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Transportation Research Procedia 45 (2020) 755–762

Transportation Research Procedia

www.elsevier.com/locate/procedia

AIIT 2nd International Congress on Transport Infrastructure and Systems in a changing world (TIS ROMA 2019), 23rd-24th September 2019, Rome, Italy

Evaluation of driving performance after a transition from automated to manual control: a driving simulator study

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Abstract

Nowadays, automated driving is one of the most discussed topic in transportation research community and media. Although several studies demonstrated that automated driving could improve road safety and operations, other evidences underscore the emerging nature of this technology and suggest that still much more research is needed before widespread benefits can be realized. One concern is surely related to the understanding if an automation period can reduce fatigue and/or distract drivers, especially when they have been inattentive and involved in a secondary task during highly automated driving. The aim of this study is to assess the driver behaviour after resuming control from a highly automated vehicle. A driving simulator study was designed and forty-three participants drove twice a highway scenario. One drive was without automation, just manual control of the vehicle (FM). In the other drive, the automation was activated in the first half of the drive and the drivers were asked to watch a movie inside the vehicle; then they resumed control from the automation and drove manually the second half of the drive (AM). In both the manual control drives, several expected (car following and passing) and unexpected (sudden brake of leading vehicle) events occurred. Several driving performance were collected, analysed and compared between the two drives for each event. Moreover, subjective measures were also collected by means of NASA-TLX questionnaire to evaluate the workload perceived while driving. The results does not show significant after-effects of the automation on driving performance, although a more dangerous behaviour of drivers who previously had a driving automation period was noted in some cases.

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Peer-review under responsibility of the scientific committee of the Transport Infrastructure and Systems (TIS ROMA 2019).

Keywords: Automated driving, Transfer of control, Driving simulator, Driver behaviour, Driving performance.

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10.1016/j.trpro.2020.02.101

1. Background

The recent literature concerning autonomous vehicles (AVs) has shown their several benefits. In fact, they can reduce both traffic congestion and emissions, increase lane capacity, lower fuel consumption, improve transport accessibility and reduce travel time and transport costs. Moreover, it is expected a 90% decrease of road fatalities that would represent the major benefit, as the road crashes attributable to human errors might be eliminated. However, the emerging nature of this technology has to be highlighted, suggesting that still much more research is needed before widespread advantages can be realized. In fact, until the highest level of automation will not be achieved, humans will remain an important part of the driving loop and their role in the driving automation has to be better understood.

As a literature review has pointed out, there is a large extent of scientific contributions on automated driving developed by means of real-life testing on automated vehicles (de Winter et al., 2014; Stapel et al., 2019; Naujoks et al., 2016), or using driving simulators and test tracks (Eriksson et al., 2017; Neubauer et al., 2012; Eriksson and Stanton, 2017; Shen and Neyens, 2017; Wright et al., 2017; Llaneras et al., 2017; Borowsky and Oron-Gilad, 2016).

Most of these researches focus on control transitions from manual driving to automated driving and take-over request (TOR) both in mildly (Eriksson and Stanton, 2017) and highly (Wright et al., 2017) complex scenarios and in both critical (Naujoks et al., 2016) and standard (Borowsky and Bar-Gera, 2017) conditions. Moreover, the literature overview has reported studies on the design of the signals (Wright et al., 2017; Llaneras et al., 2017), on the type of the warnings (Bazilinskyy et al., 2018), on the time required to allow a safe transition (TORt) and on the ways TORs are issued (Gold et al., 2013).

The alteration of the subjective psychophysical state of the driver from the automated drive to the acquisition of the control following the TOR, is another very frequent topic. Workload and situation awareness are the main variables analysed to address these issues, as well as the driving performance (Eriksson and Stanton, 2017; Stapel et al., 2019). The type and extent of engagement of the secondary task were also investigated (Neubauer et al., 2012, 2014) to evaluate the impact of autonomous driving on fatigue, stress and workload when the automation is activated. Several other studies investigated driving performance in relation to different levels of automation and secondary task (Borowsky and Oron-Gilad, 2016; Naujoks et al., 2016; Neubauer et al., 2012; Shen and Neyens, 2017) to evaluate their effects on driving safety and operations as well as on drivers' workload and fatigue.

