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Assessing the Impact of Safety Countermeasures on Dilemma Zones at Signalized Intersections of Urban Roads: a Driving Simulator Study

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Abstract

When drivers approach a signalized intersection at the start of the yellow signal, they might be reluctant to decide whether to stop or go through the intersection due to the dilemma zone (DZ), with the consequent risk of improper behaviors that can lead to rear-end collisions and right-angle crashes. The main goal of this research is to analyze the driver's behavior at the onset of the yellow signal and to identify the most effective countermeasures for the resolution of the dilemma zone in order to improve the safety and efficiency of urban signalized intersections. A driving simulator study was carried out, and three different countermeasures were specifically designed and tested: Green Signal Countdown Timers (GSCT) (C_1); a new scheme of vertical and horizontal warning signs (C_2); and an in-vehicle advanced driving assistance system that uses Augmented Reality (AR) and connected vehicle technologies (C_3). Forty-six volunteers took part in the experiments, driving the same scenario four times (three with countermeasures and one as a baseline condition). The results demonstrated that with countermeasure C_1, the length of the DZ increased with respect to the baseline condition; moreover, the stop/go drivers' decisions were found to be more inconsistent, increasing the potential risk of rear-end crashes. Conversely, countermeasures C_2 and C_3 resulted in a reduction of DZ length (-30.5% and 21.6%, respectively); in addition, C_2 was found to be the one that recorded the greatest consistency of drivers' decision-making behaviors, while C_3 provided the drivers with timely and personalized early-stop warnings and recorded fewer wrong behaviors. Based on the results of this study, C_2 and C_3 countermeasures might be a good way to improve safety and operations at urban signalized intersections and cut down on the number of drivers who aren't sure what to do when the yellow light comes on.

Keywords: Dilemma Zone; Signalized intersection; Driving simulator; Driving performance; Road safety.

1. Introduction

At the onset of the yellow signal at a signalized intersection, approaching drivers may experience some hesitation and delay in their decision on whether to cross the intersection or stop. It is due to an indecision area before the signalized intersection that is known as the "dilemma zone" (DZ) in order to indicate the potential doubt of the driver that can delay the decision and create critical interference with the other road users who

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experience similar hesitation but with potential different decisions. The dilemma zone is therefore quite critical in terms of road safety as, for example, the drivers who decide to pass through the intersection might experience red light violations and right-angle crashes, while others might stop suddenly and prematurely with the subsequent risk of rear-end collisions. The indecision and hesitation of drivers, along with their different perceptions and attitudes, lead to greater variability in drivers' stop/go decisions. This safety issue related to signalized intersections and dilemma zones is evident if the statistical reports and crash data are considered (e.g., Huang et al., 2014). In fact, it is well known that signalized intersections are one of the most dangerous parts of road networks, because they account for a lot of road crashes.

Road safety experts and researchers worldwide have investigated the topic of signalized intersections and more specifically the dilemma zone for a long time (e.g., Gazis et al., 1960) in order to analyze the behaviors and decisions of drivers approaching signalized intersections when the signal turns yellow and to evaluate the effectiveness of a number of countermeasures specifically designed and tested in several studies, both in the field and in a driving simulation environment. Generally, the findings are quite conflicting between different studies, but the review of the literature has highlighted that the most effective countermeasures for improving the safety and efficiency of signalized intersections, which can reduce the extent of the dilemma zone and help drivers make fair and safer decisions at the beginning of the yellow signal, can be distinguished into three typologies: i) countermeasures that use countdown timers (van Haperen et al., 2016; Islam et al., 2017) to tell drivers how long they have left in the green phase before the yellow phase starts; ii) countermeasures based on pavement markings or signs (Yan et al., 2007; 2009) that give warnings and/or suggestions to drivers, but research on these measures is limited; iii) early warning systems and in-vehicle warning systems (Bar-Gera et al., 2013; Yan et al., 2015; Hussain et al., 2020) that can provide real-time feedback to drivers, by means of audio or visual warnings.

