 1.432 | 0.127 | 11.30 | 0.000 | | 1.184 | 1.681 |
| P | 3.166 | 0.307 | | | | 2.618 | 3.829 |
| Log-likelihood at convergence | -104.04 | | | | | | |
| Log-likelihood at zero | -138.11 | | | | | | |
| AIC | 222.07 | | | | | | |
| BIC | 245.63 | | | | | | |
| N° of observations | 214 | | | | | | |
| N° of groups | 42 | | | | | | |

The pairwise comparison with Bonferroni's correction showed that for the baseline condition and the raised island, the values of SRT (equal to 4.76 and 5.01s for null survival probability, respectively) were significantly shorter than that for the colored paved markings (5.88 s; mean difference = 1.12s, P=0.001; mean difference = 0.87s, P=0.006, respectively). More specifically, for the colored paved markings, the SRT was 23.5% longer than that for the baseline condition (Exp($\beta$)=1.235) while for the raised island the SRT was 5.3% longer than that for the baseline condition (Exp($\beta$)=1.053). However, this difference was not significant.

The use of the Weibull AFT model with clustered heterogeneity allowed a comparison of the driver's speed reduction time for the yielding maneuver, under different configurations of the bicycle crossroad. The representation of the drivers' speed reduction patterns was possible by plotting the survival curves with the use of the estimated coefficients of the average deceleration and the countermeasures condition. The estimation of the survival curves was provided by the equation (17) (see Appendix A), where the vector **X** represents the explanatory variables of the drivers' speed reduction time, while the vector $\beta$ represents the related coefficients estimated by the Weibull AFT model. The survival curves were plotted by using the mean values of the continuous variables average deceleration (2.67 m/s$^2$), drivers' age (28.85 years) and the estimated coefficients of the average deceleration, driver's age and countermeasure conditions in Table 7.4. For example, the survival probability of SRT for the raised island and the colored paved markings after 1.5 s were respectively:

$$S(t = 1.5s) = exp\{-[exp(-3.166(1.432 + (-0.142 \cdot 2.67) + (0.006 \cdot 28.85) + \\ +0.052))] \cdot 1.5^{3.166}\} \quad (6)$$

$$S(t = 1.5s) = exp\{-[exp(-3.166(1.432 + (-0.142 \cdot 2.67) + (0.006 \cdot 28.85) + \\ +0.211))] \cdot 1.5^{3.166}\} \quad (7)$$

Using this method, the survival curve for each countermeasure was plotted (Figure 7.9).

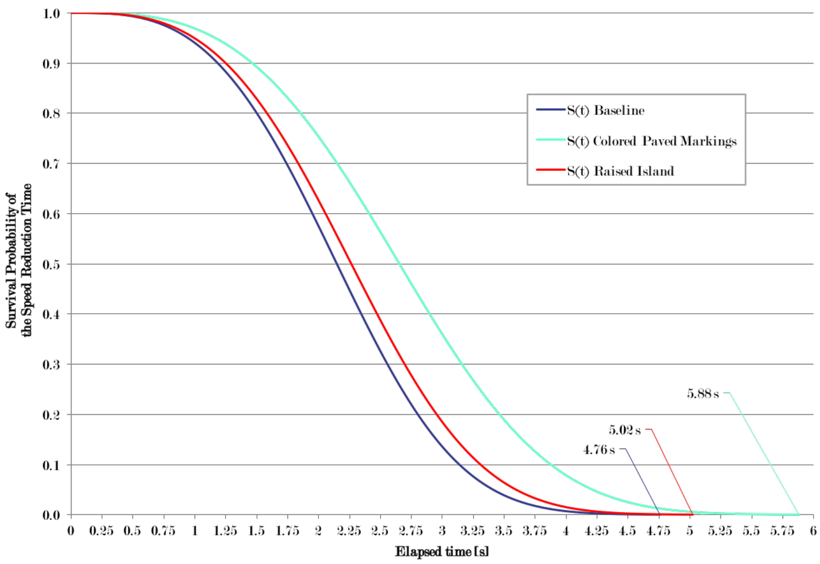



Figure 7.9: Survival curves of SRT for the different countermeasure condition in driver-cyclist interaction.

### 7.1.4 Conclusions

The experiment reported in the previous sections reports several findings concerning the driver - cyclist interaction at the bicycle crossroad, providing an overall assessment of how drivers interact with a cyclist that crossed the road, and how the driving behavior changes if a safety treatment is present compared to a standard layout of the crossroad.

The analysis of the mean speed profiles highlighted an improvement of the yielding compliance in presence of safety measure compared to the baseline condition (see Table 7.1). In particular the numbers of drivers that failed to yield was decreasing with the raised island (in the 6.3% of interactions, 5 of 79) and the colored paved markings (in the 7.7% of interactions, 6 of 78) compared to the baseline condition (in the 16.7% of interactions, 12 of 72) which is consistent with the aim of improving the driver – bicyclist condition through the use of countermeasures at bicycle crossroads. As expected, the analysis of the mean speed profiles revealed that the driver's speed behavior is affected by different groups of $\mathrm{TT}_{\mathrm{arr}}$ values and therefore by different drivers' characteristics. In fact, for all the countermeasures, the mean speed profiles highlighted that:

- the beginning of the yielding maneuver occurs from lower values with the increase of $\mathrm{TT}_{\mathrm{arr}}$
- drivers undertake lower deceleration rates with the increase of $\mathrm{TT}_{\mathrm{arr}}$

More specifically, for all of the countermeasures and for $TT_{\mathrm{arr}} \leq 3s$, the driver is approaching the bicycle crossroad 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 bicycle crossroad, and thus, he maintains the same speed until he is close to the conflict point; then, he is forced to brake to avoid hitting the cyclist. For $3s < TT_{\text{arr}} \leq 4s$ the driver adopts lower speed and less abrupt speed reductions than those observed for $TT_{\text{arr}} \leq 3s$. This behavior reveals that the driver realizes that he cannot pass before the cyclist and starts to decelerate farther from the bicycle crossroad. This behavior is more accentuated for $\text{TTTT}_{\text{arr}} > 4$ s, where the driver adopts the lower speeds and the less abrupt speed reductions highlighting a careful behavior. It should be noted that these drivers' behaviors are completely consistent with the "Threat Avoidance Model" developed by Fuller[27] and the hierarchical discrete model of Silvano et al. [29, 30]. In particular, the behavior observed for $TT_{\text{arr}} \leq 3s$ can be related to the "non-avoidance response". The driver, in fact, maintains the same speed because he considers the cyclist presence to be a "threat" but chooses a non-avoidance response, signaling to the cyclist that he has no intention to yield. This "negotiation" phase, however, is always won by the cyclist (into the simulated scenario, the cyclist was set to cross regardless of the driver's behavior) and the driver is forced to a delayed avoidance response (braking) to avoid the collision. The behavior observed for $\text{TT}_{\text{arr}} >4$ s (and to a lesser extent, also that for $3s < TT_{\text{arr}} \leq 4s$) can be related, instead, to the case of "anticipatory avoidance response". The driver considers the cyclist presence to be a "threat" and he slows down; in this way, the cyclist can pass before the arrival of the driver and a yield event is observed. Only slight differences were observed among the countermeasures for different values of $\text{TT}_{\text{arr}}$. 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. A more evident difference between the countermeasures were observed for the cyclist absence condition. For this condition, the minimum speed reached by the driver was lower for the raised island (34.6 km/h) compared with that for baseline condition (38.5 km/h) and colored paved markings (39.24 km/h). This relationship was expected because the raised island causes a physical narrowing of the driving lane, inducing the driver to adopt a lower speed.

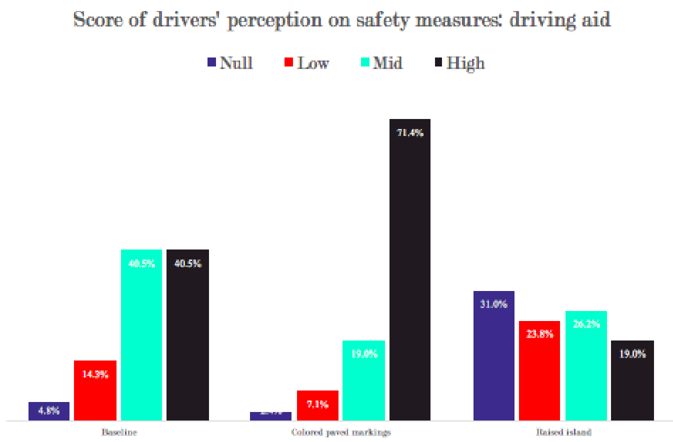
The focus on the speed adopted on the last 60 m in advance of the bicycle crossroad showed that the effect of the countermeasures on driver's speed was significant (al level of 5.2%). The mean speeds for the raised island and the colored paved markings were lower than that for the baseline condition. The observed effect of the countermeasures on drivers' speed behavior were similar with those reported by Hallmark et al. [59] and Campbell et al. [61] for the colored paved markings and by Gross et al. [62] for the raised island. These countermeasures highlight and advise the driver of the presence of a bicycle crossroad and, thus, the possible presence of a cyclist that could be cross. In this way, the driver can anticipate the maneuver to reduce the speed and make safer the interaction with the cyclist. The effect of the distance from the bicycle crossroad was significant on drivers' speed behavior. The results highlighted that the driver adapted his speed while approached the bicycle crossroad in order to yield to the cyclist. Statistical analysis showed a significant effect of the driver - cyclist interaction conditions on drivers' speed behavior. In particular, the cyclist presence induced the driver to reduce the speed in order to yield to the cyclist. For the no cyclist conditions, instead, the driver did not perceive the presence of the cyclist and, thus, maintained a higher speed. In addition, the results highlighted that there was a significant interaction effect for the distance from the bicycle crossroad by driver – cyclist interaction conditions. On overall, when the driver was farther from the bicycle crossroad (from 60 m to 40 m) he adopted the same speed both for the cyclist absence and presence. This outcome can be explained as the "no discriminative stimulus", because the driver is too far from the bicycle crossroad and, thus, he is not influenced by the possible presence of the cyclist. Near to the bicycle crossroad (from 40 m to 20 m) the driver was influenced by the presence/absence of the cyclist and changed his speed. In particular, the driver adopted higher speed for the condition of no – cyclist. This finding suggests that the "discriminative stimulus" is triggered when the driver is near the collision point. In this condition the driver reacts to the presence of the cyclist by reducing his speed, or by maintain his speed because he has not perceived the cyclist presence. The others interaction effects were not significant.

