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Traffic Flow with the Adaptive Cruise Control: The Comparison between Autonomous and Manual Driving

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Abstract: Adaptive Cruise Control (ACC) is useful in the most dangerous maneuvers such as braking and acceleration. This study assesses how ACC modifies traffic flows by analysing the differences between manual and autonomous driving in connected and autonomous vehicles (CAVs). Using a platoon of 80 vehicles, tested in pairs on the road, it was possible to define the speed trends during braking and acceleration and the reaction times to the driving maneuvers (PRT, TH, TCC) with a kinematic data detector. The interactions between the CAV and the driver, have been studied innovatively, i.e through gaze analysis. Situations of potential danger, characterized by the braking of the vehicle that precedes the car with the driver equipped with the eye tracker tool, have been recreated, considering the influence of the driver's ACC experience. Results statistically confirmed that with the ACC switched on the reaction times are greater than manual driving (2.4/3.8 sec); this can lead to a reduction in road safety, further motivated by the rapid decrease in speed. The interpolation between automated and human data, finally, has allowed the detection of some criticalities of the system that are fundamental in order to reach the second level of automation.

Keywords: perception–reaction time; speed; driving behavior; connected and autonomous vehicles (CAVs); gaze.

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1. Introduction

The complexity of a car's driving activity, consisting of several concurrent tasks, causes the driver to have an excessive mental workload and, as a result, an increased likelihood of making mistakes [1–4]. Advanced Driver-Assistance Systems (ADAS) have been introduced in vehicles to try to limit the physical and mental strain on the driver [5]. ADAS are technologically innovative devices able to monitor driving and intervene in an emergency, thanks to the presence of a series of sensors [6]. They are the basis of self-driving cars, or autonomous cars, capable of driving on the road without the help of the driver.

Connected and automated vehicles (CAVs), becoming increasingly frequent, are radically changing the interactions related to road driving [7–9]. To date, however, few studies have evaluated the interactions of systems on traffic flows; for this reason, it is important to determine their impact and, consequently, their main peculiarities, to define how they affect road safety. However, it must be recognized that these technologies, when applied to large fleets of vehicles, allow for limiting the risk of accidents, and at the same time polluting emissions, energy, and fuel consumption [10].

In general, the four main components of ADAS devices are longitudinal control, lateral control, monitoring system of the watch driving, and parking assistance [11].

The aim of these devices is, therefore, to increase safety, try to limit dangerous situations for the motorist, and establish an innovative methodology of shared driving [12,13]. To shed light on this, the study of the interaction between driver and driver assistant is fundamental; it is, in fact, interesting to evaluate how the driver approaches the task of driving in the presence of ADAS since it is not always possible to trust the effective functioning of the mechanisms. Although the devices

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have been designed to increase road safety, they do not turn out to be totally autonomous. The need for constant control by the driver, in fact, is fundamental in order to avoid situations where ADAS do not intervene in an optimal way. This, however, presupposes high attention to driving to react promptly to situations of sudden danger. According to some studies, however, it has been found that the ADAS increase the focus of the look on the dashboard, in order to control the functioning of the system, outlining a lower perception of the road and the possible dangers inherent in it [14,15].

Therefore, the safety impact of these technologies often does not meet the expected benefits, as drivers change their behavior while driving, following the concept of Behavioural Awareness (BA) [16–18]. Several factors, such as the role of secondary driving tasks, and situational awareness (SA), need to be considered in order to analyse in depth the behavioural adaptation of drivers to driver assistance systems and the degree of trust they have with ADAS in relation to their driving experience [18,19].

1.1. Impact of ACC on traffic flow

Among the new driver assistance systems, Adaptive Cruise Control (ACC), is the one of the first concrete step toward autonomous driving [7,20,21]. The term "adaptive", in fact, is expressed the main feature of the system, which the ability to vary the speed according to the traffic conditions; it, in fact, through sensors RADAR or LIDAR frontal, can accelerate and decelerate automatically depending on the vehicle detection in front. In recent years, although the widespread use of this type of device has led to various research, none has been able to define the driver-vehicle interaction considering the different reaction times between the on and off the system, considering, therefore, the actual behavioral variation on the driving behavior [22,23].

The prerogative of the ACC is to monitor the safety distance from the previous vehicle; the concept of distance on the road falls within the constraints imposed by the spacing policy [24]. Its implementation has, in fact, a direct effect on road safety and the amount of traffic, considering the different parameters of analysis of the vehicles involved. First, the time headway (TH) is introduced, which allows the time interval between the passage at the same point of two successive vehicles, within the car-following model [25]. Although [26] argue that the risk is almost null if the driver maintains a time headway of 1s, it emerged that a TH of fewer than 1.2 seconds does not ensure road safety, especially in dangerous situations that require abrupt handling [27].