An important research challenge that currently was only partially investigated consists in understanding whether an automation period can reduce fatigue and/or distract drivers, especially when they have been inattentive and involved in a secondary task during conditional or highly automated driving. This topic is typically studied during and just after TOR. However, only few studies have analyzed whether automated driving results in adverse after-effects (Levitan et al., 1998) or not. There are just some indications that, after experiencing automated driving, drivers show poorer performance as compared to drivers who have not experienced automated driving. Moreover, the results of these studies have pointed out the total time on the automated driving session and the previous experience of drivers with automated driving as important factors affecting the drivers' performance.

Therefore, in order to address the possible after-effects of automated driving, it is crucial to fully understand whether drivers' workload and performance are affected by the use of automation and, in such a case, how this effect varies with driving conditions. According to the above, the overall objective of this research consists in empirically studying driving performance and safety implications after the transition from automated to manual driving modes by means of a driving simulator capable of simulating a level three automated vehicle (SAE, 2016). In other words, the effects of an automation period on drivers are investigated once they are required to take manual control of the vehicle again and drive on a highway scenario.

2. Methodology

2.1. Driving simulator

The tests are carried using LassTRE (Laboratory of road safety of Roma Tre University, Fig. 1) STISIM driving simulator at the Engineering Department of Roma Tre University. A real vehicle, a Toyota Auris, is converted in a driving simulator by removing all unnecessary parts and connecting the driving controllers (wheel, pedals and gear) to a workstation controlling the system. To simulate the real driving environment four speakers reproduce the engine and all the external sounds.

Fig. 1. Driving simulator (left); secondary task during automated driving (right).

Furthermore, a curved screen provides the driver with 180-degree field of view projection. Several previous studies mainly addressing the driving performance under different driving conditions and road environments (Calvi, 2015; Calvi, 2018; Calvi et al., 2018) confirmed the feasibility of the instrument to the purpose of this study.

2.2. Scenario design and events

An highway scenario was implemented in the driving simulation for being driven twice by a sample of participants to the tests who therefore performed two drives: one drive was in full manual driving mode (FM), the other drive had a first part in automated driving mode (18 km) followed by a second part (18 km) in manual driving mode (AM). The cross section of the highway is 20.00 meters, consisted of a dual carriageway with two lanes for each driving direction (each lane was 3.75 meters), shoulders of 1.75 meters wide and median of 1.50 meters wide. To improve the level of realism of the simulation, several elements have been included in the scenario such as markings and vertical signs, vegetation, buildings and other vehicles. Moreover, several events are implemented in the scenario in order to analyse the drivers' behavior and performance when facing such occurrencies. In particular, as shown in Fig. 2, in the section of manual driving after the automation mode, three passing maneuvers and two car following conditions were implemented. For evaluating the drivers' decisions and performance related to the passing manoeuvres, some slow vehicles were implemented on the right lane in order to investigate drivers' passing manoeuvres and verify if there are differences in drivers behavior after a period of automation. The slow vehicles had all a constant speed of 75 km/h and a random longitudinal distance between each other. They were placed along tangent sections to avoid the geometries of the road could affect drivers' choice and decision of passing or not the slow vehicles. Moreover, in each drive 78 potential car following (CF) conditions were implemented along tangent sections of the road. In fact, the driver reached a slow vehicle ahead driving with a speed of 65 km/h on the right lane, in the meanwhile on the passing lane a platoon of vehicles, driving faster and properly spaced, made unsafe to the driver the passing manoeuvre of the slow vehicle. Under such car following condition, the slow vehicle suddenly brake and the consequent reaction of the driver was analyzed in both FM and AM drive.