The analysis was then deepened on the variables obtained from the drivers' speed profile, to quantify the changes in the driving behavior due to the countermeasures and the driver-cyclist interaction condition. The results highlighted that the $V_i$, $L_{Vi}$, $V_{min}$ and the $d_m$ were not affected in a significantly way by the countermeasure condition. However, an improvement of the drivers' speed behavior was observed. The effects on initial speed was not significant and this result was consistent with the expected driver behavior; the approaching speed could not be affected by the presence of the countermeasure at the bicycle crossroad because the driver did not perceive them when he was far from the bicycle crossroad. The variable $L_{Vi}$, which is the distance from the bicycle crossroad where the driver started the yielding maneuver, showed that under the colored paved markings the driver started to decrease the speed 1.57 m and 3.45 m before compared to the baseline condition and the raised island. This result is also consistent with previously studies [59, 61], which showed that a painted bicycle crossroad was clearly perceived by the drivers, which were better advised about the possible presence of a cyclist that could cross. In this way, the driver anticipated the yielding maneuver making safer the driver – cyclist interaction. In addition, such results are consistent with the study of Leden et al. [121], which reported that the bicycle crossroad provided with colored pavement can influence the drivers' visual search and decrease the probability of unexpected situations, improving the cyclist safety. The effect due to the advance of the yielding maneuver was clearly observed on $L_{Vmin}$, which was significantly affected by the countermeasure condition. Results showed that the driver ended the yielding maneuver farther from the bicycle crossroad in presence of colored paved markings (26.68 m) compared to the baseline condition (21.69 m) and the raised island (22.47 m). This means that the distance between the cyclist that was crossing and the driver that was yielding increased when the bicycle crossroad was provided with the colored paved markings. From the cyclist safety point of view this result is consistent with the aim of the countermeasure, which is improving the driver performance and, thus, the driver – cyclist interaction. The effects of the countermeasures on $d_m$, even if not significant, can be also linked to the possibility of the driver to advance the yielding maneuver for the colored paved markings undertaking lower deceleration rates (the average deceleration rate for the colored paved markings was 1.81 $m/s^2$, while higher values were recorded for the baseline condition and for the raised island).

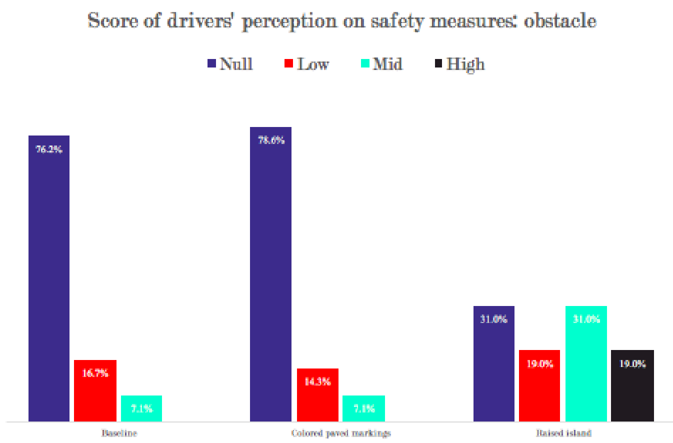
As expected, the results of the statistical analysis showed that the cyclist condition affects almost all the variables $L_{Vi}$, $V_{min}$, $L_{Vmin}$ and $d_m$, while the initial speed was not affected in significantly way. The result on $V_i$ was expected because the adopted approaching speed by the driver was independent from the presence of the cyclist. In other words, the driver did not perceived the presence of the cyclist until he reached a consistent distance from the bicycle crossroad that allowed him to see the crossing cyclist. The results on the variables $L_{Vi}$, $V_{min}$, $L_{Vmin}$ and $d_m$ were also expected and were fully consistent with the driver behavioral models in literature [27, 29, 30]. For the cyclist absence condition, the driver moves forward the point in which he starts to decrease the speed because no yielding maneuver is needed; when the cyclist was absent, in fact, the lowest value of $L_{Vi}$ was recorded (42.46 m). For the minimum speed, results showed also that the higher value of $V_{min}$ was reached when the cyclist was absent (28.9 km/h). This means that the driver does not need to slow down as much as when the cyclist is crossing, because he does not perceive the interaction and he has not to yield. The driver moves forward also the point in which the minimum speed is recorded in the condition of cyclist absence (18.37 m); as for the effect on $L_{Vi}$, the driver when does not perceive the presence of the cyclist, delays the braking maneuver and ends the deceleration phase nearer to the bicycle crossroad. The average deceleration rates ($d_m$) confirm how the driver reacts when he perceives the interaction with the cyclist. In the cyclist present condition, the average deceleration rate reached the highest value (2.66 $m/s^2$). As expected, the need of yield or avoid the potential conflict, induces the driver to adopt a more abrupt maneuver than that of the cyclist absence condition. For this last cyclist condition, the driver does not experience an interaction with the cyclist and, therefore, he performs a smoother maneuver.

The fourth analysis was an in-depth investigation on the drivers' pattern during the yielding maneuver, which was modeled trough the survival analysis of the drivers' speed reduction time (SRT). The survival curves for different countermeasure conditions show that, for a fixed value of the elapsed time, the higher survival probability of SRT was obtained for the colored paved markings while the lower survival probability of SRT was obtained for the baseline condition. For example, after 3 seconds, the speed reduction time survival probability for colored paved markings was about 60%, while for raised island and the baseline condition it was approximately 42% and 37%, respectively. The event duration, that is the speed reduction time (obtained for null value of the survival probability), was 5.88s for the colored paved markings, while it was 1.12 s shorter (significantly) for the baseline condition (4.76s) and 0.87s shorter (significantly) for the raised island (5.01s). Overall, the outcomes of the Weibull AFT model highlight that when the bicycle crossing was reorganized with the colored paved markings, the driver adopted more time to complete the braking maneuver. It should be noted that speed reduction time values represent different times of yielding maneuvers in response to a cyclist that is crossing the road. This means that longer values of the speed reduction times are linked to smoother yielding maneuver. The results of the Weibull AFT model showed that for the colored paved markings, the longer time to pass from the initial speed to the minimum speed was required. This finding suggests that in this condition of bicycle crossroad, the drivers are able to advance the yielding maneuver and the consequence is that they adopt a less aggressive braking behavior. This result can reasonably due to a better visibility of the bicycle crossing, which effectively gained the driver attention allowing him to adopt a less abrupt maneuver.

The general improvement of the drivers' performances emerged from the numerous analysis carried out on the drivers' variables obtained from the speed profiles was also consistent with the outcomes of the questionnaire. In particular the results showed that 71% of the drivers (30 of 42) selected the highest score of “driving aid” for the colored paved markings, while only 19% of the drivers (8 of 42) reported the same score of “driving aid” for the raised island. The highest score of “driving aid” for the baseline condition was reported by 40% of the drivers (17 of 42). According to this outcome, the 79% (33 of 42) of the drivers reported the lower score of the “obstacle driving effect” for the colored paved markings, while only the 31% (13 of 42) of the drivers reported the lower score of the “obstacle driving effect” for the raised island. The lower score of the “obstacle driving effect” was reported by 76% of driver (32 of 42) under the baseline condition.




(a)




(b)

Figure 7.10: Outcomes of the questionnaire about the perceived effect of countermeasures: *a) driving aid b) obstacle*

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## 7.2 Drivers overtake cyclist: effects of cross-section configuration and alignment geometries

In addition to the interaction that occurs at bicycle crossroad, for the cyclists another important interaction with drivers occurs along the road, where drivers usually overtake cyclists and the speed differential is higher especially in the rural roads. The higher difference in speed, together with the distance between the vehicle and the cyclist, are crucial factors that affect the cyclist safety. In the overall overtaking maneuver, also the geometry of the alignment could affect the trajectory of the driver making the overtaking maneuver more o less safe for both, because the driver could cross the center line and invade the other lane or tend to pass nearer the cyclist to not go on the opposite lane. In this context, the presence or not of the dedicated bicycle lane and its width could play a significant role in the cyclist safety during the overtaking maneuver.

For these reasons, a multifactorial experiment was designed to assess the effects of several two-lane rural road configurations (three cross-section configurations with and without bicycle lane with different widths) and of four geometric elements of the road (tangents with different lengths, right curve and left curve) on driver behavior (in terms of lateral position and speed) during the overtaking maneuver of a bicyclist. In particular, the driving simulator experiment was designed in such a way that, along the sections where the driver – cyclist interactions occurred, the oncoming traffic was absent.

### 7.2.1 Experiment design

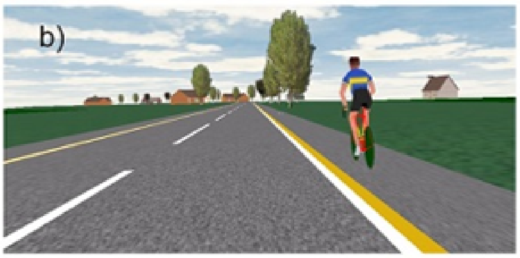
The experimental road scenario was a two – lane rural road about 11 Km long in which also the bicycle traffic was simulated. In order to assess the effect of the alignment on drivers' behavior, the horizontal curves had radii between 200 m and 600 m, while the tangents length were ranged from 150 m to 650 m. The grade of the alignment was null. The posted speed limit was 90 km/h and the cross-section was 9 m wide formed by two 3.50 m wide lanes and two paved shoulders 1.00 m wide, according to the Italian road design guidelines [113]. This configuration represents the baseline condition (Figure 7.11a); in other words, it represents a typical situation in which the cyclist has not a dedicated lane to travel. In addition to the baseline condition, two cross-sections (called countermeasures 1 and 2) (Figure 7.11b,Figure 7.11c), in which was present a bicycle lane separated from the vehicle lane by a yellow edge line [122], were investigated:

- countermeasure 1, in which the bicycle lane was 1.50 m wide; in this configuration, the vehicle lane width was 3.00 m;
- countermeasure 2, in which the bicycle lane was 1.75 m wide; in this configuration, the vehicle lane width was 2.75 m.

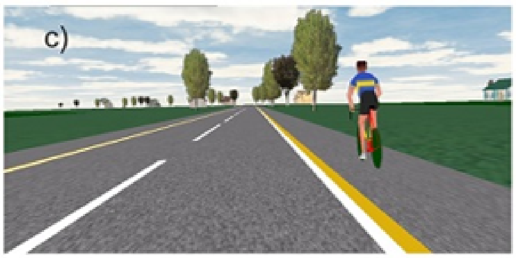
For both the countermeasures, the cross-section width was 9 m as for the baseline condition. Such bicycle lane widths are completely consistent with those suggested by the Italian regulations [123, 124] and by the guidelines for the Development of Bicycle Facilities of the American Association of State Highway and Transportation Official [125]. When the bicycle lane was present, a bike lane sign and a pavement-marking symbol on the bicycle lane were used to properly inform drivers [122]. Concerning the vehicle – bicycle interaction, along the alignment the driver overtakes a cyclist in correspondence of:

- one right curve with radius equal to 200 m
- one left curve with radius equal to 200 m
- one tangent 450 m long
- one tangent 650 m long


(a)




(b)




(c)

Figure 7.11: Cross-section configuation: *a) baseline b) countermeasure 1 c) countermeasure 2*

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For all the cross-sections, the cyclist travelled always on a trajectory that was 0.75 m far from the right edge of the shoulder and with constant speed equal to 20 km/h, consistent with the speed of the cyclist reported in previous studies in literature [126, 69, 99, 37]. To avoid potential effects due to different roadside features, the roadside configuration along the three road scenarios (i.e. baseline condition and countermeasures 1 and 2) was always the same.

To limit a potential order effect on the driver's behavior, for each of the three road scenarios (i.e. baseline condition and countermeasures 1 and 2) 2 different encounter orders (A and B) of the cyclist on the geometric elements of the alignment were implemented in the driving simulator.

