Effects of directional auditory and visual warnings at intersections on reaction times and speed reduction times

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ABSTRACT

Intersection collision warning systems (ICWSs) have an important impact on driving safety because making the potential collision at intersection predictable, allow reducing the probability and severity of accidents. Among the several types of alarms to alert the driver of an imminent collision, those most used concerning the auditory and the visual stimulus. However, it is unclear whether is more effective an audio or a visual warning. In addition, no study compared the effects on drivers' behavior induced by an acoustic and a visual directional warning. The main objective of the present study was to assess, in response to a potential conflict event at the intersections, the effects of directional auditory and visual warnings on driving performance.

A driving simulator experiment was carried out to collect drivers' behavior in response to a vehicle that failed to stop at the intersection. The parameters reaction time and speed reduction time were used for the evaluation of the effects on driving performance. These duration variables were modeled following the survival analysis, by the use of the accelerated failure time duration model with a Weibull distribution.

Results showed that when the directional warning system (auditory or visual) was present, the drivers were able to detect earlier the violator vehicle. This effect led to a more comfortable braking maneuver and, thus, less possibilities of an unexpected maneuver for the following vehicle, avoiding the car – following collisions. The effectiveness of ICWSs was more evident for the directional auditory speech message; for this condition, in fact, the lower reaction time and the longer speed reduction time were obtained.

The outcomes of the present study provide useful suggestions about the most effective collision warning systems that the automotive industry should develop and equip on vehicles.

Keywords: intersection collision warning system, driver behavior, driving simulator, survival analysis.

1. INTRODUCTION

The intersections are essential elements of the road network but constitute hazardous locations, because imply opportunities for conflicts among vehicles. Although intersections are a slight part of the road system, they emerge as the road sections where a remarkable portion of the accidents occurs. The 2012 annual statistic report by DaCoTa project (DaCoTa, 2012), which further develops the contents of the European Road Safety Observatory (ERSO), showed that in the 2010, almost 6.800 people were killed in road traffic accidents at intersections in 18 EU member states. In Italy, the last statistic report showed that over 42% of all road accidents occurred at intersections (ACI – ISTAT, 2014). All over the world, the statistics show that intersections are hazardous locations. The European database of the road accident CARE (CARE, 2015) reports that the intersection related fatalities are more than 20% in the EU during the last decade (2004–2013). In the United States more than 40% of the crashes occurred at or near an intersection while in Canada more than 30% of the deaths and 40% of serious injuries on the road occurred at intersections (Tay, 2015).

There is agreement to believe that this situation is linked to the fact that driving at intersection is one of the most dynamic and difficult task of drivers (e.g. Werneke and Vollrath, 2013). It requires large cognitive efforts by the driver to perceive and process the amount of information related to the specific intersection configuration (type of intersection, traffic signs), the traffic condition (crossing vehicles, vehicles driving ahead and oncoming) and the maneuver to act (crossing, turn on the left or right). The complexity of this driving task can be often linked to inadequate drivers' behavior and in the occurrence of accidents.

Understanding the main factors that influence the occurring of the intersection accidents and developing systems that encourage proper drivers' behaviors and help drivers in the complex task of drive at the intersections are deemed to be the keys to improve the road safety at intersections. For this reason, a lot of research were and continue to be aimed on the factors contributing to crashes at these hazardous locations (e.g. Tay, 2015) and on the development of effective driving assistance systems such as intersection collision warning systems (ICWS).

The intersection collision warning systems (ICWSs) are in – vehicular warning systems which detect obstacles with sensors in vehicles and devices located at intersection, such as detecting radar, and alert the driver of an imminent collision. These systems have an important impact on driving safety because making the potential collision at intersection predictable, allow reducing the probability and severity of accidents (Atev et al. 2004; Lee et al., 2002; Penney, 1999).

Among the several types of alarms (auditory warnings, visual warnings, vibrotactile warnings and haptic warnings), those most used concerning the auditory and the visual stimulus. The first type of alarm consists in audio signals as beep sounds, auditory icons (i.e. car horn, skidding tires) or speech message, that are sent to the driver through a vehicle on board audio system (e.g. Gray, 2011; Haas and Van Erp, 2014; Yan et al., 2015a). The second type consists in a visual warning signal such as a car symbol, flashing orange warning circle, triangular warning that appears on the vehicle dashboard (e.g. Chen et al., 2011; Penney, 1999; Scott and Gray, 2008; Werneke and Vollrath, 2013).

Several studies were oriented to the comparison of the effects on driver's behavior at the intersections due to different types of auditory warnings and different types of visual warnings.

Chang (Chang et al., 2008) used a driving simulator equipped with collision warning system to analyze the effect of different auditory warning alarm contents on driving performance at intersections. The alarm contents were a beep sound and a speech message automatically generated when a violator's vehicle entered an intersection from left or right. The beep sound was a pure tone while the speech message provided also the information about the direction of the violator. The results indicated that the reaction time was shorter for the speech message alarm. The authors argued that the largest information content of the speech message was extremely important in advising the driver of the direction of a danger and, thus, allow an earlier reaction.

Yan (Yan et al., 2015b) carried out a driving simulator study focused on right–angle collisions caused by red-light running and aimed to analyze the effects of the absence of warning, the speech message with and without the information about the direction of the violator and the delivery time of warning (from 2.5 to 5s). It was found that the reaction time under directional information warning messages was largely decreased in many scenarios. The authors concluded that if drivers had the information of the direction of the violator vehicle, they need less time to locate the violator vehicle, and hence performed faster reactions.

In a driving simulator experiment (Zhang et al., 2015) examined the effects of directional and non-directional auditory warnings on driving behavior and crash avoidance performance at signalized intersections. The results showed that drivers benefited from auditory warnings that include the direction of the danger. The reaction time when a directional information warning is given was smaller than that in the case of the non-directional information warning. Moreover, the mean deceleration in the case of a directional information warning was smaller than that in the case of a non-directional information warning, indicating that a directional warning help the driver to take more comfortable and appropriate braking action to avoid the collision.

Werneke and Vollrath (2013) analyzed the effects of three visual warnings (a flashing orange warning circle) that were presented to driver in a simulated head-up display to help to face a critical situation at an unsignalized T-intersection. Two visual signals were showed to the driver in the focus of drivers' view but with different timing (early-middle and late-middle warnings); the third signal was showed in the driver's peripheral vision and was delayed (late-sidewise warning). A clear positive effect (fewer collision and a more proper driver behavior) of the early-middle warning signal was found.

With respect of the comparison of warnings that involve different senses (i.e. the comparison between audio and visual) only few studies were conducted.

Scott and Gray (2008) examined the effectiveness of rear-end collision warnings presented in different sensory modalities (tactile, auditory and visual warnings) as a function of warning timing (3 or 5 s) in a driving simulator. All the three warnings were non-directional warnings. Driver reaction time was captured for analysis. It was found that the reaction times for all warning modalities were significantly shorter than that for no-warning condition. Despite the reaction time for visual warning was higher than that for the auditory warning, the difference was not statistically significant.