Unfortunately, drivers tend to adopt other significantly smaller ones especially when it is decided to keep a low safety distance in order not to be exceeded by other vehicles [28].

Since a spacing policy is established to ensure safety between vehicles, the collision time (TTC) should also be evaluated on the assumption that both vehicles march at a constant speed, without accelerating or decelerating. In some cases, in fact, it is possible to define the spacing error, that is, when the actual space moves away from the security space, creating instability in the flow of traffic. In fact, if in a platoon, the error increases, the traffic string becomes unstable, while if the error decreases it means that the string is kept within the considered time interval [29–31]. Drivers are not always able to perceive the right safe distance to keep to avoid an accident. In fact, 24% of accidents are characterized by a rear-end collision because most drivers cannot objectively perceive an acceptable TTC [32,33].

The last important factor for spacing policy is the reaction time of drivers in case of more or less dangerous maneuvers [7,34,35]. They, in fact, vary depending on whether it is to react to an obstacle on the road, a vehicle that crosses a junction to a car that brakes in front of us. However, to date in the literature, there is not yet a range of reaction times that have been studied in relation to the ACC. Many authors consider the range 0.4-0.5s, another 0.8-1.2s [7,36,37].

To assess how drivers evaluate the above parameters, many researchers have exemplified their behavior in the presence of strings from two or more vehicles, or a system of the vehicular platoon, monitoring the speed and distance adopted by one vehicle to another [38]. The instability of a platoon equipped with ACC refers to a dangerous situation caused by reaction times different from those required for the safety and comfort of passengers [39–41]. Marsden et al. (2001) through a detailed simulation investigation, obtained from the results a significant deceleration when the driver resumed control of the ACC system to increase the distance from a vehicle about to cut the road and deceleration, coming from the first vehicle of the platoon, has spread along the whole platoon. Thus, the presence of the ACC system reduces the standard deviation of vehicle acceleration, ensuring a potential gain in comfort [7,42,43]. Their evaluation is useful, following the analysis of the behaviors of drivers in various possible situations during a car-following, to design safe and suitable roads for the driver [44].

This paper aims to study the changes in traffic flows, evaluating the use or not of the system. Pairs of vehicles have been selected for analysis because it has been verified that strings with more than four vehicles with ACCs tend to be more unstable than smaller ones due to disturbances and interruptions related to the regularity of a traffic flow [45].

In addition, through specific controlled braking events, it was possible to define all the parameters included in the spacing policy, as well as highlight a new element of the link between vehicle and driver. Fancher et al. (1998), in fact, were able to observe that, in the same test, most drivers had different perceptions and behaviors during the reaction time. For this reason, the innovative identification of the Perception-reaction time allows to add a piece of behavioral analysis in the reaction range, so as to have a complete analysis framework [45–47].

To confirm the significance of the study, it was also verified the trend of the results, through a comparison between drivers who had the experience driving with ACC and others who had never used it.

2. Methods

A platoon of 80 connected and autonomous vehicles (CAVs), tested in pairs on the road, was equipped through the V-box. This tool allows for recording the kinematic data of vehicles in particular speed, acceleration, and position (Table 1). By synchronizing both V-boxes in the two consecutive vehicles (V1, in the lead, V2, in the end), it was possible to define some important parameters of analysis:

- Perception Reaction Time (PRT);
- Time Headway (TH);
- Time To Collision (TTC).

After testing the significance of the study of traffic flows, using two cars consecutive at the time [48], was introduced in the vehicle (V2) a visual tracking tool, properly calibrated with the driver.

The mobile eye tracker (ME) consists of two cameras that capture the external environment and the movement of the pupil (Table 1). Thanks to the overlapping of the recordings, which allows obtaining a video with the point of view, it was possible to extrapolate the visual data throughout the entire route.

Table 1. Features of instruments.

