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A comparative simulator study of reaction times to yellow traffic light under manual and automated driving

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Abstract

This study analyzes and compares reaction times of motorists at the onset of a yellow traffic light under manual and automated driving, based on two experiments performed using a driving simulator. Results show that reaction times of subjects driving an automated vehicle that experiences a failure and crosses on red when approaching a signalized intersection are higher than those of subjects driving manually. When the analysis is restricted to automated driving, results indicate significant differences between reaction times at the first system failure and those at subsequent ones.

Keywords: Driving simulator; Reaction time; Traffic light; Automated vehicle.

1. Introduction

Reaction Time (RT) is a widely discussed variable in the traffic engineering literature because of its importance in terms of both road safety and capacity. Green (2004) presents an overview of brake RTs under different conditions and investigates the variables affecting this parameter, such as age and gender, cognitive load and urgency, which are also partially analyzed in the work of Warshawky-livne et al (2002).
In addition to the possible correlation between driver characteristics and response times, the type of stimulus presented to the user also affects RT. More specifically, Green (2004) points out that the response may vary according to the

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type of situation (expected, unexpected and surprise) in which the driver is involved. In particular, the awareness that an event can occur facilitates a reduction in RT (Schweitzer et al., 1995).

Different situations may cause different driver responses to the same stimulus. For example, a stimulus such as the braking of a preceding vehicle will generate a response defined as automatic (Schneider and Shiffrin, 1977); however, such response will be attentive or controlled if the driver finds an unexpected shape in the road.

In addition to the different characteristics of the users and the different situations, there may be a variety of elements that affect the driver's attention and therefore have an impact on the duration of the time interval needed to react to a stimulus. El-Shawarby et al.(2017) examined in depth drivers' RT at the onset of the yellow indication at traffic lights, Fambro et al. (Fambro et al., 2007) dealt with RT in stopping sight distance situations, Teawan et al.(2011) analyzed the relationships among RT, driver sensitivity and time headway in congested traffic. Young et al. (2007) investigated RT in manual driving situations and for automated vehicles.

This study focuses on RTs of drivers approaching a signalized intersection based on two different experiments implemented in a driving simulator. More specifically, the objective of our work is to analyze and compare the RTs of drivers in different traffic situations in response to a yellow traffic light (experiment 1) with those of subjects who experience the failure of an automated vehicle when the light turns yellow (experiment 2). RT in non-automated vehicles has been estimated in the field to be 1.22s lower than that in automated vehicles according to the Autonomous Vehicle Disengagement Reports published by the California Department of Motor vehicles between 2015 and 2017(Dinges and Durisek, 2019). According to Young et al. (2007) vehicle automation would increase reaction times by 1-1.5s.

2. Previous works

Several previous studies have investigated RTs in relation to different situations, such as car following, the onset of yellow traffic light at a signalized intersection, the introduction of a vehicle in a traffic stream or the abrupt braking of the preceding vehicle. In addition, some studies have sought a correlation between driver characteristics and RTs. The study of El-Shawarby et al. (2017), for example, investigated whether driver's gender and age, roadway grade, mean speed, platooning scenario and time to intersection affect RT at the onset of yellow of a traffic light. The study showed, in particular, that male and young drivers' RT is shorter than that of female and older drivers.

Using a medium-fidelity driving simulator, Young et al. (2007) tested the effects of driving skills and of different driver assistance systems (adaptive cruise control with or without active steering) on RTs under both unexpected and expected system failures. Their results show that the experienced drivers' RT decreased between the first and the second type of failure. In addition, a comparison to similar experiments with manual driving showed that a longer RT was observed with automated vehicles.

Other studies, such as Consiglio et al.(2003), have analyzed RT in combination with the use of mobile phones, conversations with passengers or listening to radio; it was found that RT was not affected by the use of the radio, while conversations on mobile phones or with passengers increased RT. Rossi et al. (2013) have evaluated the potential impact of concurrent distracting tasks on brake RT.

Studies found in the literature commonly break down RT into different phases during which the driver, after perceiving the stimulus, processes the information, chooses the most appropriate response and takes action (Green, 2004).