Chen et al. (2011), using a low cost driving simulator, analyzed the effect of an auditory warning and a visual warning on driver's performance at intersections. Three event scenarios were characterized by a vehicle that committed a speeding violation at intersections (violator vehicle from left, violator vehicle from right and violator vehicle performing a right turn from the opposite direction without giving priority to the test vehicle). Both the auditory warning (an auditory tone at around 70 dB) and the visual warning (a red flashing car icon that appeared in the right corner of the dashboard area) did not provide the information about the direction of the violator vehicle. No statistically significant differences were found between visual warning and the auditory tone; only in one scenario (violator vehicle from right), the reaction time for the auditory tone warning was lower than that for the visual warning. The authors did not provide a discussion for this result. No other differences were found for the investigated variables (speed, deceleration, proportion of crashes).

The above reported studies highlight the importance of a directional auditory warning information in an intersection collision warning system: a clear warning with directional information about an urgent hazard event allows the drivers to advance the braking maneuver and, thus, avoid the potential collision. However, it is unclear whether is more effective an audio or a visual warning. In addition, no study compared the effects on drivers' behavior induced by an acoustic and a visual directional warning.

The main objective of the present study was to assess, in response to a potential conflict event at the intersections, the effects of directional auditory and visual warnings on driving performance. The parameters reaction time (RT) and speed reduction time (SRT) were used for the evaluation of the effects on driving performance.

Reaction time represents the time needed for the driver to react in response to a warning signal. It is a parameter of drivers' behavior that has concrete implication for road safety (e.g. Green, 2000; Summala, 2000) 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 (Evans, 1991).

Speed reduction time (Bella and Silvestri, 2016; Haque and Washington, 2015) gives a measure of the driver's braking behavior to avoid a potential conflict event at the intersections. The speed reduction time is defined as the elapsed time between when the driver reacts to a potential conflict event (at the beginning of this maneuver the driver has a speed called initial speed) and when he perceives to have avoided the collision and thus, ends the deceleration phase (at the end of the maneuver the driver reaches the minimum speed). The width of the interval time taken by the driver to pass from the initial speed to the minimum speed highlights if he receives an information that is more or less timely and clear about the potential conflict event at the intersection and, therefore, if he can decrease his speed with a less aggressive maneuver. In other words, this means that a small speed reduction time reveals an unsafe braking maneuver, indicating that the driver needs to decrease the speed in a limited interval time in response to a critical condition and, therefore, he adopts an abrupt maneuver to compensate the consequences of an unexpected situation.

To highlight how different warnings affect the drivers' behavior, reaction time and speed reduction time were modeled by the use of a parametric duration model, also called "survival model" or "hazard based duration model", which is particularly indicated to provide additional information of duration effects.

A driving simulator experiment was carried out to analyze the effects of directional auditory and visual warnings on drivers' behavior in response to a potential conflict event, represented by a vehicle that failed to stop at the intersection (violator vehicle).

This study was developed within a wider research program aimed at also studying the effects of traffic calming measures along the sections approaching the road intersections (Silvestri and Bella, 2016).

The remainder of the paper is organized as follows. First, the method of duration model is introduced. Then, the following section presents the driving simulator experiment. After that, the empirical results are given and discussed. The final section provides the main research conclusions.

2. METODOLOGY

2.1 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 (Collett, 2003). Such modeling is a common topic in many areas including biomedical, engineering and social sciences. In the transportation field, hazard-based duration models have been applied to study a number of time-related issues such as: analyzing the critical factors that affect accident duration and developing accident duration prediction models (Chung, 2010; Chung et al., 2011; Hojati et al., 2014), analyzing the crossing behavior of cyclist at signalized intersections (Yang et al., 2015), modeling the pedestrian behavior violator and risk exposure at signalized crosswalk (Guo et al., 2011; Tiwari et al., 2007), studying the effects of the phone use on the driver reaction time and on braking behavior in response to a crossing pedestrian (Haque and Washington, 2015, 2014) and to predict the pavement performance over the time (Anastasopoulos et al., 2014).

In this study, the reaction time and speed reduction time are the duration variables. The duration variable (reaction time or 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 the duration variable is lower than *t*. Conversely, the survivor function *S(t)* is the probability of a duration variable longer than that some specified time *t*.

$$F(t) = Pr(T<t) = 1-Pr(T\geq t) = 1-S(t) \qquad (1)$$

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* (Washington et al., 2011).

$$h(t) = \lim_{\Delta t \to 0} \frac{\Pr(t + \Delta t \geq T \geq t \mid T \geq t)}{\Delta t} = \frac{f(t)}{S(t)} \qquad (2)$$

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 (Washington et al., 2011). 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 (Haque and Washington, 2015, 2014). Given these features, AFT models were applied in this study. In the AFT model, the natural logarithm of the duration variables, *ln(T)*, is expressed as a linear function of explanatory variables, as follow:

$$ln(T) = \beta X + \varepsilon \qquad (3)$$

where X is a vector of explanatory variables, β is a vector of estimable parameters and ε is the error term. Following Washington (Washington et al., 2011), the survival function in the AFT model can be written as

$$S(t|\mathbf{X}) = S_0[t\ exp(\boldsymbol{\beta}\mathbf{X})], \quad (4)$$

which leads to the conditional hazard function

$$h(t|\mathbf{X}) = h_0\ [t\ exp(\boldsymbol{\beta}\mathbf{X})]\ exp\ (\boldsymbol{\beta}\mathbf{X}), \quad (5)$$

where h_o and S_0 are the baseline hazard and the baseline survival function respectively.

Eq. 4 and 5 show the effect of the covariates on the duration variable: the explanatory variables affect directly the duration variable by accelerating or decelerating it.

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 (Washington et al., 2011). According to Haque and Washington (2015, 2014), the Weibull distribution was selected because it is suitable for modeling data with monotone hazard rates that either increase or decrease with time. The drivers' reaction times and speed reduction times in response to a warning signal are positive duration dependence events. In other words, with the increasing of the time, the probabilities that the driver reacts and decreases his speed to avoid the conflict with other vehicle reasonably increase.

The hazard function of the Weibull duration model is expressed a

$$h(t) = (\lambda P)(\lambda t)^{P-1} \quad (6)$$

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

$$S(t) = exp\ (-\lambda t^P) \quad (7)$$

where λ and P are the location and the scale parameter respectively. A positive value of the scale parameter P means that the survival probability of the duration variable (S(t)) decreases with the elapsed time.

The location parameter, with the introduction of explanatory variables, has the following expression:

$$\lambda = exp\ [-P(\beta_o + \beta_1 X_1 + ...)] \quad (8)$$

where each β_i represents the coefficient of the explanatory variable X_i. The final expression of the survival function of the Weibull duration model is the following:

$$S(t) = exp\ \{-\ exp\ [-P(\beta_o + \beta_1 X_1 + ...)]t^P\} \quad (9)$$

The exponential value of each explanatory variable coefficient ($exp(\beta_i)$) provides an easy and meaningful interpretation about the impact on the duration variable due to an increase or a decrease of the independent variable-(X_i).

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 (Haque and Washington, 2015, 2014).

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 (Haque and Washington, 2015, 2014).

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.

The first model 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 (Cleves et al., 2008; McGilchrist and Aisbett, 1991).

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 (eq. 5) as follows:

$$h_{ij}(t|\alpha_i) = \alpha_i h_{ij}(t) = \alpha_i h_0 \, [t \exp(\boldsymbol{\beta X_{ij}})] \exp(\boldsymbol{\beta X_{ij}}), \qquad (10)$$

where h_{ij} is the hazard function for the ith driver in the jth driving test and α_i is the shared frailty, which is assumed to be gamma or inverse – Gaussian distributed, with mean 1 and variance θ.