More specifically, for the encounter order A, the presence of the cyclist along the geometric elements was set as follows: left curve R = 200 m (located about 650 m from the beginning of the alignment); tangent LT = 650 m (about 2.100 m from the beginning of the alignment); tangent LT = 450 m (about 8.400 m from the beginning of the alignment); right curve R = 200 m (bout 10.000 m from the beginning of the alignment) (Figure 7.12). For the order of encounter B, the presence of the cyclist was set as follows: tangent LT = 450 m (in the section 3+400); right curve R = 200 m (in the section 4+750); left curve R = 200 m (in the section 5+900); tangent LT = 650 m (in the section 7+300) (Figure 7.13). Each type of geometric element in which the interaction with the cyclist occurred (e.g. tangent 650 m long), although placed – for the two encounter orders - in two different points along the road (the tangent 650 m long was about 2.100 m and 7.300 m from the beginning of the alignment for the encounter orders A and B, respectively), it was preceded by the same geometric configuration of the approaching section (for the tangent 650 m long it was a left curve with radius of 500 m). Such specification was used with the aim of avoid the potential influence on the driver's behavior due to different approach conditions.

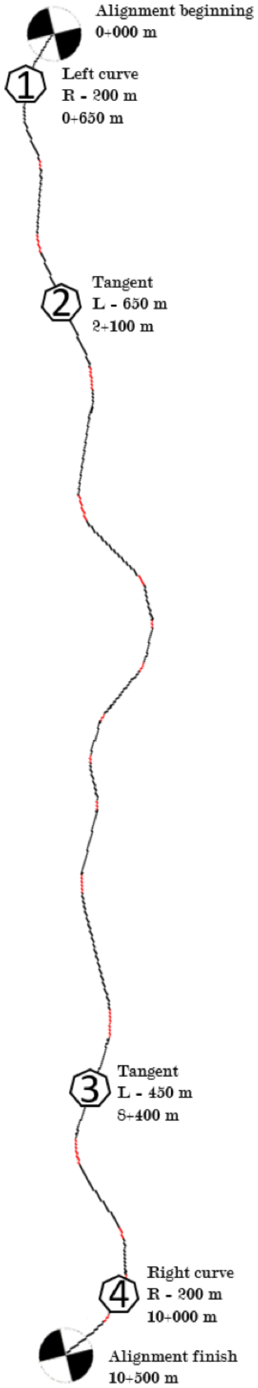


Figure 7.12: Encounter order of cyclist A.

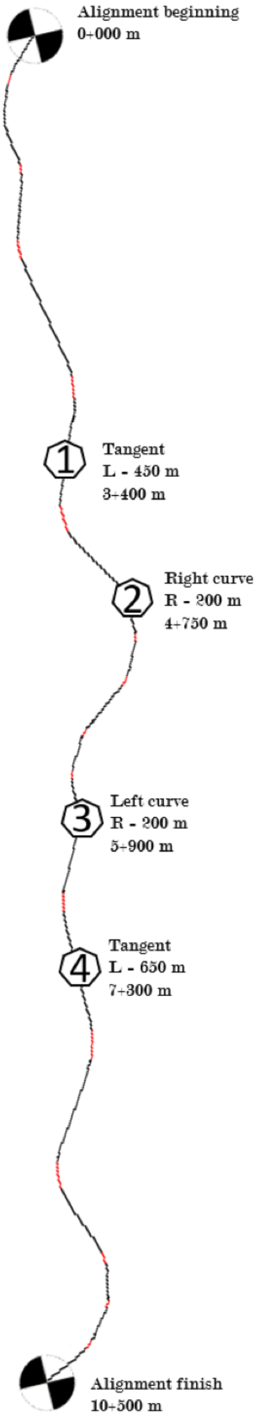


Figure 7.13: Encounter order of cyclist B.

The driving sample was composed by forty participants (24 men and 16 women), whose ages ranged from 23 to 62 (average 29); the sample was divided into 2 groups; each group drove the three road scenarios with a sequence of the encounters of the cyclist along the alignment (encounter order A or B). The sequence of the three scenarios was counterbalanced in order to avoid influences due to the repetition of the same order in the experimental conditions. Between each scenario the driver waited about 5 minutes to restore his/her psychophysical conditions and filled in of a questionnaire about the perceived discomfort during driving and the end of the simulation, to eliminate from the sample the driving performed under anomalous conditions. According to the questionnaire on perceived discomfort, one of forty drivers experienced a high level of discomfort during the simulated drive and was excluded from the sample. Thus, the size of the sample used for the following analysis consisted in 39 drivers.

### 7.2.2 Data analysis

In order to analyze how drivers behave in the interaction with the cyclist under the three different configurations of the cross–section and the four geometric elements (right curve and left curve with radius equal to 200 m, tangents 450 m and 650 m long) the following variables were collected:

- d: the lateral position, i.e. the distance between the vehicle axis and the centerline in the point along the alignment where the vehicle overtakes the cyclist; it should be noted that such variable is not the lateral clearance between vehicle and cyclist used in previous studies in literature. Considering the bicycle lane width and the position of the longitudinal axis of the bicycle (0.75 m from the right edge of the shoulder), the lateral clearance is obtained from the following equation:

$$lateral\,clearance = 4.50 - (0.75 + l_{\mathrm{h}}) - (d + w/2) \tag{8}$$

  where $l_{\mathrm{h}}$ is the width of the left-bicycle handlebar and w is the width of the vehicle.

- $d_{\mathrm{av}}$: the average lateral position from the beginning to the finish of the overtaking maneuver; the beginning and the ending points of the overtaking maneuver were located by the plotting of the lateral position profile that was adopted by driver. The beginning point was the point in which the driver started to modify his/her trajectory (moving to the centerline of the road, i.e. changing the steering wheel rotation angle) to overtake the cyclist. The ending point of the overtaking maneuver was the point in which the driver, returned on the right after the overtake, took a lateral position that remained constant (i.e. the steering wheel rotation angle remained constant);

- V: the overtaking speed, i.e. the speed at the point in which d is recorded;

- $V_{\mathrm{av}}$: the average overtaking speed, i.e. the average speed of the entire overtaking maneuver.

The lateral position (d) and the speed (V) were recorded to study the driver behavior at the point along the alignment where the vehicle overtakes overtook the cyclist. The variables which taking into account the average lateral position and the average speed ($d_{\mathrm{av}}$ and $V_{\mathrm{av}}$, respectively) were also considered to analyze the average driving behavior during the whole overtaking maneuver of the cyclist. The Figure 7.14 shows all the described variables. To obtain these variables when vehicle – bicycle interactions occurred, the lateral position profiles and the speed profiles were plotted for each driver, cross–section configuration and geometric element. Overall 468 lateral position profiles and 468 speed profiles were plotted (39 drivers x 3 cross-section configurations x 4 geometric elements). When the cyclist was not present, the variables were recorded at the same points and sections in which there would be the vehicle – bicycle interaction.

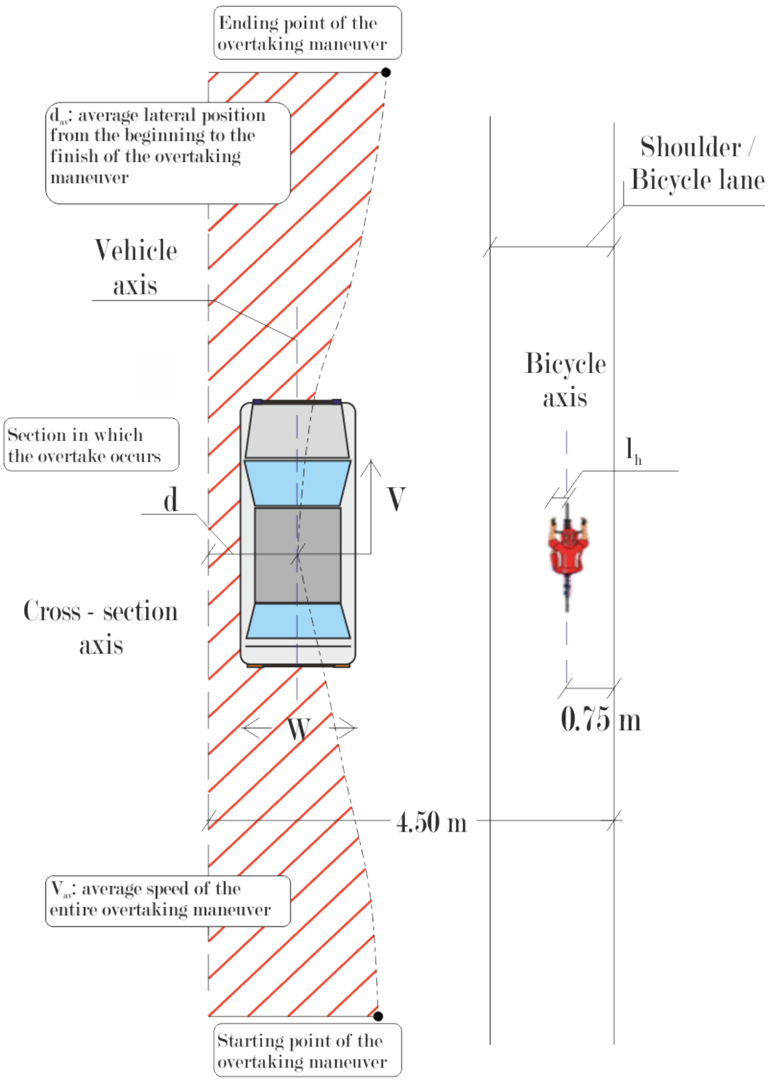


Figure 7.14: Variables of the drivers' overtaking maneuver of a cyclist.

### 7.2.3 Results

A multivariate variance analysis (MANOVA) procedure was conducted to investigate all of the interaction and main effects on the dependent variables (d, $d_{av}$, V and $V_{av}$) due to three factors: configuration of the cross-section (baseline, countermeasures 1 and 2), presence/absence of cyclist, and geometric element of the alignment. For every combination of the three independent factors, the Table 7.5 shows the descriptive statistics of the dependent variables and the values of lateral clearance obtained by the equation (8), assuming the vehicle width (w) equal to 1.60 m and the left-bicycle handlebar width ($l_h$) equal to 0.20.

Table 7.5: Descriptive statistics of the driver-cyclist interaction during the overtaking maneuver.