The variable investigated in this study is the RT between the occurrence of the stimulus (onset of yellow at the traffic light) and the beginning of the driver's reaction to it (braking).

3. Experiment 1

3.1 Method

The experiments were carried out with the driving simulator of the Transportation laboratory of the University of Padova. Each experiment consisted of two stages and lasted about 45 minutes:

- Training: in the first stage, which lasted five minutes, the participants were asked to drive the simulator in order to familiarize with its use;

- “Main Trial 1”: in the second stage, subjects had to approach 40 different signalized intersections. In 8 of them the traffic lights were green, while in the other 32 the driver was confronted with a change of traffic light phase.

At the beginning, before the first driving session, participants were interviewed in order to collect some personal data and information about their use of cars necessary to characterize the statistical sample.
Subsequently, a Simulator Sickness Questionnaire (Kennedy et al., 1993) was administered; it was repeated at the end of both “Training” and “Main Trial 1” phases as well as five minutes after the conclusion of the experiment (four times in total) to identify the possible occurrence of driving simulator sickness phenomena.

3.2 Apparatus

The apparatus used in this study is a dynamic driving simulator, which has been validated in previous multiple conditions (Rossi et al., 2018 and Rossi et al., 2020), produced by STSoftware®, Jentig 50, including a cockpit, composed of an adjustable car seat, a gaming dynamic force feedback steering wheel with a 900-degree turn angle and gas, brake and clutch pedals. The system also includes three networked computers and five full high-definition (1,920x1,080 pixels) screens creating a 330° (horizontal) by 45° (vertical) field of view and is equipped with a Dolby Surround® sound system consisting of three front speakers, two rear speakers and a subwoofer.

3.3 Participants

The 24 study participants had the following characteristics: students of the University of Padova , females (6) and males (18), minimal driving experience: 1 year, age range: 22-30 (25.6 on average), minimal average distance travelled per year: 500 km, no previous experience with a driving simulator. All subject were volunteers. No participant withdrew because of simulator sickness during the experiments.

3.4 Experiment scenario “Main Trial 1”

The scenario used for the “Main Trial 1” phase consists of a 400-meter-long dual-lane extra-urban road section approaching a four-leg signalized intersection with a speed limit of 70 km/h. The traffic light turned yellow when the distance of the subject from the stop line was 95 metres; after 5 seconds of yellow, the light turned red for 15 seconds. 40 trials were administered in random order to each subject; they can be classified in 8 different types as shown in Fig. 1.

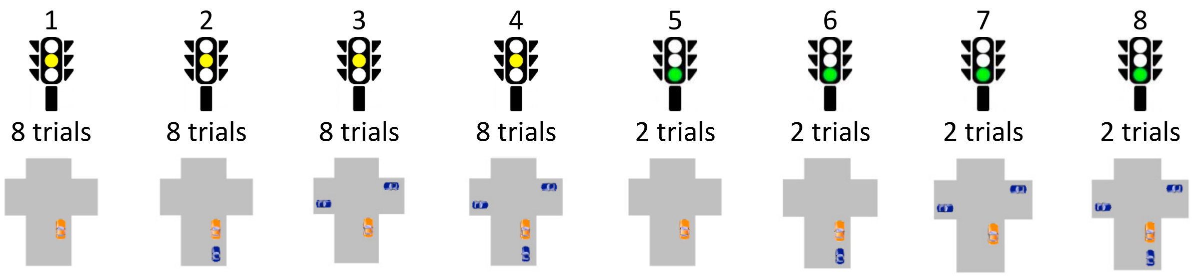

Fig. 1. Eight experimental conditions on approach to the signalized intersections. The orange car is the experimenter.

In the “Main Trial 1” phase, 32 trials were characterized by a yellow signal indication displayed to the approaching vehicle, while 8 trials presented similar surrounding conditions (absence/presence of a following vehicle and/or of vehicles on the cross road), but with green traffic lights; the latter were used in order to provide occasional interruptions of the repetitive task performed by the participants during the experiment. An average temperature between 20° C and 22° C was maintained in the laboratory in order not to induce sickness; lighting inside the room was fixed at 4 lx.