Weibull regression model with clustered heterogeneity and Weibull regression model with shared frailty were compared by the likelihood ratio statistics (Washington et al., 2011) and the Akaike's information criteria (AIC) (Akaike, 1973) 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 (Haque and Washington, 2015).

2.2 Driving simulator experiment

The study was conducted using the advanced driving simulator of the Department of Engineering – Roma Tre University. A multi-factorial experiment was designed to analyze the effects of the ICWSs (auditory, visual and no warning signal) on drivers' reaction time and drivers' speed reduction time in response to a vehicle that failed to stop at the intersection, both from test vehicle's right and left. The following section describes the road scenarios and the ICWSs that were implemented in the driving simulator.

2.2.1. Road scenarios and ICWSs

Six two-lane rural road alignments, each one approximately 38 Km long, were implemented in the driving simulator. For all the alignments, according with the Italian road design guidelines (Ministry of Infrastructures and Transports, 2001), the road cross-section was 9.50 m wide formed by two 3.50 m wide lanes and two 1.25 m wide paved shoulders. The design speed ranged from 60 Km/h (on curves with a radius equal to 118 m) to 100 Km/h (on tangent), and the posted limit was 90 Km/h. The radii changed from 118 m to 930 m and the lengths of the tangent ranged from 100 m to 1650 m. The vertical alignment had null longitudinal grade, to avoid conditionings on the dynamic variables, like speed or acceleration. Along each alignment were designed several stop – controlled intersections (four-leg intersections and three-way intersections); in 6 of these intersections, the 6 possible conditions of "ICWS X direction of the violator vehicle" (auditory speech message, visual warning and no warning X violator vehicle from right and left) were simulated. In such 6 intersections of interest a violator vehicle was implemented to fail the stop sign and cross the road (3 from test vehicle's right and 3 from test vehicle's left) at the speed of 70 Km/h.

To ensure the same approach conditions, the approach geometry was the same for all the 6 intersections of interest; the driver, after a curve with a radius of 450 m, traveled an approach tangent to the intersection 600 m long. During this approaching phase, the drivers also encountered a vehicle in the opposite direction. To avoid the potential order effect, the 6 road alignments had different sequences of the 6 intersections of interest. In addition, each alignment was divided in two parts, each one about 19 km long, which were driven by the driver in two distinct sessions (see section Procedure). Each part was characterized by the presence of three of the six intersections of interests (i.e. the six combinations of ICWS condition and direction of the violator vehicle were distributed in the two parts of the alignment, three for each one). In this way, each driver experienced all the 6 possible combinations of ICWS and direction of the violator vehicle.

Two types of ICWS were implemented in the scenarios. The first ICWS was the auditory speech message, where the direction of the violator vehicle was specified: "attention, vehicle from right" or "attention, vehicle from left". These speech messages were digitally prerecorded and saved as.wav files. Then they were reproduced into the vehicle through the audio system of the driving simulator at around 70 dB loudness level, without consider the direction of the vehicle (i.e. the auditory warning sound came from all the speakers of the audio system into the driving simulator). Baldwin and May (2011) assessed the sound pressure level of 70 dB as effective as it provides adequate level of perceived urgency without startling the drivers. Moreover, the loudness level of the present study was fully consistent with similar intersection auditory warnings investigated in literature (Chang et al., 2008, 2009; Yan et al., 2015a, 2015b).

The second ICWS was a visual warning, which consisted in a red car icon (an icon of car into a red triangle) (fig. 1.a). It was similar to visual warning used in previous studies in literature (e.g. Scott and Gray, 2008) and appeared in the right corner of the central display, near the speedometer, to simulate its appearance on a device inside the vehicle (fig.1.b). The visual warning provided the direction of the violator vehicle through the icon of car oriented in the direction of arrival of the violator vehicle and remained fixed (without flashing) in the right corner of the central display from its activation to the end of the critical situation. The view angle of the visual warning was approximately within the 10-deg of the driver's line of sight as recommended by McGehee et al. (2002). In the condition of absence of ICWS, no visual or auditory cue was presented to the driver.

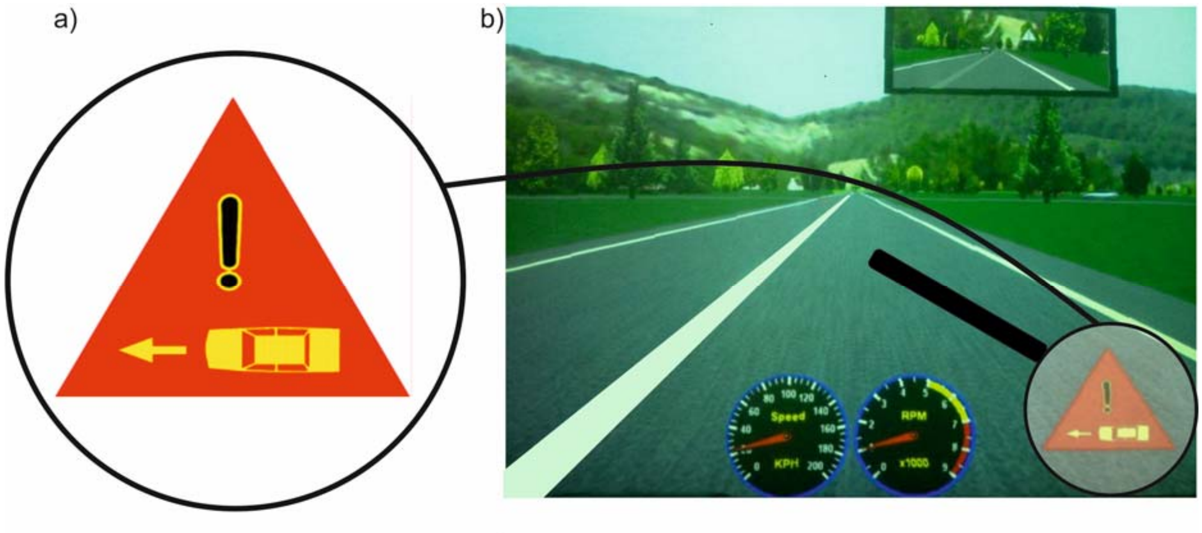

Figure 1. a) The red car icon of the visual warning and b) the visualization of the visual warning to the driver during the simulation.

The triggering point of the ICWS (both auditory and visual) was when the test vehicle reached a point 100 m in advance of the intersection. In the same moment the violator vehicle, with the speed equal to 70km/h, was at 77.7 m from the collision point with the test vehicle. In these conditions and with the hypothesis that the test vehicle is travelling at the posted speed limit (90 Km/h), the time to collision (TTC) is equal to 4 s. This value, however, is theoretical because it depends on the actual approaching speed of the driver at the intersection during the simulated drive. In other words, if the driver reaches the triggering point located at 100 m from the intersection with a higher or a lower speed of 90 Km/h, the values of TTC will be lower or higher, respectively, than 4 seconds. This triggering mode of ICWSs and the dynamic of the violator vehicle are fully consistent to those used in previous driving simulator studies (Chang et al., 2008, 2009). Moreover it should be noted that, taking into account the variability of the approaching speeds at the intersection (expected between 70 and 120 km/h), the actual values of TTC (considered as the time to collision in the moment in which the warning is triggered) recorded during the simulated drives, are expected in the interval between 3-5 s. (3s for speed equal to 120 km/h and triggering point 100 m from the intersection; 5s for speed equal to 70 km/h and triggering point 100 m from the intersection). Such values are fully consistent with those reported in literature (e.g. Scott and Gray, 2008; Yan et al., 2015b). In other terms, the design of the experiment implies the simulation of warning systems in which the TTC values are fully consistent with those suggested in literature.