| **Cross-section** | **Cyclist condition** | **Geometric element** | Lateral Clearance [m] | d [m] | | $d_{av}$ [m] | | V [km/h] | | $V_{av}$ [km/h] | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Mean | Mean | SD | Mean | SD | Mean | SD | Mean | SD |
| Baseline | Present | Right curve | 1.28 | 1.47 | 0.44 | 1.84 | 0.26 | 84.89 | 11.52 | 86.80 | 9.76 |
| | | Left curve | 1.66 | 1.09 | 0.59 | 1.83 | 0.28 | 91.87 | 11.02 | 92.09 | 7.98 |
| | | Tangent L = 450 m | 1.15 | 1.60 | 0.36 | 1.85 | 0.27 | 97.24 | 6.37 | 97.16 | 6.16 |
| | | Tangent L = 650 m | 1.10 | 1.65 | 0.44 | 1.87 | 0.32 | 98.03 | 11.30 | 97.99 | 10.98 |
| | Absent | Right curve | 0.42 | 2.33 | 0.49 | 2.29 | 0.37 | 89.06 | 11.12 | 89.24 | 10.91 |
| | | Left curve | 0.96 | 1.79 | 0.55 | 1.91 | 0.29 | 89.75 | 9.90 | 90.72 | 9.36 |
| | | Tangent L = 450 m | 0.58 | 2.17 | 0.34 | 2.17 | 0.33 | 96.88 | 7.34 | 96.80 | 7.16 |
| | | Tangent L = 650 m | 0.51 | 2.24 | 0.29 | 2.22 | 0.26 | 97.99 | 6.48 | 97.99 | 6.26 |
| Countermeasure 1 (bicycle lane = 1.50 m) | Present | Right curve | 1.26 | 1.49 | 0.38 | 1.74 | 0.21 | 85.07 | 10.98 | 87.44 | 9.32 |
| | | Left curve | 1.65 | 1.10 | 0.27 | 1.70 | 0.24 | 89.86 | 11.38 | 91.30 | 10.19 |
| | | Tangent L = 450 m | 1.17 | 1.58 | 0.25 | 1.65 | 0.25 | 97.09 | 7.92 | 97.09 | 7.96 |
| | | Tangent L = 650 m | 1.11 | 1.64 | 0.29 | 1.76 | 0.21 | 96.95 | 6.84 | 97.24 | 6.48 |
| | Absent | Right curve | 0.83 | 1.92 | 0.40 | 1.96 | 0.30 | 89.35 | 11.63 | 89.32 | 10.94 |
| | | Left curve | 1.19 | 1.56 | 0.32 | 1.71 | 0.19 | 86.51 | 17.39 | 89.75 | 9.22 |
| | | Tangent = 450 m | 0.39 | 2.36 | 0.22 | 1.99 | 0.21 | 96.95 | 8.78 | 96.80 | 8.78 |
| | | Tangent = 650 m | 0.70 | 2.05 | 0.19 | 2.01 | 0.20 | 97.52 | 7.13 | 97.52 | 7.09 |
| Countermeasure 2 (bicycle lane = 1.75 m) | Present | Right curve | 1.24 | 1.51 | 0.36 | 1.66 | 0.20 | 84.56 | 10.33 | 86.83 | 9.47 |
| | | Left curve | 1.74 | 1.01 | 0.42 | 1.58 | 0.35 | 87.66 | 12.89 | 87.48 | 18.36 |
| | | Tangent = 450 m | 1.21 | 1.54 | 0.22 | 1.66 | 0.20 | 96.55 | 8.06 | 96.19 | 7.52 |
| | | Tangent = 650 m | 1.11 | 1.64 | 0.25 | 1.71 | 0.22 | 97.02 | 7.67 | 97.42 | 7.27 |
| | Absent | Right curve | 0.93 | 1.82 | 0.36 | 1.86 | 0.25 | 88.06 | 11.88 | 88.16 | 11.38 |
| | | Left curve | 1.20 | 1.55 | 0.41 | 1.70 | 0.22 | 86.72 | 10.30 | 87.52 | 9.94 |
| | | Tangent = 450 m | 0.89 | 1.86 | 0.30 | 1.87 | 0.28 | 93.17 | 10.15 | 93.17 | 10.04 |
| | | Tangent = 650 m | 0.84 | 1.91 | 0.23 | 1.90 | 0.23 | 99.36 | 9.04 | 99.25 | 8.93 |

Table 7.6: Significant main and interaction effects on drivers' overtaking maneuver of a cyclist.

| **Independent variable** | **F** | **P** | **Wilk's Λ** | **Partial Eta Squared** | **Observed Power** |
|---|---|---|---|---|---|
| Cross- section | $F_{(8,31)} = 36.290$ | 0.000 | 0.096 | 0.904 | 1 |
| Presence/Absence of cyclist | $F_{(4,35)} = 49.774$ | 0.000 | 0.150 | 0.850 | 1 |
| Geometric element | $F_{(12,27)} = 19.483$ | 0.000 | 0.104 | 0.896 | 1 |
| Cross- section by Presence/Absence of cyclist | $F_{(8,31)} = 9.222$ | 0.000 | 0.296 | 0.704 | 1 |
| Geometric element by Presence/Absence of cyclist | $F_{(12,27)} = 11.318$ | 0.000 | 0.166 | 0.834 | 1 |

Tests of between-subject effects (Table 7.7) revealed that only the spatial variables (d and $d_{av}$) were significantly affected by the cross-section and the presence/absence of cyclist, while all the dependent variables (d, $d_{av}$, V and $V_{av}$) were affected by the geometric elements. Cross-section by presence/absence of cyclist affected only d and $d_{av}$, while geometric element by presence/absence of cyclist affected $d_{av}$, V and $V_{av}$.

Table 7.7: Main and interaction effects on dependent variables related to the drivers' overtaking maneuver of a cyclist.

| **Independent variable** | **Dependent variable** | **F** | **P** |
|---|---|---|---|
| Cross- section | Lateral position (d) | $F_{(1.359,51.627)} = 9.004$ | 0.002 |
| | Average Lateral position ($d_{av}$) | $F_{(1.708,\ 64.918)} =112.055$ | 0.000 |
| Presence/Absence of cyclist | Lateral position (d) | $F_{(1,38)} = 148.546$ | 0.000 |
| | Average Lateral position ($d_{av}$) | $F_{(1,38)} = 156.264$ | 0.000 |
| Geometric element | Lateral position (d) | $F_{(2.374,90.198)} = 28.248$ | 0.000 |
| | Average Lateral position ($d_{av}$) | $F_{(2.619,99.506)} = 18.130$ | 0.000 |
| | Overtaking speed (V) | $F_{(1.719,65.322)} = 47.412$ | 0.000 |
| | Average Overtaking speed ($V_{av}$) | $F_{(1.697,64,498)} = 46.724$ | 0.000 |
| Cross- section by Presence/Absence of cyclist | Lateral position (d) | $F_{(1.309,49.734)} = 6.466$ | 0.009 |
| | Average Lateral position ($d_{av}$) | $F_{(1.894,71.954)} = 19.533$ | 0.000 |
| Geometric element by Presence/Absence of cyclist | Average Lateral position ($d_{av}$) | $F_{(2.178,82.754)} = 9.437$ | 0.000 |
| | Overtaking speed (V) | $F_{(2.564,97.439)} = 7.315$ | 0.000 |
| | Average Overtaking speed ($V_{av}$) | $F_{(2.519,95.731)} = 4.314$ | 0.010 |

**Effects of the roadway cross-section configuration** The statistical analysis showed a significant effects of the roadway cross-section configuration on the lateral position (d) ($F_{(1.359,51.627)} = 9.004$; P = 0.002) (Table 7.7); post − hoc analysis showed that the lateral position for the baseline condition (1.79 m) was significantly higher than that for the countermeasure 2 (mean difference = 0.19 m; P = 0.000; d = 1.60 m) and not significantly different than that for the countermeasure 1 (mean difference = 0.08; P = 0.411; d = 1.71 m). No other mean difference of d was significant. The effect of the cross-section was significant also for the average lateral position ($d_{av}$) ($F_{(1.708,\ 64.918)}$ =112.055; P = 0.000) (Table 7.7); the pairwise comparisons showed that the average lateral position was significantly higher for the baseline condition (2.00 m) than that for the countermeasure 1 (mean difference = 0.18 m; P = 0.000; $d_{av}$= 1.82 m) and for the countermeasure 2 (mean difference = 0.26 m; P = 0.000; $d_{av}$= 1.74 m). Also the difference between the countermeasure 1 and 2 was significant (mean difference = 0.08 m; P = 0.000). The effect of the cross-section was not significant on the overtaking speed (V ranged between 91.8 km/h for countermeasure 2 and 93.24 km/h for baseline condition) and the average overtaking speed ($V_{av}$ ranged between 91.0 km/h for countermeasure 2 and 93.6 km/h for baseline condition). Such values were similar to the recorded values on field on two-lane rural roads with posted speed limit of 90 km/h or 55mph and with cross-sections that had similar driving lane and shoulder widths of those analyzed in the present study [65, 69].

**Effects of the cyclist presence/absence** As expected, the outcomes of the analysis showed that the driver position during the overtake (d and $d_{av}$) was affected by the presence/absence of the cyclist in a significant ($F_{(1,38)}$ = 148.546; P = 0.000 and $F_{(1,38)}$ = 156.264; P = 0.000, respectively) (Table 7.7). Test between subjects indicated that for absence of cyclist d (d = 1.96 m) was significantly higher than that for the cyclist presence condition (mean difference = 0.52 m; P = 0.000; d = 1.44 m), highlighting as the cyclist presence induces an average displacement of 0.52 m to the center of the road. It should be noted that the value of lateral position when the cyclist was present (d=1.44 m) corresponds to a lateral clearance between vehicle and bicycle equal to 1.31 m (assuming the vehicle width equal to 1.60 m and the left-bicycle handlebar width equal to 0.20). Such value is consistent with the values of lateral clearance obtained on cross-sections similar to those of the present study [99, 68, 69]. Also for $d_{av}$ similar results were obtained; for the absence of cyclist condition the average lateral position ($d_{av}$ =1.96 m) was significantly higher than that for the presence of cyclist condition (mean difference = 0.22 m; P = 0.000; $d_{av}$= 1.74 m). The effect of the presence/absence of cyclist was not significant on the overtaking speed (V was equal to 92.2 km/h in cyclist presence and 92.5 km/h in cyclist absence) and the average overtaking speed ($V_{av}$ was 92.9 km/h in cyclist presence and absence).

**Effect of the road geometries** The effect of the geometric element was significant on d ($F_{(2.374,90.198)}$ = 28.248; P = 0.000), on $d_{av}$ ($F_{(2.619,99.506)}$ = 18.130; P = 0.000), on V ($F_{(1.719,65.322)}$ = 47.412; P = 0.000) and on $V_{av}$ ($F_{(1.697,64.498)}$ = 46.724; P = 0.000) (Table 7.7). Test between subjects indicated that the lateral position on the left curve (1.35 m) was significantly lower than that on the right curve (mean difference = -0.41 m; P = 0.000; d = 1.76 m), on the tangent 450 m long (mean difference = -0.50 m; P = 0.000; d = 1.85 m) and on the tangent 650 m long (mean difference = -0.50 m; P = 0.000; d = 1.85 m). No other mean difference was significant. Similar results were obtained for $d_{av}$; the average lateral position for the left curve (1.74 m) was significantly lower than that for the right curve (mean difference = -0.15 m; P = 0.000; dav = 1.89 m), for the tangent 450 m long (mean difference = -0.13 m; P = 0.000; $d_{av}$ = 1.87 m) and for the tangent 650 m long (mean difference = -0.17 m; P = 0.000; $d_{av}$ = 1.91 m). No other mean difference was significant. As expected, the pairwise comparisons on the mean values of the drivers' speed V showed that the speed on tangents were higher compared to that recorded on the curves. More specifically, the value of this variable for the tangent 450 m long (96.58 km/h) was significantly higher than that for the left curve (mean difference = 7.52 km/h; P = 0.000; V=89.06 km/h) and for the right curve (mean difference = 9.86 km/h; P = 0.000; V=86.72 km/h). Also V for the tangent 650 m long (97.81 km/h) was significantly higher than that for the left curve (mean difference = 8.75 km/h; P = 0.000) and for the right curve (mean difference = 10.98 km/h; P = 0.000). The differences between the two tangents and between the right and left curve were not significant. Similar results were obtained for $V_{av}$. The average overtaking speed for the tangent 450 m long (96.59 km/h) was significantly higher than that for the left curve (mean difference = 6.37 km/h; P = 0.000; Vav = 90.22 km/h) and for the right curve (mean difference = 8.60 km/h; P = 0.000 $V_{av}$ = 87.98 km/h). Also for the tangent 650 m long, the average overtaking speed (97.88 km/h) was significantly higher than that for the left curve (mean difference = 7.70 km/h; P = 0.000) and for the right curve (mean difference = 9.94 km/h; P = 0.000). The values of $V_{av}$ between the tangents were not significantly different, while for the right curve $V_{av}$ was significantly lower (87.98 km/h) than that for the left curve (mean difference = -2.23 km/h; P = 0.019).