4. Experiment 2

4.1 Method

Differently from Experiment 1, this experiment was designed to analyze participants' behavior in an automated vehicle. The experiment was carried out with the driving simulator of the Transportation laboratory of the University of Padova. Each experiment consisted of three stages and lasted about one hour:

- Training: was the same of Experiment 1.
- Training 2: during the second stage, lasting about fifteen minutes for a length of 11.5 km, the vehicle was in automated mode. The purpose of this phase was to familiarize participants with the automated vehicle. During this training stage, participants had to face situations of potential accident risk (for example, vehicle entry, abrupt braking, etc.). At the beginning of the test, the subjects were informed about the type of automated vehicle they were about to drive and they were told that they would have to take action in case they encountered situations perceived as critical.
- "Main Trial 2": during the third stage, which was the core of the experiment and lasted about twenty minutes, the vehicle was in automated mode. The route had a sequence of 21 evenly spaced traffic light intersections. The speed limit was 70 km/h as in Experiment 1. The participants were informed about the possibility to intervene whenever situations that they considered critical occurred. In this test the automated vehicle failed three times on the approach to a signalized intersection. This part of the experiment was then used for the analysis of interest to this study.

At the very beginning, before the first driving session, participants were interviewed to collect personal data and information about their use of cars necessary to characterize the statistical sample. Subsequently, a Simulator Sickness Questionnaire (Kennedy et al., 1993) was administered, and then repeated at the end of "Training", "Training 2" and "Main Trial 2" tests, as well as five minutes after the end of the entire experiment (for a total of five times), in order to identify the possible occurrence of driving simulator sickness phenomena. Moreover, after "Training" participants were given a short questionnaire, based on the study by Schoettle and Sivak (2014), in order to assess their own knowledge and trust in automated vehicles. The first few questions concerned the type of vehicle they normally drove and whether they had ever heard of automated vehicles before. After reading an accurate description of the possible automation levels according to the SAE classification (SAE International Surface Vehicle Recommended Practice, 2018), participants were asked if they were concerned about driving or travelling in these vehicles. Participants were asked the general question regarding their opinion about automated vehicles again after carrying out "Training 2" and at the end of the "Main Trial 2" test.

4.2 Apparatus

The simulation system was the same used in Experiment 1.

4.3 Participants

The 33 participants had the following characteristics: students of the University of Padova, females (16) and males (17), at least 1 year of driving experience, age range 21-29 (on average 24.8), at least 2,000 km of distance travelled per year, no previous experience with any driving simulator. All subjects were volunteers. No participant dropped out due to simulator sickness during the experiments.

4.4 Experiment scenario "Main Trial 2"

The test route consisted of twenty-one signalized intersections, placed at a 1-km distance from one another, with a speed limit of 70 km/h. Four different situations were possible with regard to the aspect of the traffic light: Green Traffic Light, Red Traffic Light, Yellow "Go" Traffic light during which the vehicle crossed the intersection safely and Yellow "Stop" Traffic light, in which the vehicle stopped at the intersection. In addition to these four conditions (see Fig. 2), there was a fifth situation in which the automated vehicle approaching the intersection with a yellow light would not slow down and would cross the intersection when the light had already turned red, unless the driver took manual control of the car and reacted. This situation will be hereafter referred to as “Failure of the system”.