2.2.2 Apparatus

The driving simulator of the Department of Engineering – Roma Tre University used for this study is an interactive fixed-base driving simulator. It was previously validated (Bella, 2008a, 2005) and largely used as a reliable tool for the study of the driver's speed behavior (e.g., Bella, 2008b, 2013, 2014a, 2014b, 2014c; Bella and Calvi, 2013; Bella and Silvestri, 2015; Bella et al., 2014). The hardware interfaces (wheel, pedals and gear lever) are installed on a real vehicle. The driving scene is projected onto three screens: one in front of the vehicle and one on either side, which provide a 135° field of view. The resolution of the visual scene is 1024x768 pixels with a refresh rate of 30 to 60 Hz. The system is also equipped with a sound system that reproduces the sounds of the engine and of the auditory warning during the simulation. The simulator provides many parameters for describing the travel conditions (e.g., vehicle barycenter, relative position in relation to the road axis, local speed and acceleration, steering wheel rotation angle, pitching angle, and rolling angle). The data recording system acquired all of the parameters at spatial intervals of 2 m.

2.2.3 Participants

Forty-two drivers (32 men and 10 women), whose ages ranged from 23 to 70 (average 31) 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 rural roads of at least 2500 km. All participants reported normal or corrected-to-normal vision and they had not hearing problems.

The participants were divided into six groups; each group were composed by seven participants, of which one or two women; the average age of the six groups ranged between thirty and thirty - two years old. Each group drove one of the six scenarios, which were each one characterized by a specific sequence of intersections where a violator vehicle failed to stop.

According to the questionnaire on perceived discomfort (see next section Procedure), 41 of 42 participants experienced null or light levels of discomfort; only one participant was not able to finish the experiment. Thus, the sample used for the analysis consisted of 41 drivers.

2.2.4 Procedure

The experiment was conducted with the free vehicle in its own driving lane. In the other driving lane, a slight amount of traffic was distributed to induce the driver to avoid driving into that lane. The simulated vehicle was a standard medium-class car with automatic gears. The participants were first briefed about the use of the hardware interface (i.e. wheel and pedals and automatic gear) and then invited to start a training drive at the driving simulator on a specific alignment for approximately 8 minutes, to become familiar with the driving simulator. In this training drive, participants encountered several cars on their own lane in order to test the braking, the steering wheel and the accelerator pedal by overtaking a car or acting an emergency brake. After the training, participants came out of the driving simulator for about 5 -10 minutes to restore their initial condition; in this phase, also some information about the experiment were provided. In particular, drivers were instructed to drive as they normally would in the real world and were informed that the vehicle was equipped with an alarm system that advised him of a potential critical situation through an auditory or visual warning. In addition, participants were told that the ICWS system would not generate signal to simulate the condition of driving without an ICWS.

In order to limit the duration of the drive and, thus, reduce the probability of sickness for driver, the experiment was divided in two sessions. In the first, the participant drove the first part of one of the six road alignments and after that, he filled in a questionnaire about his personal data and his driving experience. In the second session, the participant drove the second part of the road alignment and then he filled in another questionnaire. Each participant, therefore, experienced all the six combinations of ICWS X direction of the violator vehicle. The driving sequence of the two halves of the road alignment was counterbalanced across participants. This questionnaire consisted in two parts: perceived discomfort and effectiveness of the ICWSs. For the first, there were 4 types of discomfort: nausea, giddiness, fatigue and other; each question could be answered by a score of 1-4 in proportion to the level of the discomfort experienced: null, light, medium and high. The null and light level for all 4 types of discomfort is considered to be acceptable for driving. For the effectiveness for both of the ICWSs, it was asked to the participants if they perceived an effect during the drive. For those who perceived an effect, it was asked to indicate the type of influence (increasing or decreasing the speed, increasing or decreasing the level of attention) and the level of the perceived effect by a score of 1-10.

3. DATA PROCESSING

The speed profile of each driver was plotted 150 m in advance of each one of the 6 intersections where the combinations of factors ICWS (3 levels: auditory, visual and no warning) and direction of the violator vehicle (2 levels: right and left) were implemented. Overall, 246 speed profiles (6 intersections x 41 drivers) were analyzed.

From each speed profile, the following variables of the driver's behavior while approaching the intersection were determined:

- V_i: driver's initial speed value, identified at the moment when the driver starts to decrease his speed, releasing the accelerator pedal, in response to the violator vehicle;
- V_f: minimum speed value reached by the driver to avoid the collision;
- d_m: the average deceleration rate during the speed reduction phase from V_i to V_f; this variable is given by the following equation:

  $$d_m = (V_i^2-V_f^2)/2*S \tag{11}$$

  where S is the distance between the points where the speed is equal to V_i and V_f.
- RT: driver's reaction time, which is the elapsed time between the activation of the warning signal (when the test vehicle was at 100 m from the intersection) and the moment in which the driver starts to decrease his speed. In the intersections where no warning was provided to the driver, the reaction time was assumed equal to the elapsed time between the moment when the test vehicle was at 100 m from the intersection and the moment in which the driver starts to decrease his speed, in response to the violator vehicle;
- SRT: driver's speed reduction time, is the elapsed time between the moment in which the driver reacts (initial speed) and when he perceives to have avoided the collision, and thus, ends the deceleration phase (minimum speed).

From the sample were excluded the data of the following cases:

- the driver adopted a too much low (on average under 60 Km/h) (2 data: 1 for the condition "No warning" and 1 for the auditory speech message) or too much high speed (on average over 100 Km/h) (9 data: 6 for "No warning" condition, 2 for the visual warning and 1 for the auditory speech message) and, thus, the violator vehicle did not affect the driver's behavior (the driver crossed the intersection much late and well in advance compared with the violator vehicle, respectively);

- the driver collided with the violator vehicle: 12 collisions were recorded in the condition "No warning". No collision was recorded when the warning was provided to the driver.

Thus, 223 observations were used for the analysis (see table 1). It should be noted that such data highlight a first clear effect of the warning systems (both visual and audio), which allowed the driver to always avoid the collision with the violator vehicle. When the warning was absent, instead, in 16% of the driver-violator vehicle interactions (12 collisions on 75 interactions, see table 1) a collision was recorded.

	Visual warning		**Auditory speech message**		**No ICWS**		**Total**
	Right	Left	Right	Left	Right	Left	
N° of observations (a)	**41**	**41**	**41**	**41**	**41**	**41**	**246**
N° of exclusion for (b)							
High speed	1	1	0	1	1	5	9
Low speed	0	0	0	1	1	0	2
Remaining observations (a-b)	**40**	**40**	**41**	**39**	**39**	**36**	**235**
Collisions (c)	**0**	**0**	**0**	**0**	**6**	**6**	**12**
% of collision [c/(a-b)]	0	0	0	0	15.4	16.7	
Remaining observations (a-b-c)	**40**	**40**	**41**	**39**	**33**	**30**	**223**

Table 1. Summary of the number of excluded drivers and number of collisions.