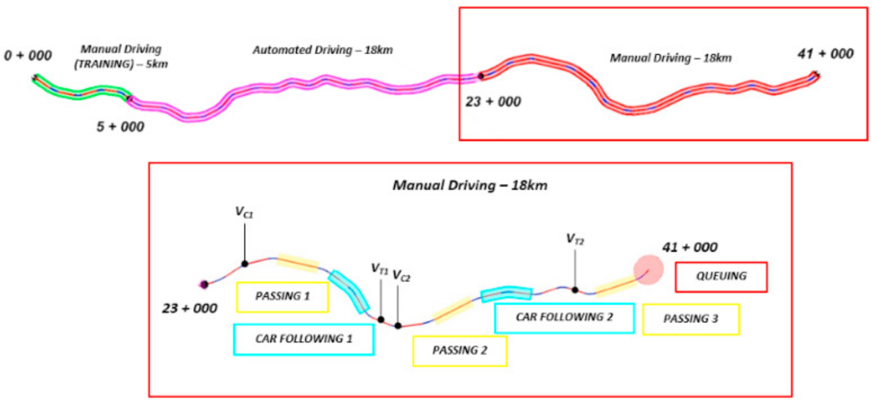

Fig. 2. - Scenario layout and location of events and speed measurement points.

2.3. Vehicle automation

Vehicle automation was simulated by means of the "*Control Vehicle*" STISIM Drive event. It allowed to control the movement of the wheel and the speed of the vehicle during the simulation. The inputs of the event were the desired speed to which the vehicle was requested to travel in automated mode, the parameters to control the wheel, the lateral position of the vehicle during the automated mode and, lastly, the transition time. A key point of the vehicle automation system consisted in the choice of the TOR: an audio warning with female voice was used in this stydy, according to Bazilinskyy et al. (2018) who indicated this warning set-up as the most effective in terms of drivers' reaction to the taking over action. Moreover, close to the passage of the commands, a "*beep*" sound was added too. All the messages were recorded and then implemented in the software.

2.4. Participants

Forty-three drivers (31 male, 12 female; average age 31.9 years) with no previous experience with the driving simulator and automated driving took part of the driving experiment. After the tests, two participants were excluded from the post-processing of data because they experienced a degree of discomfort while driving; other two drivers were further excluded from analysis as they were statistically recognized as outliers based on sample speed data. Thus, the final sample consisted of 39 drivers (30 male, 9 female) with an average age of 30.3 years (SD = 10.1 years).

2.5. Procedure

For each driver the same test procedure was applied. Each drive (FM and AM) was about 45 minutes-long. The order of the drives was randomized between participants (22 participants drove first FM and then AM; 21 participants drove first AM and then FM) to avoid the results to be biased by the sequence of the scenario. During the first drive, the experimenter explained the operating of the driving simulator and the driver drove the training scenario in order to get used to the tool of simulation. Training scenario was 15 kilometers long and contained several events in order to allow the driver to get familiar with the the driving controllers (e.g. brake and acceleration pedal, wheel and gear). For each drive (FM and AM), participants were required to fill three questionnaires: one before-driving session, one after-driving and the NASA Task Load Index test (NASA-TLX). The questionnaire compiled before driving allowed collecting basic information on drivers (i.e. age, experience with automated driving), while that filled after driving allowed to investigate the possible discomfort of the driving during the test and to have an opinion on the experience with the automated driving. The NASA-TLX was submitted to each participant twice, after FM and AM drive. This test is a widely used, subjective, multidimensional assessment tool that rates perceived workload (Colligan et al., 2015). It is largely used in all the research field related to human factors. By incorporating a multi-dimensional rating procedure, NASA-TLX derives an overall workload score based on a weighted average of ratings on the following six subscales: mental demand, physical demand, temporal demand, performance, effort, frustration. For the experimental scope, the original English questionnaire has been translated in Italian and slightly modified to make easier the comprehension of each item.

2.6. Secondary task

During the automated driving mode, drivers were asked to perform a distracting secondary task. Specifically, drivers were required to watch some short videos of maximum 6 minutes each on a created "ad hoc" YouTube channel. Five categories of videos were included on the channel in order to effectively direct choice of drivers among comic, musical, sport, funny and "how it is made" videos. Drivers had to select the videos they preferred and watch them once the automated driving was activated.