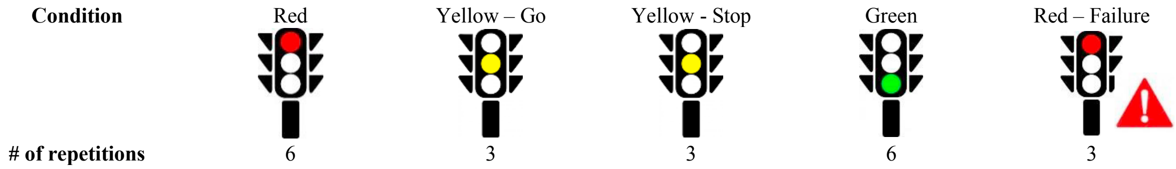

Fig. 2. Five experimental conditions on approach to the signalized intersections

After intersection 6, three failures of the system were programmed to occur (the first randomly between intersections 7 and 11, the second randomly between intersections 12 and 16, the third randomly between intersections 17 and 21). The traffic light colors were determined randomly so that each participant would find six red lights, six green lights, three traffic lights with yellow “stop” and three traffic lights with yellow “go” while approaching the 18 intersections where the vehicle did not fail. Low-volume conditions were simulated for traffic in the opposite direction. On the cross road at the intersections there were vehicles coming from both right and left. As in the first experiment, an average temperature between 20° C and 22° C was maintained in the laboratory and lighting inside the room was fixed at 4 lx.

4.5 Sample of participants used in subsequent analyses

Out of the thirty-three participants, only twenty-eight were considered suitable for quantitative analysis, considering that five subjects did not show any form of intervention at the time of the failure, thus providing no elements to estimate reaction time to the stimulus. At the end of the test they were asked the reason for this behavior, and unanimously stated that they trusted the automated vehicle so much that they deemed unnecessary to intervene.

5. Results

In all statistical tests reported in this section, a significance level of 0.05 was assumed.

5.1 Experiment 1

As already observed in the introduction, a correct approach to the analysis of RTs should take into account whether in the situation being investigated the event to which drivers react can be classified as expected, unexpected or “surprise” (Green, 2004). As far as experiment 1 is concerned, right before the test participants were informed that they would have to drive through a sequence of 40 intersections. For this reason, a light turning yellow cannot be defined as totally unexpected but more properly as temporally uncertain. In this type of situations, a realistic simulation requires the implementation of a correct level of uncertainty in order to prevent early responses (Boff, Kenneth R.; Lincoln, 1988). Each one of the 24 participants performed 32 trials in which the traffic light turned yellow, with a total of 768 sampled data. However, only 713 trials were considered valid, whereas those in which the participants did not brake and passed either during the yellow phase (accelerating or proceeding towards the intersection at a much higher speed than allowed) or during the red phase were discarded. The aim was to ascertain whether there was a significant difference in the results as a consequence of experience. Considering the small sample size, the partial violation of assumptions of parametric methods, and also for the sake of consistency among analyses, all the analyses described in the following were carried out with non-parametric methods. The results are summarized in Table 1. The Kruskal-Wallis test (McKight and Najab, 2010) was conducted to test the differences between three or more independent groups, while Friedman’s test (Pereira et al., 2015) was used to test the difference between three or more related groups. The Mann-Whitney U test (McKnight and Najab, 2010) was conducted to test the differences between two independent groups. It was possible to detect all 32 RTs values at yellow of only 17 subjects, on which Friedman’s test was used showing no significant differences ($\chi^2(31)=38.22$; p=.174). Hence, the subsequent step of the analysis was to determine whether there were significant differences in RTs when the surrounding traffic conditions (as defined in Fig.1) varied. This analysis was carried out on 713 trials with reaction to yellow light. The Kruskal-Wallis test showed no significant differences ($F(3)=3.748$; p=.290). This result is similar to that obtained by El-Shawarby et al.

(2017), who found no significant differences in RTs according to different platooning scenarios (see Table 1). The RT sample (713) was then analyzed according to the prevailing usage of the car (daily/non-daily) stated by participants in the initial questionnaire. The Mann-Whitney U test showed a significant difference (U=69267; p<.001) (see Table 1). As expected, the values of RTs are lower for subjects who use their car daily (Mdn=1.64) compared to those who do not (Mdn=2.02). In addition, their reaction times appear to be more homogeneous compared to those of less regular drivers, as indicated by the lower value of the standard deviation. The RT sample (713) was subsequently analyzed in order to identify any possible effect of the type of road usually travelled (urban and local vs. suburban and highway). The Mann-Whitney U test showed a significant difference (U= 44787; p<.001). As shown in Table 1, subjects usually driving on suburban and highway roads (Mdn=1.59) have lower and less dispersed RTs compared to those driving on urban and local roads (Mdn=1.96).