As noted before, previous studies have given conflicting results, and more research is needed to come up with the right measures that can make intersections safer and cut down on crashes.

The goal of the driving simulator study in this paper is to look at how well different types of countermeasures work at giving drivers information and suggestions that can help them make better decisions and improve the safety and efficiency of an urban signalized intersection when the yellow light comes on.

2. Methodology

2.1 Driving simulator

A fixed-based medium-fidelity driving simulator in which an actual car (Toyota Auris) was modified and placed in front of a curved screen (180-degree field of view) was used for the experiment. Three overhead projectors generated a total resolution of 5760 by 1200 pixels at a frame rate of 60Hz. The simulator had a force-feedback steering wheel and a performance measurement system. The driving simulator was used and validated in previous studies (Calvi, 2018; Calvi et al., 2020) for the investigation of drivers' behaviors and driving performance in several road environments, traffic situations and operations. There are several benefits to using a driving simulator for studies aimed at investigating the role of human factors and the drivers' decision-making behaviors. Using a computer to run tests and studies is a lot cheaper than doing them in the real world, and the tests and studies are very similar for all the drivers who use the same simulated situations in a controlled environment (Calvi et al., 2015; Calvi et al., 2018). This means that the results can be very similar for all the drivers who use the same simulated situations in a controlled environment.

2.2 Configurations and countermeasures

For the purpose of the study, a four-kilometer, two-lane urban road scenario was designed and simulated with a speed limit of 50km/h, a lane of 3.0m, and shoulders and sidewalks on both sides of 0.5m and 4.0m, respectively. Five signalized intersections were included in the scenario with the traffic light turned from green to yellow at five different distances to the stop line (DTSL): 28m, 42m, 56m, 69m, and 83m. In other words, for each intersection, the signal turned yellow when the driver was in a different position and distance (DTSL) from the intersection, and the driver's decision to stop or cross the intersection was analyzed. Two signalized intersections were also added to the scenario with green lights to make sure that the driver didn't think the lights would change from green to yellow at each signalized intersection.

The same scenario was used for creating four different configurations and each driver had to perform four drives accordingly: one configuration was related to a baseline condition (B) where no countermeasures were implemented (Figure 1a), while the other three configurations were characterized by a different countermeasure tested in the study. The three countermeasures were specifically designed and tested in this study with the overall aim of resolving the dilemma zone; they are shown in Figure 1 and can be described as follows:

1. The green signal countdown timer (GSCT) for vehicles (C_1 in Figure 1b) has an auxiliary display that shows the green numbers 3, 2, 1 in sequence. It tells drivers how long they have left before the signal turns yellow. The green numbers were shown for three seconds before the signal turned yellow.
2. New horizontal marking and vertical warning sign (C_2 in Figure 1c): this countermeasure consists of a yellow horizontal line painted on the road pavement exactly at the location where it is installed a vertical sign that reports the words "STOP/GO", aimed at assisting the driver in making the right decision and taking the right action. Specifically, the vertical sign and the horizontal line marking were placed at the stopping sight distance from the stop line of the intersection, calculated under the assumption and hypothesis that drivers approach the intersection at the speed limit. According to the overall idea of the countermeasure, if the driver had not yet crossed the yellow horizontal line when the signal turned yellow, then he/she should slow down and stop; conversely, if the driver had already crossed the yellow horizontal line when the signal changed from green to yellow, then it was better to go ahead and cross the intersection.
3. An in-vehicle advanced driving assistance system based on augmented reality and connected vehicle technologies (C_3 in Figure 1d): contrary to what is assumed in the design of C_2 (driver's speed = speed limit), this countermeasure, here specifically designed and tested for the first time, is able to provide the driver with a more accurate and dedicated warning. In fact, C_3 took into consideration the actual speed of the approaching driver as well as the distance from the intersection at the onset of the yellow signal and provided the driver with a timely and personalized "STOP" warning, directly displayed on the vehicle's windshield; the "STOP" warning was given to the drivers when it was not safe to cross the intersection,

meaning that the distance the driver should be able to travel during the yellow interval was lower than the distance needed to cross the intersection safely (equal to DTSL plus the width of the intersection). The warning is based on augmented reality technology and the system needs vehicles that are connected to each other to exchange information about speed and location with the infrastructure connection system, which already knows how long each traffic light phase will last. The system then decides whether to send the "STOP" warning to the driver.