2.7. Data collection

Several driving performances (speeds, accelerations, lateral/longitudinal positions) and surrogate safety measures (TTC, PET) were collected, analysed and compared between the two scenarios for each investigated event. In this paper, the authors will present the preliminary results of a macro analysis developed for evaluating possible differences in driving behavior and performance when the driver has to face two driving events (passing of a slow vehicle and reaction to a sudden braking of a leading vehicle) after a period of automated driving. Moreover, the average speed of each driver along the section investigated (V_M) was computed for FM (V_{FM}) and AM (V_{AM}) drive, as well as some spot speeds data were collected and analysed in the midpoint of two selected tangent sections (V_{T1} and V_{T2}) and two curve sections (V_{C1} and V_{C2}) located far from the occurrence of the events. Finally, subjective measures were also collected by means of NASA-TLX questionnaire.

3. Results

3.1. Macro analysis on driving events

3.1.1. Passing manoeuvres

The first step of the analysis consisted in identifying the passing manoeuvres acceptable for further evaluations. Specifically, only the cases when the driver began the passing manoeuvre from the right lane, moved to the passing lane and then returned to the right lane once passed the slow vehicle were considered. Under such constrains, 197 passing maneuvers were identified, 97 in FM drive and 100 in AM drive. Successively, the passing manoeuvres characterized by the overtaking of a single slow vehicle (single passing) were distinguished from those where more than one slow vehicle (multiple passing) was overtaken. As the distance between slow vehicles was randomly selected, to compare drivers' passing decisions among FM and AM drives, it was needed to analyse such single/multiple passing manoeuvres in relation to the spacing between slow vehicles. For this aim, three different classes have been identified in terms of distance: shorter than 250 meters (class A), including 69 passing manoeuvres (31 in FM and 38 in AM); between 250 meters and 350 meters (class B), with 65 passing manoeuvres (32 in FM and 33 in AM); longer than 350 meters (class C), with 63 passing manoeuvres (34 in FM and 29 in AM). Under such condition, as illustrated in Fig. 3, it was found that in FM drive there are much more single passing manoeuvres when the distance between slow vehicles was longer (62.5% in class B and 79.4% in class C); on the contrary, the multiple passing manoeuvres were 70.9% of the total in class A. Overall, in FM drive single passing manoeuvres resulted in 57.7% of the total. Conversely, in AM drive it was found that drivers preferred to perform multiple passing maneuver (76.0% overall, with 78.9% in class A, 57.6% in class B and 93.1% in class C), demonstrating a difference in drivers' passing decisions when the drivers had experienced a previous automated driving. In fact, in this case, the drivers, once moved to the passing lane, preferred to overtake more than one slow vehicle before moving back to the right lane, independently of the distance between them. This difference has been statistically confirmed (χ^2=23.23, p<.001).

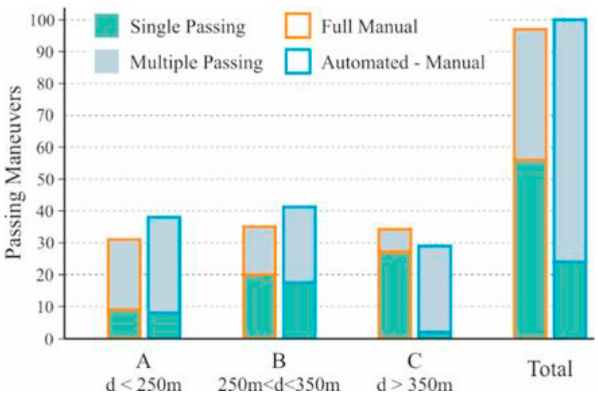

Fig. 3. Results of the macro analysis on passing events.

3.1.2. Car following

A preliminary analysis consisted in evaluating the first decision of driver while approaching the slow vehicle. In fact, it was found that, once noted the slow vehicle ahead not all the drivers preferred to remain on the right lane accepting to follow the slow vehicle: some drivers did not reduce their speed and chose to move to the passing lane despite the platoon of the fast vehicles and the unsafe gaps between them. It occurred in 22 out of 78 cases (28.2%) in FM drive and even more in AM drive (29 out of 78, 37.2%). It is a first interesting result, revealing a different behaviour of drivers who had previously experienced a period of automation: in AM drive there were more drivers than in FM drive who preferred taking higher risks than decreasing their speed. However, this difference was found to be not statistically significant (χ^2=1.43, p=0.232).