4. DATA ANALYSIS AND RESULTS

The descriptive statistics of the variables obtained from the speed profiles are reported in table 2.

Variable	ICWS	Direction	Mean	SD	Number of observations
V_i [Km/h]	Video	Right	83.50	14.08	40
		Left	83.76	10.48	40
	Audio	Right	82.11	12.46	41
		Left	85.04	10.95	39
	No Warning	Right	82.66	8.11	33
		Left	81.07	13.22	30
V_f [Km/h]	Video	Right	32.70	16.94	40
		Left	31.02	16.14	40
	Audio	Right	39.08	15.45	41
		Left	27.56	11.52	39
	No Warning	Right	35.10	16.29	33
		Left	35.24	11.02	30
d_m [m/s^2]	Video	Right	4.84	1.52	40
		Left	4.83	1.42	40
	Audio	Right	4.67	1.30	41
		Left	4.81	1.31	39
	No Warning	Right	4.63	1.10	33
		Left	4.92	1.37	30
RT [s]	Video	Right	0.88	0.41	40
		Left	0.99	0.51	40
	Audio	Right	0.89	0.49	41
		Left	0.76	0.37	39
	No Warning	Right	1.30	0.79	33
		Left	1.53	0.66	30
SRT [s]	Video	Right	3.03	1.15	40
		Left	3.18	1.02	40
	Audio	Right	2.61	0.83	41
		Left	3.45	1.00	39
	No Warning	Right	2.86	0.85	33
		Left	2.59	0.59	30

Table 2. Descriptive statistics of the driver speed profiles variables.

Two statistical models (Weibull AFT model) of survival time for the reaction time and speed reduction time were developed using the continuous variable driver's initial speed, and average deceleration and the categorical or indicator variables ICWSs condition and the direction of the violator as explanatory variables. The mean values and standard deviations of the continuous and categorical variables are reported in table 3.

For the reaction time only the initial speed value was used as explanatory variable, due to the fact that the driver's reaction in response to a violator vehicle is not affected by the variables minimum speed and average deceleration (such variables are recorded at the end of the decreasing speed maneuver). Conversely, for the speed reduction time, only the average deceleration d_m was used as explanatory variable due to the high representativeness of the phenomenon provided by this variable. This approach also allows to avoid correlation among the variables V_i, V_f and d_m, ensuring the reliability of the model.

Dynamic variable	**Mean Value**	**SD**
V_i	83.01 Km/h	11.60 Km/h
d_m	4.78 m/s^2	1.33 m/s^2
ICWS Condition	**Mean Value**	**SD**
Auditory speech message	0.34	0.47
Visual warning	0.35	0.48
No ICWS	0.31	0.46
Direction of the violator vehicle	**Mean Value**	**SD**
Right	0.51	0.50
Left	0.49	0.50

Table 3. Statistics of explanatory variables included in the Weibull AFT duration model

4.1 Hazard – based duration model

Weibull accelerated failure time (AFT) was used for modeling the diver's reaction times (RT) and speed reduction times (SRT) by the use of the statistical software STATA version 13.1. Two extensions of this model were tested: the Weibull AFT model with clustered heterogeneity and the Weibull AFT model with shared frailty. The frailty was gamma distributed. The two models were compared with their likelihood ratio statistics and with the Akaike's Information Criterion (AIC) test. For the RT, the likelihood ratio statistic of the Weibull AFT model with clustered heterogeneity was -145.82 while that for the Weibull AFT model with shared frailty was -167.532, highlighting that the first was preferable. The AIC test also confirmed the previous result; for the clustered heterogeneity model and for the shared frailty model the AICs were 305.64 and 348.65 respectively (the model with the lower AIC is preferable). For the SRT, the likelihood ratio statistic of the Weibull AFT model with clustered heterogeneity was -32.86 while that for the shared frailty model was -36.87, highlighting that the first was preferable. The AIC test also confirmed the previous result; for the clustered heterogeneity model and for the shared frailty model the AICs were 79.71 and 87.72. Thus, based on both likelihood ratio statistics and the AIC, the Weibull AFT model with clustered heterogeneity was the preferable both for the reaction time and the speed reduction times of the drivers in response to a violator vehicle at the intersections, under different conditions of warning signals and directions of the violator vehicle.

The table 4 shows the significant parameter estimates for the Weibull AFT model with clustered heterogeneity for RT. The scale parameter P has an estimate value equal to 3.895, meaning that the survival probability of RT decreased with the elapsed time. On average, in fact, the probability of fail to detect the violator vehicle after 2 s was approximately 7 times higher than that after 1 s (i.e., $(2/1)^{3.895-1}$). The scale parameter P higher than 1 implies that the hazard function of the reaction times was monotone and with positive duration dependence; this is consistent with the hypothesis of the applied model.

The model identified that the driver initial speed was statistically significant for the drivers' reaction times. The coefficient of the initial speed was negative, which implies that when the value of this variable increased, the RT value decreased. More specifically, for 1 Km/h increase in the driver's initial speed, the time required to react was 1% lower (Exp (β)=0.99).

Among the ICWS conditions, both the visual warning and the auditory speech message were statistically significant (P= 0.00) and negatively associated with the reaction time. The visual warning and the auditory speech message had values of RT (equal to 1.49s and 1.26s for null survival probability, respectively) shorter than for the no ICWS condition (2.18 s; mean difference = 0.69s, P=0.000; mean difference = 0.92s, P=0.000, respectively) (figure 2). More specifically, for the visual warning the time to react was 32% shorter (Exp (β)=0.68), while for the auditory speech message was 42% shorter (Exp (β)=0.58). In addition, a pairwise comparison with Bonferroni's correction was also performed; results showed that RT for the auditory speech message was statistically significantly shorter than that for the visual warning (mean difference = 0.23s; P = 0.018). It should be noted that for the condition of No ICWS a coefficient was not provided because it was the reference condition.

Comparing the directions of the violator, the reaction time with violator vehicle from right was 6% longer (Exp (β)=1.06) than that for violator vehicle from left (the reference condition) but the difference was not statistically significant (P=0.362).

Variable	Estimate	SE	z - Statistic	p-value	Exp (β)	95% Conf. Interval	
V_i [Km/h]	-0.012	0.002	-4.77	0.000	0.99	-0.016	-0.006
ICWS condition							
No ICWS	-	-	-	-	-	-	-
Visual warning	-0.379	0.045	-8.34	0.000	0.68	-0.468	-0.289
Auditory speech message	-0.546	0.069	-7.82	0.000	0.58	-0.682	-0.409
Direction of the violator							
Left	-	-	-	-	-	-	-
Right	-0.057	0.058	-0.98	0.326	1.06	-0.171	0.056
Constant	1.217	0.212	5.73	0.000		0.800	1.633
P	3.895	0.613				2.861	5.304
Log–likelihood at convergence (Pseudo)	-145.82						
Log–likelihood at zero	-178.24						
AIC	305.64						
N° of observations	223						
N° of groups	41						

Table 4 Weibull AFT model with clustered heterogeneity estimates for reaction times.

The use of the Weibull AFT model with clustered heterogeneity allowed a comparison of the driver's reaction time in response to a violator vehicle, under different ICWS conditions. The representation of the drivers' reaction patterns was possible by the plotting of the survival curves with the use of the estimated coefficient of the initial speed and the warning signals; the coefficient of the direction of the violator vehicle was not used because this variable was not statistically significant.