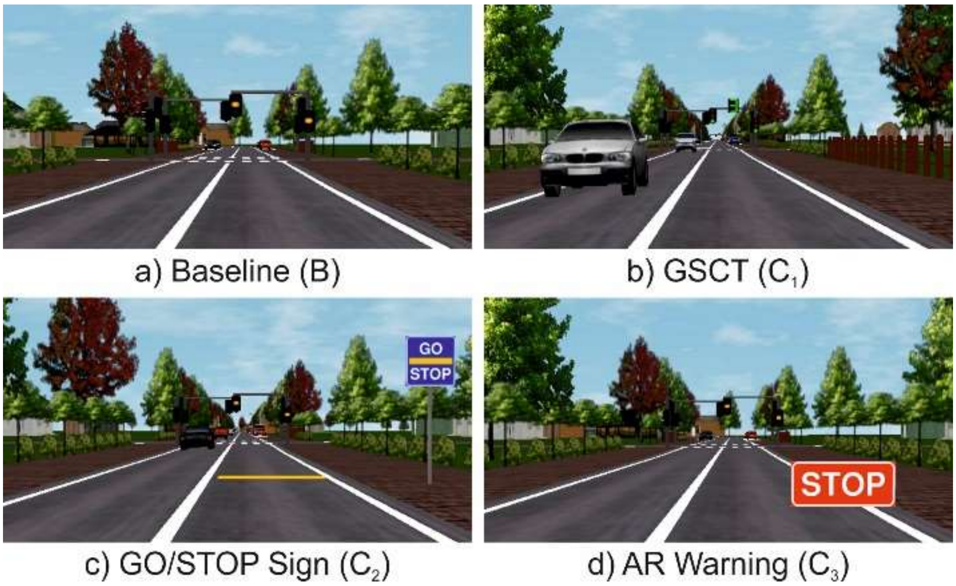

Figure 1: Scenario and Countermeasures.

2.3 Participants and procedure

The same scenario was driven four times corresponding to the four configurations (B, C_1, C_2, and C_3) by 46 participants (31 men and 15 women, with an average age of 39.4 years, ranging from 20 to 67 years). The sequence of the four drives was diversified by groups of drivers to avoid any conditioning of the results relating to the order in which the configurations were proposed and tested. The participants had a preliminary drive of a training scenario to help them become familiar with the tool and be aware of the implemented countermeasures. Moreover, before the drives, they had training with explanations of the designed countermeasures and their operation and use. The tests were conducted on two different days so that the driver wouldn't be able to remember the scenario and might be tired, which could bias the results of the experiments.

2.4 Experimental design and variables

In order to analyze the behavior and decisions of the drivers approaching the intersection, the numbers of drivers who stopped and crossed the intersection were collected for each DTSL and for each countermeasure, allowing to compute the lengths of the different dilemma zones and compare them among the different countermeasures. In addition, the speed of the driver at the start of the yellow signal was recorded and gathered. Based on the DTSLs that were tested, the number of wrong or correct drivers' decisions to stop or cross the signalized intersections was determined for each countermeasure and each DTSL.

3. Results and discussion

3.1 Length of DZ

Data collection on driver decisions to stop or cross the intersection allowed the length of the dilemma zone to be determined; in fact, Zegeer (1977) calculated it as the distance between two points where 10% to 90% of drivers decided to stop at the signalized intersection when the signal turned yellow. Therefore, the length of DZ can be related to the drivers' indecision to stop or cross the intersection: the longer the DZ is, the more indecisive drivers are, which could lead to rear-end collisions; the shorter the DZ, the more consistent and homogeneous drivers' decisions are, which means that the signalized intersection is more likely to be safe.