Features	Video V-box	Mobile Eye Tracker
Accuracy	± 0.1 km/h	0.5–1° (approximating the angular width of the fovea)
Frame rate	10 Hz	30 Hz
Components	GPS, Software, IMU	Spectal Mounted Unit (SMU), Display Transmit Unit (DTU), ME PC
Camera	2 cameras	1 eye camera, 1 scene camera

The 10 km route is a separate two-lane road. According to the experimental procedure, the system tested, i.e., the ACC was turned on only for half the route, so as to compare the real and

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autonomous driving behavior. To further highlight the crucial role of the system, 6 controlled braking events were planned for each couple of vehicles. This has shed light on the effectiveness of the system on the car following model and consequently on traffic flows. In fact, ACC allows modulating the cruise speed with the distance of the previous vehicle, avoiding sudden stop-and-go phenomena. In relation to the use of the system, different types of drivers have been recruited: 40 drivers who have used the ACC for at least 3 months (Mean-age = 45.81 years; Range: 35÷50; SD = 6.02) and 40 who have never used it (Mean-age = 40,84 years; Range: 35÷55; SD = 5.57); these were called 'ACC-Skilled' and 'Inexpert' respectively [15].

2.1. Speed trend: the times of analysis

The use of the V-box allowed tracking of the speed. During the controlled braking event, it was possible to define two trends:

- deceleration : $v_l(t_{i,s} + \tau) < v_f (t_{i,s} + \tau)$ (1)
- acceleration : $v_l (t_{i,s} + \tau) > v_f (t_{i,s} + \tau)$ (2)

where *i* is an index of the event, *s* is the beginning and τ is the next discrete point in the measurement timeline [49].

Figure 1 shows the speed and acceleration trend of V2. By synchronizing the V-boxes, it was possible to trace the reaction time (RT) within the braking event. It is enclosed within the range:

- T_L (blue line), indicating the braking of vehicle V1, when the Led stop appeared;
- T_B (grey line), which is the effective braking moment of vehicle V2, coinciding with the minimum y-acceleration.

In order to create a compendium of kinematic and visual data, the Mobile Eye was introduced. This allowed for reducing this interval of time, providing specific data of the moment when the driver of the V2 vehicle notices the braking.

The moment of fixation (T_F) therefore represents the moment at which the cursor is positioned for the first time, after T_L time, on V1 vehicle stop lamps (Figure 2). This interval, defined as the reaction-perception time (PRT), therefore allows the specific interval of reaction to the braking event to be evaluated.

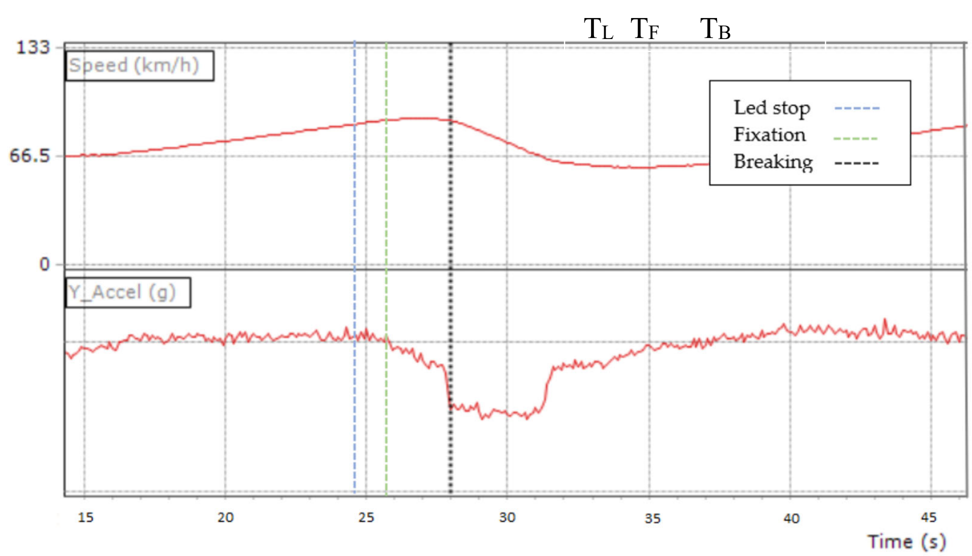

Figure 1. Range of Perception-Reaction Time. It starts with the green line (T_F) and it ends with grey ones (T_B).

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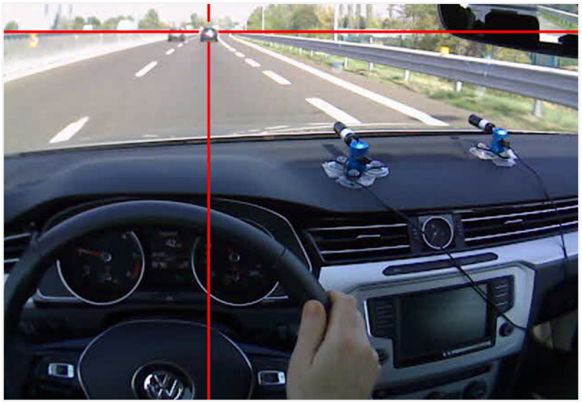

Figure 2. Output frame of ME which represent the moment of fixation (T_F).