The estimation of the survival curves was provided by the eq. 9, where the vector ***X*** was represented by the driver's reaction time variables, while the vector $\boldsymbol{\beta}$ was represented by the related coefficients. The survival curves were plotted by using the mean value of the continuous variable initial speed (tab. 3) and the estimated coefficients of the ICWS conditions in table 4.

For example, the survival probability of RT for the visual waning and the audio speech message after 1.5 s were respectively:

$S(t=1.5) = \exp\{-[\exp(-3.895(1.217+(-0.012*83.01)+(-\underline{\mathit{0.379}})))]*1.5^{3.895}\}$

$S(t=1.5) = \exp\{-[\exp(-3.895(1.217+(-0.012*83.01)+(-\underline{\mathit{0.546}})))]*1.5^{3.895}\}$

Using this method, the survival curve for each ICWS condition (no ICWS, visual warning and audio speech message) was plotted (fig. 2).

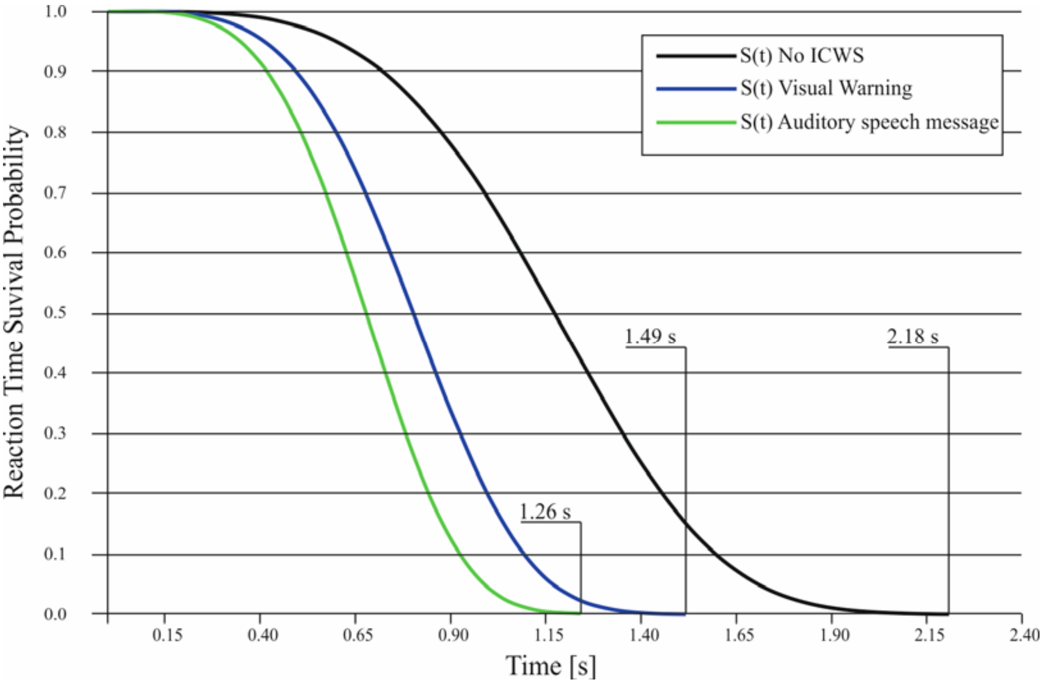

Figure 2. Survival curves of RT for ICWS conditions (the values of RT for null survival probability are also shown).

Concerning the speed reduction time, the table 5 shows the significant parameter estimates for the Weibull AFT model with clustered heterogeneity.

Variable	Estimate	SE	z - Statistic	p-value	Exp (β)	95% Conf. Interval	
d_m [m/s^2]	-0.103	0.015	-6.69	0.000	0.90	-0.133	-0.073
ICWS condition							
No ICWS	-	-	-	-	-	-	-
Visual warning	0.109	0.042	2.59	0.010	1.11	0.027	0.193
Auditory speech message	0.207	0.043	4.82	0.000	1.23	0.123	0.291
Direction of the violator							
Left	-	-	-	-	-	-	-
Right	-0.062	0.035	-1.80	0.151	0.94	-0.130	0.005
Constant	1.634	0.097	16.84	0.000		1.444	1.825
P	4.235	0.403				3.515	5.105
Log–likelihood at convergence (Pseudo)	-36.86						
Log– likelihood at zero	-67.59						
AIC	79.71						
N° of observations	223						
N° of groups	41						

Table 5. Weibull AFT model with clustered heterogeneity estimates for speed reduction times

The scale parameter P has an estimate value equal to 4.235, meaning that the survival probability of SRT decreased with the elapsed time. On average, in fact, the probability of decreasing the speed from V_i to V_f after 3 s was approximately 4 times higher than that after 2 s (i.e., $(3/2)^{4.235-1}$). As for RT, the value of the scale parameter P higher than 1 implies that the hazard function of SRT was monotone and with positive duration dependence, which is consistent with the applied model.

The variable d_m affected SRT in a statically significant way. The coefficient of the average deceleration was negatively associated with SRT; more specifically, for a 1 m/s^2 increase in the drivers' average deceleration SRT was 10% shorter (Exp (β)=0.90).

The comparisons among the ICWS conditions and the directions of the violator vehicle were conducted in the same way that for the drivers' reaction times. Among the ICWS conditions both the visual warning and the auditory speech message were statistically significant (P=0.010 and P=0.000, respectively) and positively associated with the speed reduction time. Compared with the no ICWS condition (SRT=5.40 s) the time to reduce the speed from the initial speed to the minimum speed for the visual warning (5.99 s) was 11% longer (Exp (β) =1.11), while for the auditory speech message (6.64 s) was 23% longer (Exp (β) =1.23, (see also fig. 3). A pairwise comparison with Bonferroni's correction among the ICWS conditions was also performed; the results indicated that the speed reduction time for auditory speech message was statistically significantly longer than that for the visual warning (mean difference = 0.65 s, P =0.043).

Concerning the direction of the violator no statistically significant difference was recorded; the speed reaction time for violator vehicle from right was approximately the same (Exp (β)=0.94) than that for violator vehicle from left. No other difference was statistically significant.

With the use of the same procedure described above for RT, the survival curves of SRT of each ICWS condition were obtained. The survival curves (fig. 3) were plotted by using the mean value of the continuous variable d_m in table 3 and the estimated coefficients of the ICWS conditions in table 5.