The results of the analysis revealed that under the baseline condition, the extension of DZ (29.2m) was longer than that computed in the C_2 and C_3 configurations (20.3m and 22.9m, -30.5% and -21.6%, respectively), for which the effectiveness of the countermeasures was demonstrated in terms of the improvement of the drivers' decision-making behaviors, as they were more consistent and homogeneous. Although evaluating different countermeasures than C_2 and C_3 originally proposed and tested in this study, other researchers found similar results in terms of reduction of DZ length by means of measures based on signs and markings (Yan et al., 2007; 2009) and on in-vehicle warning systems (Bar-Gera et al., 2013; Yan et al., 2015).

Conversely, countermeasure C_1 was revealed to be ineffective as it resulted in a longer DZ (41.1m) than that computed in the baseline condition and an increase in the number of drivers who stopped at the intersection, as well as for those DTSLs (28m, 42m, and 56m) where drivers could safely cross the intersection. Islam et al. (2017) and Van Haperen et al. (2016) both found that in the presence of timers, the number of stopping decisions is higher, which means that early stopping rates go up, which makes the intersection less efficient.

3.2 Stop/Go decisions

Table 1 shows the total number of drivers who stopped and crossed the intersections at the start of the yellow phase for each countermeasure with reference to the set DTSLs.

In the event that the driver's speed at the onset of the yellow signal was equal to the speed limit (50km/h), then the right decision should have been to cross the intersection at DTSL = 28m and 42m and to stop when the signal turned yellow at DTSL = 56m, 69m, and 83m. The results in Table 1 show that with countermeasures C_2 and C_3, most of the drivers behave according to the above assumptions, demonstrating the significant effectiveness of the countermeasures in suggesting to the drivers the safest stop/go decision to take. In fact, the percentage of drivers who crossed the intersections when the signal turned yellow at DTSL = 28m and 42m was, respectively, 100% and 96% in C_2, and 100% and 70% in C_3, higher than the percentage recorded in C_1 (83% and 63%), which, conversely, did not provide benefits either in terms of improvements in decision-making behavior nor in terms of the efficiency level of the intersection, and resulted in the highest percentages of drivers who stopped at the intersection for all the DTSLs where drivers could safely cross it.

Table 1: Stop/go (Total and Percentage) for all the Countermeasures and DTSLs.

DTSL [m]	Stop/Go	Countermeasures			
		Baseline (B)	*GSCT (C_1)*	*Go/Stop sign (C_2)*	*AR warning (C_3)*
28	*Stop*	0 (0%)	8 (17%)	0 (0%)	0 (0%)
	Go	46 (100%)	38 (83%)	46 (100%)	46 (100%)
42	*Stop*	7 (15%)	17 (37%)	2 (4%)	14 (30%)
	Go	39 (85%)	29 (63%)	44 (96%)	32 (70%)
56	*Stop*	30 (65%)	36 (78%)	36 (78%)	42 (91%)
	Go	16 (35%)	10 (22%)	10 (22%)	4 (9%)
69	*Stop*	45 (98%)	44 (96%)	46 (100%)	46 (100%)
	Go	1 (2%)	2 (4%)	0 (0%)	0 (0%)
83	*Stop*	46 (100%)	46 (100%)	46 (100%)	45 (98%)
	Go	0 (0%)	0 (0%)	0 (0%)	1 (2%)

Conversely, for the DTSLs where drivers should have stopped, it is interesting to note that only for DTSL = 56m, all the countermeasures resulted in an improvement in the homogeneity of drivers' decisions with respect to the baseline condition. Especially in C_3, most of the drivers stopped correctly at the intersection (91%), while only 65% in the baseline condition and 78% in C_1 and C_2 decided to stop under the same condition. With DTSL = 69m and 83m, no significant differences were recorded among the configurations: the percentage of drivers who stopped at the intersection correctly was close to or even at 100% in all of the configurations, even in the baseline condition.