**Interaction effects** MANOVA showed also significant interaction effects. Specifically, the combined effects of cross-section by presence/absence of cyclist affected in a significant way the lateral position ($F_{(1.309,49.734)}$ = 6.466; P = 0.009) and the average lateral position ($F_{(1.894,71.954)}$ = 19.533; P = 0.000) (Table 7.7). The Figure 7.15a shows that the cyclist presence induced the driver to move towards the centerline (compared to the recorded position for cyclist absence) with a decreasing trend while the shoulder width or the bicycle lane width increased (the driver moved 0.68 m for the baseline condition; 0.52 m for the countermeasure 1 and 0.36 m for the countermeasure 2). That highlights a different level of interference, due to the presence of the cyclist, on the driver trajectory for the several cross – sections.

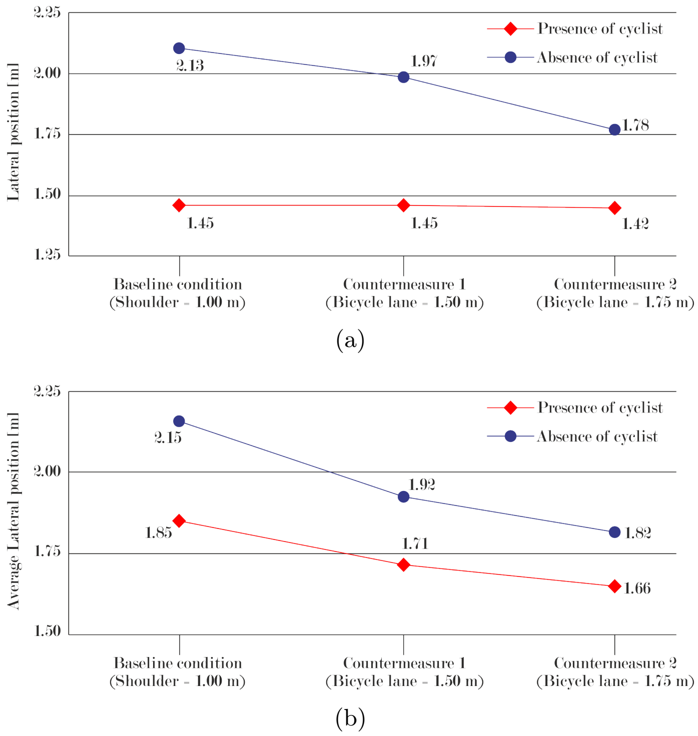


Figure 7.15: Interaction effects cross-section configuration by cyclist presence/absence: *a) lateral position b) average lateral position*

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Results in terms of average lateral position (Figure 7.15b) were similar to those obtained for d. It should be noted that as the shoulder (or bicycle lane) width increased, the driver travelled closer to the centerline ($d_{av}$ was 1.85 m for baseline condition, 1.71 m per countermeasure 1 and 1.66 m per countermeasure 2) and, thus further from the cyclist. The interaction geometric element by presence/absence of cyclist affected in a significant way $d_{av}$ ($F_{(2.178,82.754)} = 9.437$; $P = 0.000$), V ($F_{(2.564,97.439)} = 7.315$; $P = 0.000$) and $V_{av}$ ($F_{(2.519,95.731)} = 4.314$; $P = 0.010$) (Table 7.7). No interaction effect geometric element by presence/absence of cyclist was found on d ($F_{(1.692,64.305)} = 0.771$; $P = 0.447$). However, it should be noted that for absence of cyclist condition, the driver assumed on the left curve a less lateral position than that on the other geometric elements (for left curve d was 1.64 m while for the others element the values of d were between 2.02 m and 2.13 m) (Figure 7.16a), highlighting in this way a clear propensity to cut the left curve.

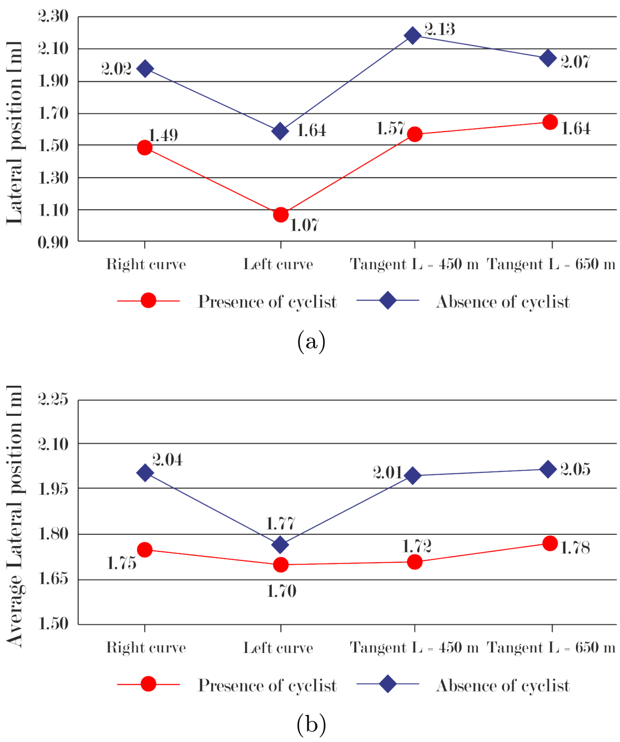


Figure 7.16: Interaction effects road geometries by cyclist presence/absence: *a) lateral position (not significant) b) average lateral position*

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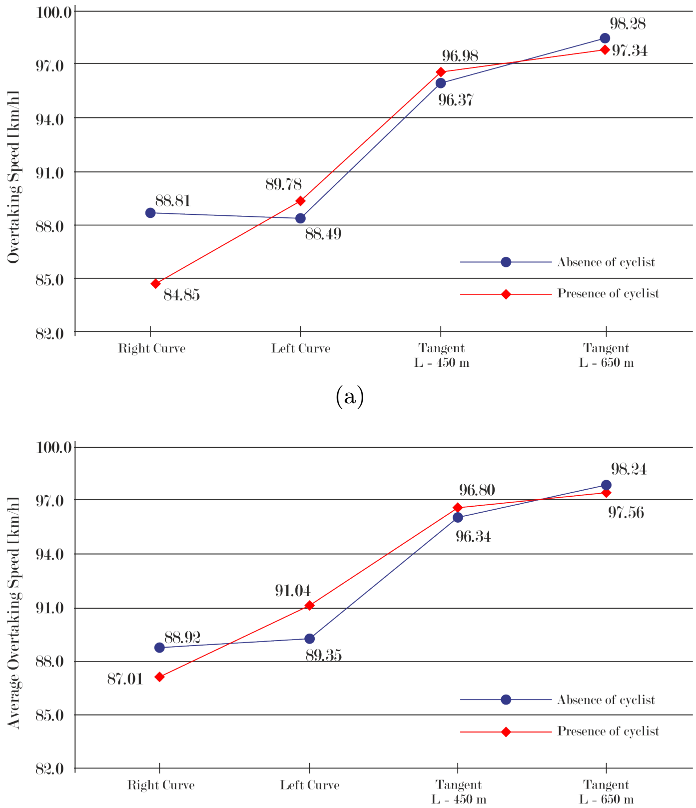
The presence of the cyclist induced the driver to displace towards the centerline in variable extent between 0.43m on the tangent 650 m long and 0.57 m on the left curve. It should be noted that the lateral position values when the cyclist was present are equivalent to lateral clearance between vehicle and bicycle equal to 1.11 m on tangent 650 m long, 1.18 m on tangent 450 m long, 1.26 m on right curve and 1.68 m on left curve (assuming the vehicle width equal to 1.60 m and the left-bicycle handlebar width equal to 0.20 m). It should also be noted that the displacement towards the centerline on the left curve due to the presence of the cyclist determines a distance of the vehicle left side from the opposing lane of only 0.27 m (1.07 m – 0.80 m that is the half width of the vehicle). Therefore, the cyclist presence on the left curve, inducing on the driver trajectory a concordant effect (moving away from the cyclist) with that induced by the geometry (tendency to cut the curve), determines an excessive and risky displacement of the vehicle to the opposing lane. With respect of the average lateral position it was observed that, for absence of cyclist condition, the values of $d_{av}$ confirms the driver propensity to cut the left curve (the minimum value equal to 1.77 m was recorded for left while for the others element the values of $d_{av}$ were 2.01 m or 2.05 m) (Figure 7.16b). The interaction effects geometric element by presence/absence of cyclist for V and $V_{av}$ were similar (Figure 7.17). Results indicated that speeds on tangents were almost the same in the condition of presence and absence of the cyclist. A similar result was observed for the left curve; in this case, the driver tended to cut his/her trajectory and, thus, he/she did not need to reduce the speed. Conversely, for the right curve, the speeds (V and $V_{av}$) were lower for the condition of presence of the cyclist.




(a)

(b)

Figure 7.17: Interaction effects road geometries by cyclist presence/absence: *a) overtaking speed b) average overtaking speed*

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### 7.2.4 Conclusion

The results of the experiment presented above aimed at assess the effects of the cross-seciton configuration, the road geometries and the presence/absence of cyclist on the drivers' pattern during the overtaking maneuver. The analysis was carried out by means of MANOVA, which highlighted several key points.

In particular, results showed that the effect of the cross-section was statistical significant on d and $d_{av}$ but not on speeds (V and $V_{av}$). Specifically, d and $d_{av}$ were higher when the vehicle lane was wider (i.e. the shoulder or bicycle lane width was the narrowest). This finding highlights that the width of the vehicle lane affects the lateral position adopted by the driver inducing him/her to choose a trajectory close to the axis of the vehicle lane. However, the width of the vehicle lane does not affect the driver's speed. Considering that the 3 cross-sections have the same width (equal to 4.50 m, sum of the widths of the vehicle lane and shoulder or bicycle lane), the obtained result shows that the driver, for the speed adoption, perceives the 3 cross-sections in the same way, although they are differently organized in terms of lane and shoulder width. This result is consistent with previous findings that highlighted a different driver speed behavior by varying the overall width of the cross-section [127, 128] It should be noted that the results on the speed and the average speed highlight that with the increasing of the bicycle lane width, the driver tended to maintain the same speed but passed at higher distance from the cyclist. This missed significant effect leads to an increasing of the cyclist safety during the overtaking maneuver and, at the same time, could ensure the same operating speed compared to the same wide cross-section with wider driving lane and narrower shoulder in case of free flow traffic conditions.

The effect of the presence/absence of the cyclist was significant on d and $d_{av}$, while the recorded speeds (both the overtaking speed and the average overtaking speed) were not affected by the presence/absence of the cyclist. This means that the cyclist affected only the trajectory of the driver but not its speed. This result is in line with the outcomes of a study by Garcia et al. [69], who observed speed reductions (from the condition of free − flow to the condition of cyclist presence) near to zero on some two-lane rural roads. The lateral position (d) and the average lateral position ($d_{av}$) were higher when the cyclist was absent. Conversely, when the cyclist was present, the driver perceived him as an obstacle and, thus, he/she moved closer to the centerline of the road. This result was expected and confirms the outcomes of previous studies [e.g. 99, 68, 69]

Interesting results were highlighted from the interaction effect cross-section by presence/absence of cyclist (significant) on d and $d_{av}$. Results on the lateral position showed a decreasing level of influence on the driver trajectory due to the presence of the cyclist with the increasing of the shoulder or bicycle lane width (the displacement towards the centerline was 0.68 m for the baseline, 0.52 m for the countermeasure 1 and 0.36 m for the countermeasure 2). The results on average lateral position highlighted that a wider bicycle lane ensures a higher later clearance distance between driver and cyclist, allowing safer overtaking maneuver. These results confirm the crucial role of the bicycle lane width on the lateral clearance [68, 69]. Statistical analysis showed that the geometric elements affected all the variables (d, $d_{av}$, V and $V_{av}$). The lateral position for the left curve (1.35 m) was significantly lower than that for the tangents (1.85 m) and for the right curve (1.76 m). Moreover, the result on $d_{av}$ was similar. These findings highlight that the driver took a different trajectory on the left curve; in particular, he/she was closer to the centerline, meaning that he/she tended to cut the curve. This outcome is consistent with the findings of several studies [129, 69], conducted on field, in which authors observed that in curves the vehicle tends to moves towards the center compared to straight stretch and this displacement was found higher in left curves compared to right curves during the overtaking of a cyclist.