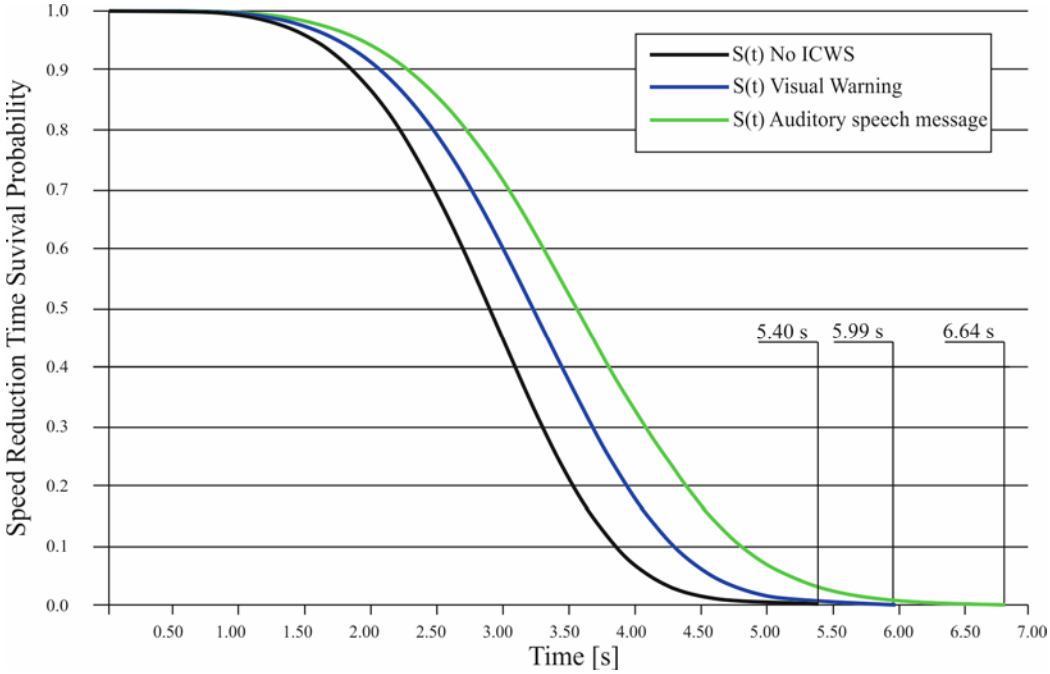

Figure 3. Survival curves of SRT for ICWS conditions (the values of SRT for null survival probability are also shown).

4.2 Outcome of the questionnaire

The results of the questionnaire about the perceived effectiveness of the warning signals showed that the entire sample indicated that both the visual warning and the auditory speech message were effective.

Concerning the score for the type of the effectiveness induced by each warning signal, both the speed reduction and the increase of the level of attention obtained high scores, highlighting the remarkable effect induced by the warning signals (fig. 4). More specifically, with respect of the speed reduction effect, the higher scores were reached for the auditory speech message (mean = 8.3, SD = 1.3); the score for the visual warning was slightly lower (mean = 7.8, SD = 1.4). The trend of the scores related to the effect in the increase of the level of attention during the drive was similar. The higher values were recorded for the audio speech message (mean = 7.3, SD = 2.3) while the visual warning obtained a lower score (mean = 6.6, SD = 1.9). These results indicate that the participants believed to have been more influenced when the warning signals were present; moreover, the auditory speech message was believed more effective than the visual warning.

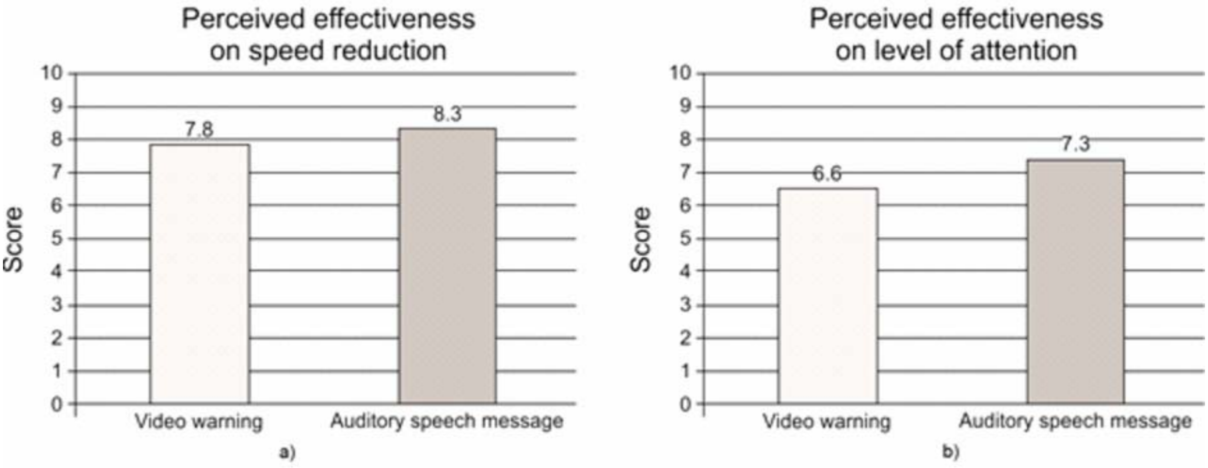

Figure 4. Results of the questionnaire about the type of influence of the warning signals that the drivers experienced

5. DISCUSSION

As expected, the survival probability both of the reaction time and the speed reduction time during the evasive maneuver decreases with the elapsed time (fig. 2 and 3); thus, the probabilities that the driver reacts in response to the violator vehicle and completes the speed decreasing maneuver to avoid the collision increase with the elapsed time.

The survival curves for different ICWS conditions show that, for a fixed value of the elapsed time, the lower survival probability of RT was obtained for the auditory speech message while the higher survival probability of RT was obtained for the condition of No ICWS. For example, after 0.75 s, the probability that the driver fails to react in response to the violator vehicle is approximately 38% for the auditory speech message, 60% for the visual warning and 89% for the No ICWS condition. Concerning the SRT survival curves, instead, for a fixed value of the elapsed time, the higher survival probability was recorded for the auditory speech message, while the lower survival probability of SRT was obtained for the condition of No ICWS. The survival curves of SRT show, for example, that after 4 s, the survival probability of SRT is approximately 31% for the auditory speech message, 20% for the visual warning and 6% for the No ICWS condition.

Considering the null values of the survival probabilities, the shorter RT was 1.26s for the auditory speech message, while it was 0.23 s longer (statistically significant) for visual warning (1.49s) and 0.92 s longer (statistically significant) for the no ICWS condition (2.18s). The longest SRT was obtained for the auditory speech message (6.64 s) and it was statistically significantly longer than that for the visual warning (5.99 s) and the No ICWS condition (5.40 s).

Considering that a low reaction time is better for driving safety (the driver reacts in advance in response to a warning signal) and that a high speed reduction time implies a less aggressive maneuver (i.e. the driver passes from the initial speed to the minimum speed through an high interval time), such results highlight that in absence of warning signals were obtained the worst driving performance (high RT and low SRT), while the best performances were obtained for auditory speech message. In presence of visual warning were recorded good performances, although less relevant with respect of those obtained for the auditory speech message.

The results obtained for RT and SRT are directly connected each other; with the improvement of the ability to react early in response to a critical situation (i.e. low RT in the condition of auditory speech message), the driver advances the braking maneuver. This means that he has more time to reduce the speed (and then higher SRT) in order to avoid the collision, adopting a less abrupt braking maneuver. In other words, for the auditory speech message (where the shortest RT was obtained) the driver were more able to react earlier, and thus, advance the beginning of the braking maneuver. In this way the driver had more time to reduce the speed from V_i to V_f and undertake a less abrupt braking maneuver. This finding confirms the results of previous studies (Lee et al., 2002; Zhang et al., 2015) who found that the drivers who started earlier the deceleration brake more moderately than those who started late. It should be noted also that the improvement of the drivers' reaction time due to the presence the ICWSs (both auditory speech message and visual warning) also was fully consistent with the previous studies (e.g. Chang et al., 2008, 2009; Chen et al., 2011; Scott and Gray, 2008).