3.3 Correctness of Stop/Go decisions

A further and more detailed analysis has been developed to evaluate the effectiveness of the tested countermeasures considering the actual speeds of the drivers at the onset of the yellow signal instead of the assumption that the drivers drove at the speed limit. In such a way, it was possible to evaluate the correctness of drivers' decisions based on the actual speed they adopted when the signal turned yellow. Figure 2 summarizes the drivers' stop/go decisions in relation to the different configurations and to the different DTSLs. Specifically, for each configuration and DTSL, the single driver's speed at the onset of the yellow signal is reported in the figure using a colored point (green in the case where the driver then crossed the intersection and red when he/she stopped). In addition, for the C_1 configuration, it is also reported the driver's speed at the time when the number 3 was displayed on the countdown timer display (namely, $C_{1\text{-}3s}$). In Figure 2, four areas have been highlighted with different colors: i) the stop area (red), where a driver, based on the actual speed at the onset of the yellow signal, should stop as it would not be possible to safely cross the intersection unless they increased the speed. As a result, any green points within this area indicate potential erroneous behavior, namely "wrong Go" in Table 2 and Table 3; ii) the dilemma zone (orange), where neither stopping nor crossing safely is possible; any colored point in this area represents potential misconduct; iii) the go area (green), where drivers should cross the intersection safely; any red points within this area indicate potential erroneous behavior, namely "wrong Stop" in Table 2 and Table 3; iv) the option zone (OZ, light blue), in which the driver could either stop or cross safely; it is interesting to note in Figure 2 that this last area is generated only in the C_1 configuration: the advance warning that consists of displaying the last 3s of the green phase, determined the elimination of the dilemma zone while generating an option zone for each DTSL (C_{1}-

$_{3s}$). OZ constitutes a particularly critical point as an expected inhomogeneity in drivers decisions in this area can lead to an increase in potential rear-end collisions. In addition, there could be a decrease in the number of crossings and therefore in the efficiency of the intersection, as already demonstrated in the previous section.