Table 1. Experiment 1. RT as a function of context conditions and subjects' characteristics

			Reaction Time (s)							
		# Trials	Min	Max	Mean	SD	15%	50%	85%	95%
Surrounding traffic condition	1	172	0.32	9.64	1.97	1.02	1.22	1.70	2.84	3.71
	2	177	0.46	8.70	2.02	1.09	1.27	1.72	2.84	3.76
	3	180	0.88	10.02	2.23	1.34	1.30	1.76	3.35	4.88
	4	184	0.62	6.30	1.98	0.95	1.20	1.73	2.91	3.93
Type of road	suburban and highway	350	0.32	8.70	1.78	0.82	1.16	1.59	2.39	3.39
	urban and local	363	0.62	10.02	2.31	1.28	1.36	1.96	3.47	4.46
Usage of the car	Non-daily	213	0.62	10.02	2.51	1.44	1.36	2.02	3.78	4.99
	Daily	500	0.32	9.86	1.85	0.86	1.22	1.64	2.44	3.40

5.2 Experiment 2

Even though the variable investigated in this experiment is the same as in Experiment 1 (RT on approach to a signalized intersection), the event causing the reaction (failure of the automated vehicle) can be defined as "surprise" according to the classification proposed by Green (2004). During the test, participants encountered three failures. Out of 28 participants, only 14 braked in all three failures. Friedman's test was performed on the repeated trials of subjects who had reacted by braking to all three failures (see Table 2); significant difference among the trials was found ($\chi^2(2)$=10.43; p=.005). Pairwise comparisons between failures were carried out using Connover's post hoc tests, which showed a significant difference only among failures 1 and 3 (Mean Difference=0.97 p=.002).
All data collected on the three failures (see Table 2) were later compared using the Kruskal-Wallis test and significant difference was found (F(2)=6.467; p=.039). The Dunn's post hoc test provides p value with Bonferroni correction. Dunn's Post Hoc Comparisons showed difference among failures 1 and 3 (Mean Difference= 0.87; p=.023).
The RT sample at the occurrence of the three failures (69 observations) was then analyzed according to the prevailing usage of the car (daily/non daily). The Mann-Whitney U test showed no significant difference (U=409; p=.651).
Last, the RT sample at the occurrence of the three failures (69 observations) was analyzed according to the type of road usually travelled (urban and local vs. suburban and highway). Again, the Mann-Whitney U test showed no significant difference (U=570; p=.909). Both results appear to be reasonable since the frequency of car usage and the type of road usually travelled relate to previous experiences accumulated by participants with manual driving, and do not necessarily imply different behaviours under automated driving. The results are shown in Table 2.

Table 2. Experiment 2. RT for the three system failures and as a function of subjects' characteristics

			Reaction Time (s)							
		# Trials	Min	Max	Mean	SD	15%	50%	85%	95%
Subjects reacting to all failures	first failure	14	1.61	5.73	3.52	1.26	2.10	3.41	5.01	5.73
	second failure	14	1.89	4.26	2.75	0.65	2.11	2.72	3.57	4.26
	third failure	14	1.35	3.81	2.55	0.73	1.54	2.67	3.29	3.81
All subjects	first failure	15	1.61	5.73	3.55	1.21	2.11	3.48	4.97	5.73
	second failure	27	1.61	4.85	3.16	0.94	2.13	3.07	4.24	4.83
	third failure	27	1.35	4.10	2.68	0.80	1.60	2.91	3.45	4.00
Type of road	suburban and highway	40	1.35	5.07	3.00	0.95	1.71	2.99	4.02	4.66
	urban and local	29	1.61	5.73	3.13	1.08	2.09	2.94	4.61	5.29
Usage of the car	non-daily	52	1.35	5.73	3.04	1.05	1.89	2.95	4.27	4.92
	Daily	17	1.61	4.83	3.11	0.84	2.09	3.18	4.08	4.83