Therefore, only 105 (56 in FM and 49 in AM) out of 156 (67.3%) events implemented for reproducing car following conditions were further investigated. These events were then divided according to drivers' reaction to the braking manoeuvre of the leading vehicle. In fact, it was noted that some drivers braked while others reacted moving suddenly, under risky conditions, to the passing lane and overtaking the leading vehicle. In FM drive, 57.1% of drivers braked while a lower percentage of such drivers was recorded in AM drive (49.0%), where two drivers (4.1%) had even a collision with the leading vehicle. This analysis seems to confirm a more dangerous behaviour of drivers who previously had a driving automation period. Table 1 summarizes the results of this macro analysis. However, also in this case, statistical analysis did not reveal significant difference between drives (χ^2=0.38, p=0.537).

Table 1. Results of the macro analysis on car following events.

Car Following Condition	***Slow vehicle ahead***			***Braking of lead vehicle (under CF condition)***			
	Accept CF	No CF	Total	Braking	Passing	Crash	Total
FM drive	56 (71.8%)	22 (28.2%)	78	32 (57.1%)	24 (42.9%)	0	56
AM drive	49 (62.8%)	29 (37.2%)	78	24 (49.0%)	23 (46.9%)	2 (4.1%)	49

3.2. Analysis on driving speed

The local drivers' speeds were collected on the midpoint of two tangents (V_{T1} and V_{T2}) and two selected curves (V_{C1} and V_{C2}). the mean speed recorded along the investigated section (V_M) was also collected for each driver in both FM and AM drive. Table 2 gives the mean values and standard deviations (SD) of the drivers' speeds as well as the difference between mean speeds in AM and FM drive along with the results of the statistical analysis performed. It is interesting to note that in AM drive the drivers adopted similar speeds (although always a bit higher), than in FM drive (+1.57 km/h) along the investigated section. It is also confirmed by the comparison of speeds recorded on both the tangents and curves (from +1.39 km/h for V_{T2} to 2.12 km/h for V_{T1}). In order to verify whether the previous automated driving affected the drivers' speeds, a paired sample t-test was used to ascertain whether the differences in mean speeds between the two FM and AM samples were statistically significant. The application of the t-tests was prompted by the Kolmogorov Smirnov test of normality which proved that the speeds in both the drives were normally distributed. The statistical analysis reported that the differences between AM and FM speeds were not statistically significant for the four sites and the overall section. In other words, it was found that the period of automation did not affect drivers' speed choice along the investigated section.

Table 2. Results of t-test analysis on speed data.

Speed data	***FM [km/h]***		***AM [km/h]***		**V_{AM}-V_{FM} *[km/h]***	***t-test (p)***
	Mean	SD	Mean	SD		
V_M	102.22	11.35	103.79	11.91	1.57	0.52 (0.60)
V_{T1}	109.31	9.96	111.43	10.93	2.12	0.94 (0.35)
V_{T2}	111.88	11.95	113.27	11.81	1.39	0.56 (0.58)
V_{C1}	90.63	9.53	92.25	11.29	1.62	0.70 (0.49)
V_{C2}	89.48	10.08	90.94	10.82	1.47	0.61 (0.55)

3.3. Nasa TLX questionnaire

Fig. 4 summarizes the results of the NASA-TLX questionnaire providing the mean and standard deviation for each subscale based on the rating provided by drivers after FM and AM drive..

It is found that AM drive involved a lower mental (-2.0%) and physical (-14.1%) demand to driver as well as a lower frustration (-9.4%). Conversely, temporal demand and effort ratings were higher in AM drive (+7.8% and +10.4%, respectively), most probably caused by the new driving experience for the participants in driving an automated vehicle. Finally, the performance subscale (+1.3% in AM) and, above all, the overall task load index (+0.2% in AM) provided almost the same rating in the two questionnaires.