The effects on V and on $V_{av}$ were similar; the overtaking speed and the average overtaking speed were almost the same for the tangents 450 m and 650 m long (about 96.5 km/h and 97.6 km/h respectively), while were lower on the left and the right curve. These results were expected and show that the driver adopts a higher speed on the less demanding geometric elements. Moreover, for the left curve V (89.06 km/h) and $V_{av}$ (90.22 km/h) were higher than those for the right curve (86.83 km/h and 87.98 km/h, respectively). This outcome was determined by the trend of the driver to cut the left curve; this allows him/her to maintain higher speed compared to that for the right curve. The interaction effect geometric element by presence/absence of cyclist highlighted that the presence of the cyclist induced the driver to displace towards the centerline in variable extent for the different geometric elements. On the less demanding geometric elements, the minimum lateral clearances between driver and cyclist (equal to 1.11m on tangent 650 m long and 1.18 m on tangent 450 m long) were recorded. However, such lateral clearances (both higher than three feet, which is the minimum value suggested by several guidelines [130] were sufficient to allow the driver to maintain the same speed adopted in the condition of cyclist absence. On the left curve, the presence of the cyclist, inducing on the driver trajectory a concordant effect (moving away from the cyclist) with that induced by the geometry of the left curve (tendency to cut the curve), determined a high lateral clearance between driver and cyclist (1.68 m), but also an excessive and risky displacement of the vehicle to the opposing lane. This critical condition was also amplified by the high speed adopted by the driver, which was similar to that adopted for the condition of cyclist absence. On the right curve, the presence of the cyclist determined also a displacement towards the center of the road and then a lateral clearance of 1.26 m, higher than the lateral clearance values recorded in tangents. This outcome can be reasonably explained by the driver propensity to move further from the cyclist (compared to the same interaction on tangents) to perform the demanding maneuver of entering in the right curve. The complexity of the interaction with the cyclist on such demanding geometric element also led to a speed reduction compared to the cyclist absence condition.

# Chapter 8

# Conclusions and further perspectives

The present research aimed at investigating how drivers' behave during the interaction with the VRUs, comparing the common facilities of pedestrians and cyclists (i.e., the baseline conditions of each experiment) to several improved facilities that helps the driver to behave more correctly and that aims at increasing the safety levels of the VRUs. The experiments reported in the previous chapters revealed interesting findings, that filling some gaps present in the literature concerning the complex process of interactions during the driver-VRUs interactions. Moreover, the outcomes of the statistical analyses provided objective comparisons among safety countermeasures based on the huge amount of data recorded during the experiments carried out by the driving simulator, characterized by full controlled experimental conditions.

## 8.1 On driver - pedestrian interaction

Concerning the driver - pedestrian interaction at pedestrian crossing, the experiment results showed that increasing the visibility of the pedestrian crossing has a great potential in decreasing the fatality risk of pedestrian, in terms of correct driving behavior and better driving performances.

Specifically, countermeasures at pedestrian crossing increased the drivers' willingness to yield toward the pedestrian. For the curb extensions, which is the countermeasure aimed at increasing the visibility of the pedestrian narrowing the driving lane in proximity of the crosswalk, the lowest number of non-yield events was recorded (5%). This result could reasonably linked to the improved visibility conditions of the pedestrian provided by the countermeasure.

Focusing on the drivers' mean speed profiles, it was clear that drivers behavior was actually affected by the the conditions of the vehicle-pedestrian interaction (different groups of $TTZ^*_{arr}$ values, representing different drivers' propensity and driving aggressiveness). The plotting of the mean speed profiles compared among the safety countermeasures and for different values of the $TTZ_{arr}$, however, revealed only slight differences between the countermeasures; specifically, the more evident difference was observed for the condition of pedestrian absence.

In particular, the recorded minimum speed for the safety countermeasures that improve the visibility of the pedestrian, such as curb extensions and parking restrictions, was reached farther from the zebra crossing compared to that recorded for the baseline condition and advanced yield markings. This outcome highlight that the driver was able to complete the yielding maneuver farther from the potential collision point.

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.

Such outcome was also confirmed by applying the hazard-based duration model to the variable SRT (speed reduction time), which was aimed at analyzing the braking behavior patterns of the drivers among the safety countermeasures at pedestrian crossing. The speed reduction time was modeled with the Weibull AFT model with shared frailty, to take into account the possible correlations due to the repeated measures and to compare the effects on driver's braking behavior of vehicle dynamic variables and different countermeasures. The hazard-based duration model identified that five vehicle dynamic variables (the initial speed and the distance from zebra crossing were the initial speed is located, the minimum speed and the distance from zebra crossing were the minimum speed is located and the average deceleration rate) and only the countermeasure curb extensions affected, in a statistically significant way, the driver's speed reduction time in response to a pedestrian crossing. The Weibull AFT model showed that for the curb extensions the drivers adopted a smoother maneuver to yield to the pedestrian. The speed reduction time for this countermeasure was longer (statistically significant) than those for the baseline condition and the other countermeasures. No other difference was statistically significant. These findings suggest that the driver, due to the improved visibility of the pedestrian allowed by the curb extensions, was able to receive a clear information about the presence of the pedestrian and effectively adapt his approaching speed to yield to the pedestrian, avoiding abrupt maneuvers and decreasing the risk of fatality in case of impact. The ability to perform a smoother braking maneuver during the yielding phase towards the pedestrian, also allows to avoid unexpected situations for the following vehicles and, thus, reduce the likelihood of rear end collisions. The findings reported here, referred to unsignalized crosswalks, highlight that the pedestrian crossings should be provided with curb extensions, which are the most effective countermeasures that can potentially respond in a significant way to the speed management issues referred to the pedestrian safety. However, additional experiments should carried out to verify the effectiveness of this countermeasure also at signalized intersections.

The objective results of the statistical analyses were also confirmed by the 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 were consistent with the statistical analyses.

In addition to the crossroad facilities for the pedestrian, which represent an improvement of the road factor that affect the VRUs safety, the experiments were also oriented to assess the effects of the Pedestrian Protection System (PPS), which represent the vehicle factor that can help the driver in critical situations. The effects of the PPS on drivers' behavior were evaluated in the condition of jaywalker pedestrian and, then, on a pedestrian that cross the walk at zebra crossing among different road environments. These two topics, in fact, received notably less attention in literature.

As expected, the illegal crossing conditions affected the driving behavior; in particular, when the pedestrian crossed outside of the crosswalk the driver tended to maintain higher speed values, to delay the braking response and to act abrupt braking maneuver. These findings are consistent with the previously studies and show that the unexpected situations induce the driver to assume unsafe driving behavior, which could lead to also rear – end collisions.

The results on the PPS showed that the effect was significant on drivers' minimum speed. In particular, the minimum speed was the lower when the vehicle was equipped with the warning systems; this outcome highlights that drivers alerted by means of a warning system tended to yield to the pedestrian at lower speed, decreasing the potential fatality risk in case of impact. Furthermore, a significant interaction effect crossing condition by PPS condition on the drivers' reaction time was observed. It should be noted that the collision rates reported in Table 6.8 showing a decreasing trend on the numbers of drivers that collided with the pedestrian when the PPS was present, which produces an increasing of the VRU safety condition. The pairwise comparison among the crossing conditions showed that drivers RT was similar among the No PPS, audio PPS and visual PPS condition when the pedestrian crossed outside of the crosswalk, showing the tendency of drivers to ignore the warning for ensuring the priority.

Furthermore, in the condition of legal crossing, the statistical analysis highlighted an improvement of the driving performance due to the PPS by a reduction of the RT, which is directly linked to an improvement of the pedestrian safety. Finally, the statistical analysis showed also that the aggressive drivers are characterized by higher initial speed ($V_i$), higher values of the distance at which the braking maneuver begins ($L_{Vi}$), lower values of the distance at which the braking maneuver end ($L_{Vmin}$), higher deceleration rates ($d_m$) and lower speed reduction times (SRT). This outcome is proper of aggressive drivers, which tends to assume a competitive behavior towards the pedestrian that is crossing by maintaining the same approaching speed to signal low willingness to yield; consequently, if the pedestrian assumes a competitive behavior too, the driver is forced to act an abrupt braking maneuver to avoid the conflict, which leads to adopt high deceleration rates and short interval time to finish the braking maneuver.

The positive effects of the PPS were also evaluated among different road environments in the condition of a pedestrian that crosses the road at the zebra crossing. As expected, this kind of factor affected the driving behavior. For the urban and the sub – urban environment the analysis showed that the drivers behave in similar way. The two road scenarios, in fact, had similar characteristics of the cross - road section and of the boundary conditions, differentiated only for the building density along the alignment. For the rural road, characterized by a wider driving lane and less obstacles at the sides, the driver adopted higher initial speed, a higher minimum speed and adopted the maximum deceleration at a distance farther from the pedestrian crosswalk, highlighting that the driver compensates the higher risk due to the higher speeds by advancing the yielding maneuver. Results on the effects of PPS regardless of the road environment and pedestrian condition showed that the driver was effectively affected by the presence of the driving assistance system; more specifically, in the case of PPS presence, the driver acted an earlier response to the pedestrian that was crossing the road. This outcome was explained by the distance at which the driver started to decrease the speed ($L_{Vi}$), which was, on average, 8.50 m farther from the pedestrian crosswalk compared to that for PPS absence (statistically significant at the level of 94%). Furthermore, when PPS was present, the driver reached a higher minimum speed ($V_{min}$). This outcome can be explained because starting earlier the yielding maneuver allow the driver to adopt a smoother maneuver and, thus, to gradually reduce the speed avoiding reaching low speed values. The results on the several driver – pedestrian interaction condition (i.e. several values of $TTZ^*_{arr}$) showed that the aggressive drivers (lower values of $TTZ^*_{arr}$) started the braking maneuver at higher speeds and nearer to the crosswalk, while cautious drivers (higher values of $TTZ^*_{arr}$) acted the yielding maneuver farther from the pedestrian crosswalk and at lower speed.

Finally, statistical analysis showed a significant interaction effect for the road environment by pedestrian interaction condition and by PPS condition. In particular, the cautious drivers (characterized by higher values of $TTZ_{arr}$) adopted comparable approaching speed values among the three road environments, highlighting that the specific features of the urban, suburban and rural road did not influence this class of drivers.