5.3 Experiment 1 vs Experiment 2

After carrying out the analysis on the experiments individually, they were compared with each other. As for experiment 1, only the trials whose RT under condition 3 had been recorded were taken into account, i.e. with traffic on the left and right arms of the intersection. This situation was considered similar to that of the automated vehicle. In addition, only the trials which had a speed in the range of ±5% of 70 km/h when the light turned yellow were considered comparable to the trials recorded during experiment 2 in which the automated vehicle speed was set at 70 km/h. According to these criteria we obtained 27 trials performed by 15 participants in experiment 1.
By comparing one randomly selected RT measurement for each of the 15 subjects of manually driven vehicles (experiment 1, condition 3, speed ±5% of 70 km/h) with RT values of the 14 subjects reacting to all failures (experiment 2), the Kruskal-Wallis test showed significant difference between the four situations ($F(3)=21.17$; $p<.001$). Pairwise comparisons carried out using Dunn's post-hoc analysis with Bonferroni's correction showed significant differences among RTs for manual driving and failure 1, (Mean Difference=1.74; $p<.001$), RTs for manual driving and failure 2 (Mean Difference=0.97; $p=.005$) and RTs for manual driving and failure 3 (Mean Difference=0.77; $p=.032$), (Table 3). These values are generally consistent, both in terms of sign and magnitude, with the differences of RT between manual and automated vehicles reported in some previous studies (Young and Stanton, 2007; Dinges and Durisek, 2019).

Table 3. Experiment 1 vs Experiment 2. RTs for manually driven and automated vehicle

			Reaction Time (s)							
		# Trials	Min	Max	Mean	SD	15%	50%	85%	95%
Exp 1	one RT (scenario 3) ±5% of 70 km/h for each subject	15	1.28	3.36	1.78	0.55	1.40	1.62	2.428	3.36
Exp 2	first failure	14	1.61	5.73	3.52	1.26	2.10	3.41	5.01	5.73
	second failure	14	1.89	4.26	2.75	0.65	2.11	2.72	3.57	4.26
	third failure	14	1.35	3.81	2.55	0.73	1.54	2.67	3.29	3.81

6. Conclusions

This study presented the results of an analysis of RTs based on experiments with a driving simulator performed with manual driving and automated driving. Analyses of the first experiment did not reveal any significant differences in repeated situations nor with different traffic conditions. Statistically significant differences emerged, however, between drivers who use their vehicle daily and those who use it less frequently. Another factor leading to significant differences in terms of RT was the type of road usually travelled. The habit of reacting in situations characterized by higher speeds seems to determine a lower reaction time. In the second experiment, significant differences were found among RTs related to the first and the last failure. Analyses of the other variables did not show significant differences, perhaps due to the small size of the RTs sample analyzed (69 observations). As for the comparison between the two experiments, however, a significant difference was found: RT in the case of automated vehicle failures was higher than in the case of manual driving. This result is generally consistent with the findings reported in the literature on this issue (Young and Stanton, 2007 ; Dinges and Durisek, 2019).
One of the causes of the difference between the RTs for manual vs. automated driving could be attributed to mental underload due to the automation of the driving task. Underload is an important factor to take into consideration because it might lead to harmful consequences on performance (Desmond and Hoyes, 1996; Leplat, 1978). The difference could also be attributed to what is commonly referred to as mind-wandering. If not concentrating on driving, drivers could keep their minds busy with other thoughts. Mind-wandering is an inattention defined as "low vigilance due to loss of focus"(Talbot et al., 2013). Yanko et al. (2014) demonstrated that in a simulated environment the brake RT of participants who were mind-wandering was higher than the RT of participants who kept themselves focused on the task.
There are several possible developments of the research described in this paper, such as:

- analyzing the effect of gender and age on RT;
- performing analyses on the time elapsed between the beginning and the end of the movement i.e Movement Time (MT), both during manual driving tests and during intervention in case of automation failure;
- performing new tests using a sound as reinforcement when the light turns yellow.

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