It should be noted that the results on RT and SRT showed that, despite the two warning signals provided the same information to the driver (i.e. the direction of the vehicle), the auditory speech message was better than the visual warning (RT was significantly shorter, while SRT was significantly longer). Differently from the case of car – following in which the additional information in the warning signals is not necessary because the driver have not to discern the direction of the vehicle (Chang et al., 2008), the benefits of the additional information in the speech message for the ICWS remarks the results of the previous studies (Chang et al., 2008; Yan et al., 2015b).

The higher reaction time for the visual warning (1.49 s) compared with that for the auditory speech message (1.26 s) can be due to the fact that for the first, the driver had to focus his attention, and thus his glance, before on the visual signal to identify the direction by the red car icon, and then on the intersection to detect the violator vehicle. For the auditory speech message the driver, instead, could directly detect the position of the violator after he heard the audio signals with the directional information and, thus, advance the beginning of the braking. This result is consistent with previous studies (e.g. Chen et al., 2011; Green, 2000) where the fastest reaction times were found for the auditory signals and remarks the nature of the physical stimuli that are solicited by the warning signals. According Green (Green, 2000) the auditory transduction is mechanical (and thus, it requires less time to react), whereas visual transduction requires a relatively slow, biochemical process (and thus, it implies a longer time to react). In addition, most of the driving activity requires the visual task; this implies that the comprehension of the video signal (i.e. an additional visual task) could disturb the driving activity and, thus, delay the reaction of the driver.

The dynamic variable initial speed (V_i) was negatively associated with the drivers' reaction times. This is consistent with the expected drivers' behavior; when the driver arrives at the intersection with higher speed he tends to compensate the higher risk by increasing his attention, and thus, decreasing the reaction time in response to an unexpected event such as a violator vehicle. This result is also consistent with the findings of Triggs and Harris (1982), Chang et al. (1985), Törnos (1995) and Jurecki and Stanczyk (2014) where the speed of vehicle was negatively associated with the driver reaction time.

SRT was affected in a statistical significant way by the average deceleration d_m.. More specifically the average deceleration was negatively associated with SRT. This result was expected because if the driver acts a more abrupt deceleration he needs less time to pass from the initial speed V_i to the minimum speed V_f.

For the direction of the violator, both for RT and SRT no statistical difference was recorded and this result highlight that the effectiveness of the different ICWSs was the same with respect of the direction of arrival of the violator vehicle.

6. CONCLUSIONS

The present study aimed to investigate how the intersection collision warning systems (ICWSs) affect the driving performances in response to a violator vehicle at the intersections under two different warning signals and directions of the violator vehicle. The warning signals were the visual warning and the auditory speech message and both provided the direction of the violator vehicle.

The driver's reaction time (RT) (the time needed for the driver to react in response to a warning signal) and the speed reduction time (SRT) (the time between when the driver reacts and when he perceives to have avoided the collision) were the variables used to analyze the driver's behavior.

RT and SRT were modeled with the Weibull AFT model with clustered heterogeneity, to taking into account the possible correlations due to the repeated measures and to compare the effects on driver's behavior of vehicle dynamic variables and different warning signals and direction of the violator vehicle.

The survival model identified as significant explanatory variables of the driver's reaction time (RT) in response to a violator vehicle the initial speed (Vi) and the warning signal condition. The shape of the survival curves of RT for the different ICWS conditions showed that for the auditory speech message the drivers were more able to react and start to decrease the speed earlier than that for the visual warning and the No ICWS condition. The reaction time for both the warning signals were lower (statistically significant) than that for the No ICWS condition. Moreover, RT of the auditory speech message was lower (statistically significant) than that for the visual warning. This result highlights that for the auditory speech message the driver could advance his braking maneuver because his glance was always focused on the road environment, while for the visual warning the driver had to focus his attention first on the visual warning to understand the direction of the violator vehicle, and then on the road environment to detect the violator vehicle.

For SRT, the Weibull AFT model identified the average deceleration (d_m) and the warning condition as explanatory variables that affected the speed reduction time in a statistically significantly way. The survival curves of SRT for the different ICWS conditions showed that for the auditory speech message and visual warning the drivers had longer (statistically significant) SRT than that for the No ICWS condition. Moreover, SRT for the auditory speech message was longer (statistically significant) than that for the visual warning condition.

These results highlight that the driver, when the vehicle was equipped with one of the directional warning signals, was able to advance the braking maneuver due to the earlier reaction in response to the violator vehicle. The benefits of the directional warning were clearly evident in the number of collisions, which were 12 when the vehicle was not equipped with an ICWS and null when the vehicle was equipped with a directional warning. This outcome was completely consistent with the objective of assess the effectiveness of the directional warning, showing a huge improvement of the driving safety through the improvement of the driving performance. In addition, acting in advance the braking maneuver to react to an imminent possible collision, led the driver to have much time to complete the maneuver to avoid the conflict with the violator vehicle, adopting in this way a smoother braking maneuver, which could also avoid possible rear – end collisions. This effectiveness was more evident for the directional audio speech message.

The benefits of advance the braking maneuver resulted in no collision event for the warning signals, while for the No ICWS condition, in 16% of the driver-violator vehicle interactions a collision was recorded. These findings were also confirmed by the outcomes of the questionnaire on the perceived effectiveness of the warning signals; the entire sample reported that the warning signals were effective. Moreover, the drivers reported that the auditory speech message was more effective of the visual warning in terms of speed reduction and improvement in the level of attention.

Therefore, the outcomes of the present study provide useful suggestions about the most effective collision warning systems that the automotive industry should develop and equip on vehicles.

The current study was conducted using the advanced driving simulator of the Department of Engineering – Roma Tre University. Therefore, the caveats that are usually referred to driving simulator studies must be raised. More specifically, the most relevant limitations arise from: a) different risk perception between simulated and real road environment; b) approximated fidelity of simulated driving conditions compared to the real ones (e.g. appearance of the scenarios, systems warning simulation). It should be noted that such limitations, that are typical of driving simulator experiments, could return driving behaviors that are not completely matching with the ones actually adopted by the driver in the real world.

However, it should be also highlighted that:

- driving simulators are deemed to be effective tools for studies whose field survey is made impossible by the high risks that the experimenters would be subjected to and the difficulty of ensuring controlled experimentation conditions;
- more specifically, many studies demonstrated the great potential of driving simulators for the investigation of driving performances under different conditions of warnings (in addition to the already mentioned references in the section Introduction, e.g. Baldwin and May, 2011; Biondi et al., 2014; Chang et al., 2009; Lee et al., 2002);
- the driving simulator of the Department of Engineering – Roma Tre University was previously validated for the analysis of drivers’ behavior on rural roads (Bella, 2008);
- the recorded data showed that the drivers reacted differently at the different road scenarios, giving reasonable results. The results based on the drivers’ behavior recorded during the simulations were fully confirmed by the subjective ratings acquired through the questionnaire about the effectiveness of the ICWSs.

Therefore, it is deemed that there are sufficient guarantees of the goodness of the obtained results; more specifically, it is believed that the present driving simulator study provides reliable findings in terms of relative effectiveness of the different tested ICWSs. In other words, it is deemed that there is a reasonable assurance that the relative effectiveness of the different types of warnings is the same in the real driving.

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