On the contrary, a significant difference in the speed adoption was found for the aggressive drivers (characterized by lower values of $TTZ_{arr}$), whose behavior was influenced, instead, by the specific road environment. Furthermore, the results on PPS conditions among the road environments showed that for the rural road the drivers, when aided by the driving assistance system, were able to end the yielding maneuver farther from the pedestrian crosswalk. This finding highlights the great potential of the warning systems in those road environments where, due to the high speeds, the consequence of impact are the worst for the vulnerable road users.

## 8.2 On driver - cyclist interaction

The aspects related to the visibility characteristics of the crossroad, which is an important factor in improving the safety of the VRUs, was also the key point in the interaction between driver and cyclists at bicycle crossroads. Results, in fact, showed an important improvement of the driver-cyclist interaction at crossroads for the safety measure characterized by the red painting pavement, which gains the attention of the driver and allow a safer maneuver towards the cyclist.

The analysis of the drivers' speed in the last 60 m in advance of the bicycle crossroad highlighted that the driving behavior was affected by the presence of the countermeasure; this effect was significant at level of. 5.2%. For the colored paved markings and the raised island lower speeds were recorded (39.2 km/h and 38.9 km/h, respectively) compared with that obtained for the baseline condition (41.4 km/h). The results on driver speed due to distance from the bicycle crossroad showed that the driver reduced significantly his speed while he approached the bicycle crossroad. This behavior was expected; the driver, in fact, decreases the speed near the bicycle crossroad because he perceives the presence of the cyclist, which induces him to decelerate and give way. The statistical analysis showed also that the driver – cyclist interaction conditions affected significantly the driver speed. In particular, for the condition of cyclist presence the driver speed was lower (statistically significant) than that for the no cyclist condition. When the cyclist is not present, the driver does not perceive the possible “treat” of a potential conflict and, thus, he maintains higher speeds. The interaction effect distance from bicycle crossroad by driver – cyclist interaction conditions was statistically significant. Comparing the outcomes for the conditions of cyclist presence and absence, the results showed that the driver behaves differently only in the section near the bicycle crossroad (between 40 m to 20 m from the bicycle crossroad). Despite the interaction effect of the distance from bicycle crossroad by countermeasure was not statistically significant, the results highlight the drivers’ behavior was actually influenced by the specific peculiarities of the two countermeasures.

The in-depth analysis on the variables of the driving behavior showed that the effect of the countermeasures was statistically significant only for the variable $L_{Vmin}$. However, the general trend becoming from also the other variables ($L_{Vi}$, $V_{min}$, $L_{Vmin}$ and $d_m$) shows an improvement of the driver performances in the presence of the colored paved markings. In this condition, the driver started the yielding maneuver at a distance that was higher (non-statistically significant) compared to the baseline condition (50.63 m) and the raised island (48.75 m). This capacity of the driver to advance the yielding maneuver due to the better visibility provided by the colored pavement, allowed him to end the yielding maneuver at a distance from the bicycle crossroad that was higher (statistically significant) than that for the baseline condition (21.69 m) and the raised island (22.47 m), increasing the cyclist safety during the driver – cyclist interaction at the bicycle crossroad. Moreover, these outcomes implied that the driver adopted a smoother maneuver characterized by less deceleration rates.

Also for the interaction between driver and cyclist at the bicycle crossroad the hazard-based duration model was applied to the variable SRT to analyze the braking behavior of drivers. The analysis was carried out by the Weibull AFT duration model, which identified the average deceleration $d_m$, the countermeasure condition and the drivers’ age as explanatory variables that affected the speed reduction time in a statistically significant way. The plot of the SRT survival curves for each countermeasure highlighted that the time taken by the driver to reduce the speed during the yielding maneuver was longer (statistically significant) when the colored pavement was present compared to the baseline condition and the raised island. For the last, a slightly effect on drivers’ SRT was also recorded compared to the baseline condition but it was not significant. The better visibility of the bicycle crossroad provided by the presence of the colored paving allowed the driver adopts smoother braking maneuver to yield to the cyclist.

In summary, the results concerning the driver-cyclist interaction at bicycle crossroad highlight that the countermeasures are effective and influence the driver’s behavior consistently with their expected functions. In addition, both countermeasures determined a better yielding behavior compared to that for the baseline condition (see Table 7.1); compared to the baseline condition, for the colored paved marking and the raised island only in 2.6% (6 of 229) and in 2.2% (5 of 229) of the driver – cyclist interactions the driver did not yield, while when the countermeasures were absent the failed yielding rate was 5.9% (12 of 229). Therefore, they can be considered equivalent in terms of yielding behavior, although the questionnaire revealed a greater acceptance of the colored paved markings compared with that of the raised island. This result is also reasonable, because the colored paved markings is a purely perceptual cue which does not cause a physical obstruction, while the raised island is a “physical” cue and, as such, less “accepted” by the driver.

Overall, the results of the drivers mean speed profiles of the experiments related to the interaction between driver and VRUs at crossroads were fully consistent with the behavioral model developed by Fuller [27], according to which the driver could adopt a “non– avoidance response”, warning the VRU of his intention to not give way, or could adopt an “anticipatory avoidance response”, slowing down and giving way. This last occurrence was recorded for the cautious drivers, which were characterized by higher values of $TTZ^*_{arr}$. For the aggressive drivers, characterized by low values of $TTZ^*_{arr}$, the "delayed avoidance response", as consequence of an initial "non-avoidance response", was recorded due to the fact that the VRU was set to cross regardless of the driving behavior, simulating a "competing" VRU, which forced the driver to an abrupt brake to avoid the conflict. Moreover, the results were also consistent with the hierarchical model of Silvano et al. [29, 30], in which the driver starts a “negotiation” with the cyclist upstream the conflicting zone to ensure his priority. However, due to the experiment design, only the case in which the cyclist wins the “negotiation” occurred, which consistently represents the case in which the driver forces the brake to avoid the conflict with the cyclist.

The analysis of the driving behavior in the interaction with the VRU moved then to the driver overtaking maneuver of a cyclist in the rural road, to analyze the most effective cross-section reorganization that ensures higher levels of safety for the cyclist, considering also several road geometries. In particular, the results showed that the width of the vehicle lane affects the lateral position adopted by the driver, inducing him/her to select a trajectory that is close to the axis of the vehicle lane, but it does not affect the driver’s speed. The same driver speed behavior recorded on the 3 cross-sections seems to depend on the overall width of the cross-section (the same for the 3 cross-sections) and not on the different widths of the vehicle lane and shoulder or bicycle lane. The cyclist affected the trajectory of the driver but not his/her speed. The driver perceived the cyclist as an obstacle and, thus, he/she moved closer to the centerline of the road without reducing the speed.

The presence of the cyclist determined different levels of influence on driver’s trajectory for the 3 cross-sections: compared to the lateral position adopted when the cyclist was absent, the displacement towards the centerline was decreasing with the increasing of the shoulder or bicycle lane width. In addition, it was clear that a wider bicycle lane ensures a higher later clearance distance between driver and cyclist, allowing safer overtaking maneuver. The driver had a different behavior in terms of lateral position on the left curve compared to those that were recorded on the other geometric elements. More specifically, the driver travelled nearest to the centerline on the left curve, meaning that he/she tended to cut the trajectory. The results on the speeds were expected and showed that the driver adopts a higher speed on the less demanding geometric elements.

The interferences of the cyclist on driver’s behavior depend on the geometric elements. On tangents, the lowest lateral clearances (nevertheless higher than that the suggested minimum values in literature) were recorded and no speed reduction, compared to the condition of cyclist absence, was observed. On the left curve, the highest lateral clearance was recorded. Two concordant causes determined it: the tendency of the driver to move away from the cyclist and to cut the curve. This led to an excessive and risky displacement of the vehicle to the opposing lane, whose criticality was also emphasized by the high speed adopted by the driver. Finally, on the right curve, the lateral clearance was higher than that recorded on tangents, probably due to the necessity of the driver to perform the demanding maneuver of entering in the right curve, which also determined a speed reduction. These results provide useful suggestions for the most efficient cross-section reorganization of existing two-lane rural roads to improve the road safety. More specifically, in lights of the present results on the driving overtaking maneuver of a cyclist, it should be recommend to reserve as much as possible wide bicycle lanes to ensure higher later clearance distances between driver and cyclist during the overtaking maneuver and reduce the speed limit to reduce the dangerous dynamic effects on the cyclist (in particular on tangents, where the less lateral clearance was recorded) and to make less critical and less difficult the overtaking maneuver of a cyclist on the curves.

## 8.3 Caveats and limitations

A particular mention has to be exposed for the main tool used to achieve the objectives exposed at the beginning of the present research, which was the advanced driving simulator of the Department of Engineering – Roma Tre University that ensured full control of the experimental conditions and no risk to the participants. However, the caveats that are usually referred to driving simulator studies must be raised. Among these, the main is referred to the possibility that the driver's behavior observed in driving simulation can be different from that in the real world. Although the driving simulator used in the present study was validated for the analysis of drivers' behaviors on two-lane rural roads [103], 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.

From what reported above, it is not possible to implicitly assume the validity of the simulator for the driver – VRUs interaction studies. In other words, the actual correspondence between the behavior observed in simulation and that recorded on field in the same condition of driver – cyclist interaction should be verified. A such specific validation study has not yet been developed.

However, it should be noted that for the aim of the current research, only the relative validity (which refers to the correspondence between the effects of different variations in the driving situation) is required [131].

Considering the data and the results reported in the previous chapters, the recorded data during the experiments highlighted that the drivers reacted differently at the different pedestrian/cyclist crossroad facilities and cross-section reorganization among the road scenarios, giving reasonable and reliable results.

## 8.4 General conclusion and further perspectives

The results reported in the present research are considered as solid basis for further investigations as well as findings for decision support on how improve the existing pedestrian and cyclist facilities. It should also be noted that the safety countermeasures analyzed here remain cost effective and easy to install, allowing an important increasing in VRUs safety with effectiveness and efficiency.

In general, the assessment of the effectiveness of the countermeasures in terms of improved driving performances reported in the present research is referred to the single countermeasure itself. Thus, further studies might examine combinations of treatments, such as curb extensions and advanced yield markings or parking restrictions and advanced yield markings, as well the combination of the colored paved markings with the raised island, combining a visual countermeasure with a physical one. 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.

Moreover, the interaction between driver and VRUs was analyzed for a single pedestrian or cyclist that crosses the road or travels along a bicycle path. However, further studies might analyze the driver – VRUs interaction under different interaction condition as groups of pedestrian or cyclists, with the aim of assessing the effectiveness of the countermeasures in the most common pedestrian and cyclist traffic conditions and highlighting additional effects on driver behavior. Results related to driver performances [132, 133, 134], in fact, showed that the groups of pedestrian and cyclist affected the driving yielding behavior as well their performances in terms of speed, which was lower in presence of multiple VRUs. However, the decreased speed values recorded during the presence of multiple VRUs did not result in less serious potential conflicts compared to the case of interaction with single VRU at intersections without the presence of safety measures, for which, the present research highlighted positive results.

In general, positive results were showed also for the PPS (Pedestrian Protection System), which were audio and visual warning. However, further studies, should examine the combination of audio and visual warning as well as directional warning to assess the effectiveness of the pedestrian detection systems also in the worst condition of a pedestrian that crosses outside of the crosswalk. Moreover, other experiments should test the efficacy of an improved PPS with the suggestions provided by the participants' questionnaire (advancing the warning message, clearer warning symbol, providing direction warning). Furthermore, it could be useful to study the efficacy of PPS under different warning times related to the actual driving behavior in approach to the zebra crossing.