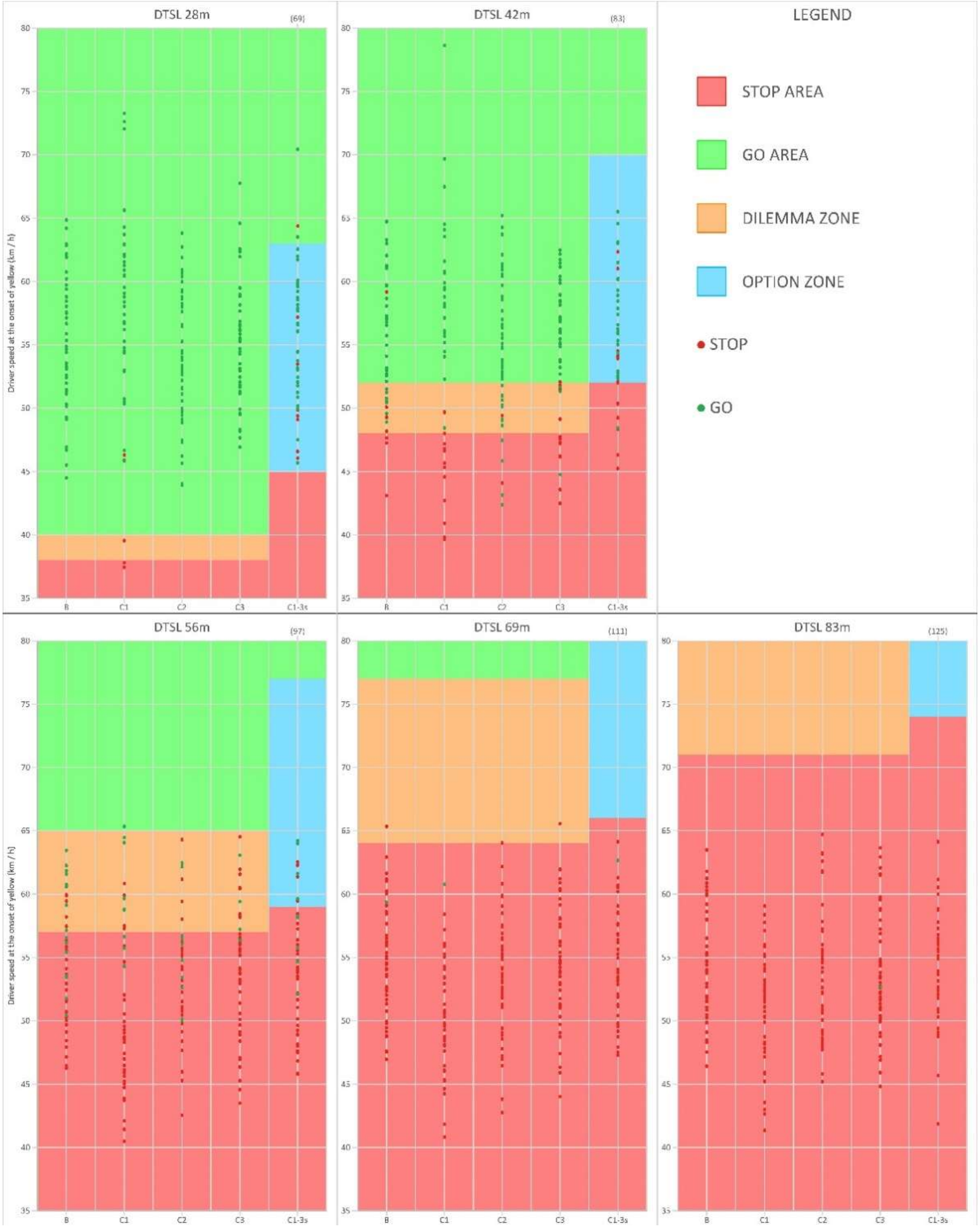

Figure 2: Drivers Stop/Go decisions for the different countermeasures and DTSLs.

Such analysis, whose results are graphically illustrated in Figure 2, allowed to collect the number of drivers making wrong/right decisions for each countermeasure, as reported in Table 2, and more in detail for each DTSL, as reported in Table 3. Specifically, in the tables, the number of drivers who behaved incorrectly, along with those who experienced the dilemma zone (DZ) as well as the option zone (OZ), are reported. Countermeasure C_3 recorded the smallest number of wrong behaviors: only 3 drivers compared to the 9 recorded in B and 12 in C_2.

Table 2: Drivers' Stop/Go Decisions Along with DZ, OZ and Wrong Behavior.

Countermeasures	**Go DZ**	**Stop DZ**	**Tot DZ**	**Go OZ**	**Stop OZ**	**Tot OZ**	**Wrong Go**	**Wrong Stop**	**Wrong Tot**
Baseline (B)	16	11	27	-	-	-	8	1	9
GSCT (C_1)	7	9	16	-	-	-	4	2	6
GO/STOP sign (C_2)	11	7	18	-	-	-	12	0	12
AR warning (C_3)	5	16	21	-	-	-	3	0	3
GSCT ($C_{1\text{-}3s}$)	-	-	-	68	24	92	9	1	10

Table 3: Drivers' Stop/Go Decisions Along with DZ, OZ and Wrong Behavior for DTSL and Countermeasure.