Paired sample t-test for each subscale has been developed to understand if the previous automated driving could affect driver workload. It is found that there is no significant effect for any subscales and for the overall task load index ($t=0.046$; $p=0.96$). This result is not surprising considering the most recent literature. In fact, Stapel et al. (2019) found that, when using the automation, automation-experienced drivers perceived a lower workload. This assumption is also confirmed by other previous studies (de Winter et al., 2014) that indicated a workload reduction of 21% on average from manual to automated driving. Conversely, Stapel et al. (2019) found that automation-inexperienced drivers perceived their workload to be similar to manual driving. Considering that in the study presented in this paper the participants sample consisted in automation-inexperienced drivers, the overall results of the NASA-TLX questionnaire are consistent with Stapel et al. (2019). Moreover, it should be added that the secondary task during automated driving was quite low in this study. In view of that, further investigations of driving perception and performance are in progress, with varying the type and extent of engagement of the secondary task during automation as well as the drivers' experience with automated driving.

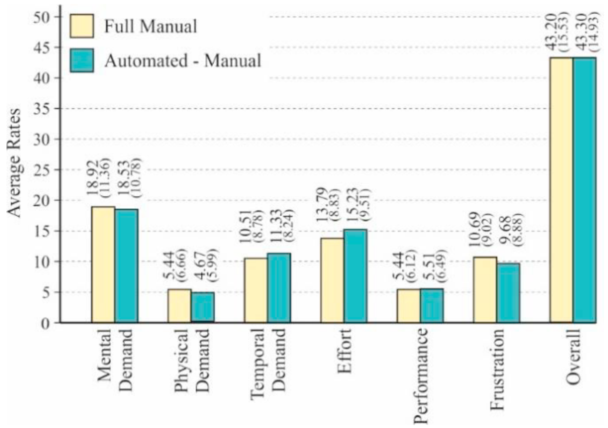

Fig. 4. NASA-TLX task assessment results.

4. Conclusions

The study presented in this paper provides the first results of a wide campaign of driving simulation experiments aimed at investigating the possible after-effects of automated driving on drivers' workload and performance. Moreover, the full research wants to identify which are the overall factors that play a crucial role in the safety and operating conditions related to automated driving and their interactions with all the driving actors (driver and other road users, vehicle, road, environment). In fact, one of the overall objective of this investigation is to provide an original, useful and effective contributions to the knowledge of this emerging technology, as it is widely demonstrated that still much more research is needed before widespread benefits of automated driving can be realized. Specifically, in this paper the driver behavior after resuming control from a highly automated vehicle has been investigated. The preliminary results of the macro analysis aimed at investigating drivers' decisions on the maneuvering to perform when facing slow vehicles highlighted some interesting differences. Specifically, as regards to the macro analysis of the passing maneuver, it was found that in AM drive the drivers preferred to perform multiple passing maneuvers. The opposite occurred in FM drive, where drivers preferred to perform single passing of slow vehicle. As regards to the analysis of the car following conditions, the first results seem to indicate a more dangerous behavior of drivers who previously had a driving automation period. In fact, the percentage of drivers who did not reduce their speed and moved to the passing lane despite the platoon of the fast vehicles and the unsafe gaps between them was definitely higher in AM than in FM.

The analysis of local and average driving speeds on FM and AM drive showed that speeds were always a bit higher in AM than in FM, although these differences were not statistically significant.

Finally, the analysis of NASA-TLX questionnaire did not provide significant differences between the drivers ratings of the workload perceived in AM and FM drive, although some interesting results have been obtained.

Research is underway to overcome the limitations of this study. An in-depth analysis of the drivers passing manoeuvres and car following conditions with braking of slow vehicles is being developed, using driving performance parameters and surrogate safety measures (PET, TTC). In future researches the behavior of drivers who experienced a previous automated driving will be investigated on other road environments (rural and urban roads) and facing different expected and unexpected events. Moreover, different secondary tasks, both in terms of type and extent of engagement, will be studied. Finally, the sample of participants will be enlarged, in terms of participants' ages (young and older drivers) and level of automation-experienced that could provide different results of after-effects of automated driving on drivers' workload and performance.

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