Finally, the analysis on the driving overtaking maneuver was analyzed for different bicycle lane width and different road geometries. Results showed that the wider bicycle lanes, maintaining the same roadway width, can ensure higher safety levels for the cyclist, while the critical situation during the overtaking maneuver was recorded on the road curve. However, the current study investigated only one value of the curve radii (200m); considered the criticality of the driver-cyclist interactions on curves, further analysis should be carried out to study the driver behavior on a wider range of radii values. In addition, considering that the oncoming traffic was found by several studies in literature as one as the main variables that affect the driver behavior during the overtaking maneuver of a cyclist, further researches should be focused to evaluate the influence of several levels of oncoming traffic. Also for the overtaking maneuver, further studies could extend the analysis to the effects of groups of cyclists, which is a frequent condition of cycling on two-lane rural roads.

# Appendices

# Appendix A

# Hazard-Based duration model

A hazard-based duration model is a probabilistic method that is used for analyzing data in the form of time from a well-defined time origin until the occurrence of some particular event of an end-point [135]. Such modeling is a common topic in many areas including biomedical, engineering, and social sciences. Several studies concerning the transportation field applied this method to model time related variables in order to : analyze the critical factors that affect accident duration and developing accident duration prediction models [136, 137, 138], analyze the crossing behavior of cyclist at signalized intersections [139], model the pedestrian behavior violator and risk exposure at signalized crosswalk [140, 141], study the effects of the phone use on the driver reaction time in response to a crossing pedestrian [142, 143], prediction the pavement performance over the time [144], explore the factors that affect airport security transit times [145], develop a subway operational incident delay model [146], develop a accident duration model with endogenous variable [147], model the duration of freeway and highway traffic incident [148, 149, 150], investigate the traffic delay due to incident frequency, durations and lanes blockage [151] and model the braking behavior patters of drivers during the interaction with pedestrian and cyclist [152, 153]. In the present research, speed reduction time (SRT) is the duration variable. The speed reduction time is a continuous random variable T with a cumulative distribution function and probability density function, F(t) and f(t) respectively; the first gives the probability that a driver ends to brake with a speed reduction time lower than t. Conversely, the survivor function S(t) is the probability of a speed reduction time longer than that some specified time t.

$$F(t) = Pr(T < t) = 1 - Pr(T \geq t) = 1 - S(t) \tag{9}$$

The hazard function h(t) gives the conditional failure rate. More specifically, h(t) is the conditional probability that an event will end between time t and t + dt, given that the event has not ended up to time t [144].

$$h(t) = \lim_{\Delta t \to 0} \frac{Pr(t + \Delta t \geq T \geq t | T \geq t)}{\Delta t} = \frac{f(t)}{S(t)} \tag{10}$$

The proportional hazard (PH) and the accelerated failure time (AFT) models are two alternative parametric approaches that allow incorporating the influence of covariates on a hazard function. The proportional hazard model assumes that the hazard ratios are constant over the time. The AFT model, instead, allows the covariates to accelerate time in a baseline survivor function, which is the survivor function when all covariates are zero [154]. The AFT assumption allows a simple interpretation of results because the estimated parameters quantify the corresponding effect of a covariate on the mean survival time [142, 143]. Given these features, AFT models were applied in this study. In the AFT model, the natural logarithm of the speed reduction times, ln(T), is expressed as a linear function of explanatory variables, as follow:

$$ln(T) = \beta X + \varepsilon \tag{11}$$

where X is a vector of explanatory variables, $\beta$ is a vector of estimable parameters and $\varepsilon$ is the error term. Following Washington [154], the survival function in the AFT model can be written as:

$$S(t|\mathbf{X}) = S_0\left[t \cdot exp(\beta \mathbf{X})\right] \tag{12}$$

which leads to the conditional hazard function

$$h(t|\mathbf{X}) = h_0\left[t \cdot exp(\beta \mathbf{X})\right] exp(\beta \mathbf{X}) \tag{13}$$

where $h_0$ and $S_0$ are the baseline hazard and the baseline survival function respectively.

Equations (12). and (13) show the effect of the covariates on the speed reduction time: the explanatory variables accelerate or decelerate the elapsed time to reduce the speed to the minimum value during the yielding phase. In order to estimate the hazard and the survival function in a fully parametric setting, a distribution assumption of the duration variable is needed. Common distribution alternatives include Weibull, lognormal, exponential, gamma, log-logistic and Gompertz distribution [154]. The drivers' speed reduction times in response to a crossing pedestrian are positive duration dependence events. In other words, with the increasing of the time, the probability that the driver is reducing his speed in response to a crossing pedestrian reasonably increases. Such physical phenomenon is consistent with the form of the lognormal, $log - logistic$ and Weibull survival functions. The selection of the appropriate distribution form was based on the probability plot method [155]. The Weibull distribution was assessed as the best fitting (the plotting showed that the best linear relationship between the speed survival times and the cumulative distribution function was for the Weibull function), and thus, selected as survival function for the following analysis. In addition, this function is suitable for modeling data with monotone hazard rates that either increase or decrease with time [142, 143], which is consistent with the present study. The hazard function of the Weibull duration model is expressed a:

$$h(t) = (\lambda P)(\lambda t)^{P-1} \tag{14}$$

and the survival function of the Weibull duration model is expressed as

$$S(t) = exp(-\lambda t)^P \tag{15}$$

where $\lambda$ and P are the location and the scale parameter respectively. The location parameter, with the introduction of explanatory variables, has the following expression:

$$\lambda = exp[-P(\beta_0 + \beta_1 X_1 + ...)] \tag{16}$$

where the $\beta_i$ are the coefficients of the explanatory variables $X_i$. The final expression of the survival function of the Weibull duration model is the following:

$$S(t) = exp\left\{-exp\left[-P(\beta_0 + \beta_1 X_1 + ...)\right] t^p\right\} \tag{17}$$

The duration model as above specified assumes that the individual observations are independent. However in the present study data were obtained from a repeated measures experiment. Therefore the observations might be subjected to individual level of heterogeneity or frailty, which implies that data from an individual might be correlated [142, 143]. Without accounting for shared frailty or heterogeneities and potential correlations, the duration model would suffer from a specification error that could lead to erroneous inferences on the shape of the hazard function. In addition, the standard error estimates of the regression parameters might be underestimated and inferences from the estimated model might be misleading [142, 143]. To taking into account the effects of the repeated measures on the individual observations, two possible extensions of the AFT model could be used; Weibull regression model with clustered heterogeneity and Weibull regression model with shared frailty. Several previous studies applied the frailty type models in order to include the unobserved heterogeneity (i.e. frailty) with the aim of exploring the effect of freeway work zones on the non – recurrent traffic congestion [156], estimating the capacity reduction that is attributable to accidents in the opposite direction of accident [157] and developing models for the estimation of the temporal and spatial extent of congestion impact caused by accidents [158]. The model with clustered heterogeneity fits the standard duration model and then, adjusts the standard error estimates to account for the possible correlations induced by the repeated observations within individuals [159, 160]. Weibull regression model with shared frailty allows to taking into account the correlation among observations obtained from the same driver and maintains independence among observations across different drivers. The shared frailty model can be expressed by modifying the conditional hazard function (13) as follows:

$$h_{ij}(t|\alpha_i = \alpha_i h_{ij}(t) = \alpha_i h_0\left[t\, exp(\beta \mathbf{X}_{ij})\right] exp(\beta \mathbf{X_{ij}}) \tag{18}$$

where $h_{ij}$ is the hazard function for the $i_{th}$ driver in the $j_{th}$ driving test and $\alpha_i$ is the shared frailty, which is assumed to be gamma or inverse – Gaussian distributed, with mean 1 and variance $\Theta$. Weibull regression model with clustered heterogeneity and Weibull regression model with shared frailty were compared by the likelihood ratio statistics [154], the Akaike's information criteria (AIC) [161] and the Bayesian information criteria (BIC) [162] to identify the best fitting model. To determine the effects of explanatory variables, the exponents of the coefficients were calculated. The exponent of a coefficient provides an intuitive way of interpreting the results by translating to a percent change in the survival duration variable resulting from a unit increase for continuous explanatory variables and a change from zero to one for categorical or indicator variables [145].

# Appendix B

# Publications

## B.1 Publications on International Journals and International Conference Proceedings

1. F. Bella, M. Silvestri. Effects of safety measures on driver's speed behavior at pedestrian crossings. *Accident analysis and prevention* 83, 2015. pp. 111-124.

2. F. Bella, M. Silvestri. Driver's braking behavior approaching pedestrian crossing: a parametric duration model of the speed reduction times. *Journal of Advanced Transportation*, 2016; 50 (4):630-646

3. M. Silvestri, F. Bella. Effects of Intersection Collision Warning Systems and Traffic Calming Measures on Driver's Behavior at Intersections. *In Advances in Human Aspects of Transportation.* Series Advances in Intelligent Systems and Computing. Springer International Publishing.

4. F. Bella, M. Silvestri. Interaction driver–bicyclist on rural roads: Effects of cross- sections and road geometric elements. *Accident Analysis and Prevention.* Volume 102, 2017.

5. F. Bella, M. Silvestri. Effects of directional auditory and visual warnings at intersections on reaction times and speed reduction times. *Transportation Research Part F: Psychology and Behaviour.* Vol. 51, 2017, pp. 88–102.

6. F. Bella, V. Natale, M. Silvestri. Driver-pedestrian interaction under different road environments. *Transportation Research Procedia.* Volume 27, 2017, Pages 148-155.

7. F. Bella, M. Silvestri. Drivers' Behavior at Bicycle Crossroads. *Advanced Concepts, Methodologies and Technologies for Transportation and Logistics, Advances in Intelligent Systems and Computing* vol. 572, Pages 355-369

8. F. Bella, M. Silvestri. Driver-cyclist interaction under different bicycle crossroad configurations. In book. *Advances in Human Aspects of Transportation, Advances in Intelligent Systems and Computing* vol. 597, pp 855 – 866. Springer International Publishing.

9. F. Bella, V. Borrelli, M. Silvestri, F. Nobili. Effects on Driver's Behavior of Illegal Pedestrian Crossings. In Book. *Advances in Intelligent Systems and Computing* 786, pp. 802-812. Springer International Publishing.

10. F. Bella, M. Silvestri, V. Natale, F. Nobili, 2019. Divers' Behavior in Pedestrian Detection: Effect of Road Types. In Book. *Advances in Intelligent Systems and Computing* 786, pp. 813-822

11. F. Bella, M. Silvestri, 2018. Survival Model of Drivers' Speed Reduction Time at Bicycle Crossroads: a driving simulator study. *Journal of advanced transportation* Volume 2018. Article number 4738457, 12 pages.


## B.2 International Conference Proceedings (peer reviewed papers)


1. F. Bella, M. Silvestri A hazard-based duration model of the speed reduction times of drivers at Pedestrian Crossings: Parametric Duration Model of Speed Reduction Times. Paper for RSS2015. Road Safety & Simulation International Conference RSS2015 October 6-8, 2015 Orlando, Florida, USA

2. M. Silvestri, F. Bella. Effects of intersection collision warning systems on drivers' reaction time: a hazard-based duration model. "Fifth European Conference on Human Centered Design for Intelligent Transport Systems". 30 June and 1st July 2016, Loughborough, UK

3. F. Bella, M. Silvestri. Effects of countermeasures on drivers' behavior at bicycle crossroads: a driving simulator study. RSS2017 – Road Safety & Simulation International Conference. 17 - 19 Oct. 2017. The Hague, NL.

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