DTSL [m]	**Countermeasures**	**Go DZ**	**Stop DZ**	**Tot DZ**	**Go OZ**	**Stop OZ**	**Tot OZ**	**Wrong Go**	**Wrong Stop**	**Wrong Tot**
28	*Baseline (B)*	0	0	0	-	-	-	0	0	0
	GSCT (C_1)	0	1	1	-	-	-	0	2	2
	GO/STOP sign (C_2)	0	0	0	-	-	-	0	0	0
	AR warning (C3)	0	0	0	-	-	-	0	0	0
69	*GSCT ($C_{1\text{-}3s}$)*	-	-	-	36	7	43	0	1	1
42	*Baseline (B)*	7	3	10	-	-	-	0	1	1
	GSCT (C_1)	1	4	5	-	-	-	0	0	0
	GO/STOP sign (C_2)	9	1	10	-	-	-	4	0	4
	AR warning (C_3)	2	5	7	-	-	-	1	0	1
83	*GSCT ($C_{1\text{-}3s}$)*	-	-	-	28	11	39	1	0	1
56	*Baseline (B)*	9	7	16	-	-	-	7	0	7
	GSCT (C_1)	6	4	10	-	-	-	3	0	3
	GO/STOP sign (C_2)	2	5	7	-	-	-	8	0	8
	AR warning (C_3)	3	10	13	-	-	-	1	0	1
97	*GSCT ($C_{1\text{-}3s}$)*	-	-	-	4	6	10	6	0	6
69	*Baseline (B)*	0	1	1	-	-	-	1	0	1
	GSCT (C_1)	0	0	0	-	-	-	1	0	1
	GO/STOP sign (C_2)	0	1	1	-	-	-	0	0	0
	AR warning (C_3)	0	1	1	-	-	-	0	0	0
111	*GSCT ($C_{1\text{-}3s}$)*	-	-	-	0	0	0	2	0	2
83	*Baseline (B)*	0	0	0	-	-	-	0	0	0
	GSCT (C_1)	0	0	0	-	-	-	0	0	0
	GO/STOP sign (C_2)	0	0	0	-	-	-	0	0	0
	AR warning (C_3)	0	0	0	-	-	-	1	0	1
125	*GSCT ($C_{1\text{-}3s}$)*	-	-	-	0	0	0	0	0	0

This result was expected as countermeasure C_3 was specifically designed to provide the drivers with early stop warnings, timely and personalized according to the actual speed adopted by each driver. Conversely, the wrong behaviors in C_2 are attributable both to the driver's failure to comply with the countermeasure and to the innovative functioning of the countermeasure itself, not to its ineffectiveness. Finally, Tables 2 and 3 also show that while in B, C_1, C_2 and C_3 the driver experiences the dilemma zones, as previously discussed, in $C_{1\text{-}3s}$ the dilemma zone is eliminated with the consequent creation of an option zone. Countermeasure $C_{1\text{-}3s}$ has 10 wrong behaviors, and the option zone shows conflicting decisions with 68 go and 24 stop, which could be dangerous because they could cause rear-end collisions.

4. Conclusions

The driving simulator study presented in this paper was aimed at analyzing the driver's behavior at the onset of the yellow signal and identifying the most effective countermeasures for the resolution of the dilemma zone in order to improve the safety and efficiency of urban signalized intersections. The results revealed that countermeasure C_2, based on vertical signs and horizontal markings that suggested to the driver the right decision to take (to stop or to go), and countermeasure C_3, consisting of a virtual "STOP" warning provided to the driver and based on augmented reality and connected vehicle technologies, might represent a valid tool to reduce the indecision of approaching drivers at the start of the yellow signal and potentially improve safety and operation at urban signalized intersections. In fact, it was observed that with both the countermeasures, the extension of the dilemma zone is reduced (especially using C_2) and the consistency and correctness of drivers' decisions are improved (especially using C_3). Conversely, countermeasure C_1, based on a green signal countdown timer that informed the driver of the residual seconds of the green phase before the signal turned yellow, resulted in a longer dilemma zone and an increase in potentially conflicting behaviors among drivers that could lead to rear-end collisions, as determined by the generation of an option zone interpreted differently by drivers. Moreover, using C_1 many drivers have chosen to stop at the intersection, even if they could safely cross the intersection: this has reduced the capacity of the intersection.

In future research, other DTSLs will be investigated as well as other warnings, especially those based on augmented reality and connected vehicle technologies, will be tested in order to optimize and improve the proposed original and new countermeasure C_3, for example, by providing the driver with further suggestions (e.g., "go," "speed up," etc.) and using auditory warnings. There are also studies taking place on other roads (like rural roads) and with different types of intersections to generalize the results and get around any limitations of this study. This will help to choose effective countermeasures to improve the safety and efficiency of signalized intersections.

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