The availability of the geographical coordinates of vehicles V1 and V2 allowed the evaluation of the relative distance between them, using the Haversine formula [48]. From this data, it was also possible to define:

1. Time to Collision (TTC), the time that elapses before two vehicles collide if the trajectories and speeds remain constant [49]. TTC is calculated as follows:
2. Time Headway (TH), the time between the passage of two vehicles at the same point [49]. TH is expressed as:

$$TH = \frac{d}{v_2} \tag{4}$$

d is the distance between vehicles V1 and V2 [m]; v_2 is vehicle V2 speed [m/s].

In literature, the point from which the distance of the two indicators is calculated refers to the front bumper of the two vehicles [49]; whereas in our study the position of the GPS sensor was placed in the center of the vehicle, on the roof of the car to use a barycentric position.

3. Results

3.1. The minimum distance

The vehicles have achieved a total of 240 controlled braking events, half with the system On. The distance covered for each event differs according to the experience of users with ACC; in fact, inexperts have shorter distances (0.2 km) than of ACC-Skilled (0.3 km). This immediately highlights a different approach to driving, which is confirmed by the minimum distances recorded. As shown in Table 2, ACC-Skilled have high average values, both on and off system. In the first case, in fact, after having set a minimum distance from the previous vehicle of 21 meters, users, knowing how the ACC works, tend to change lanes as soon as they notice a first deceleration, so as to avoid too many speed variations (average = 5 km/h). A different situation, however, appears when the system is turned Off. The difference distance of the events (9.48 meters) underlines the high reduction of space, according to an average speed variation of 15 km/h. In the case of Inexpert, the trend between ACC On and Off is the same, but a substantial decrease in the respective distances is detected. In fact, with the system On, users are just above the minimum distance set by the ACC (21.7 m), as they have a driving behavior that leads to staying behind the vehicle that precedes them, without preferring to overtake a clear lane.

$$TTC = \frac{d}{|v_2 - v_1|} \tag{3}$$

d is the distance between vehicles V1 and V2 [m]; v_2 is the vehicle V2 speed [m/s]; v_1 is the vehicle V1 speed [m/s].

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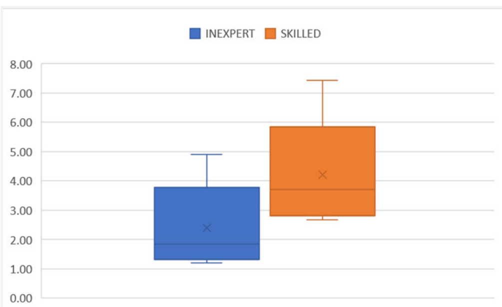
Table 2. The minimum distance in the controlled braking events of inexpert and skilled drivers, considering ACC On and Off.

	ACC ON	ACC OFF
Inexpert	21.71	16.35
Skilled	28.34	18.86

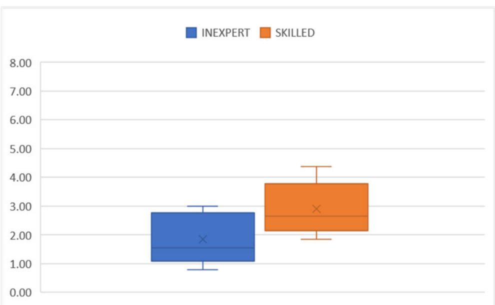
3.2. The Perception-Reaction Time, TH,TTC

Figure 3 shows the values of perception-reaction time, considering the system in On and Off conditions. ACC-Skilled and Inexperienced users reveal very different driving behavior depending on the state of the system. With the On system (Figure 3a), in fact, the Inexperts have PRT (Average = 2.1; SD = 0.9; $p < 0.01$) lower than the skilled pilots (Average = 3.8; SD = 1.1; $p < 0.01$), which allows confirming the trend recorded by the minimum distances and the TH. In fact, TH has values above the security limit (1.2 seconds) that are higher for experienced users (Average = 1.8 sec; SD = 0.08; $p < 0.03$) than those who have never used the system (Average = 1.3 sec; SD = 0.7; $p < 0.03$). The ACC-Skilled user, in fact, knowing the system, tries to reduce the discomfort related to sudden braking, and changing lanes to keep speed as constant as possible. This also justifies skilled TTC values (Average = 9 sec; SD = 3.8; $p < 0.02$) well above the critical value of 5 seconds, compared to inexpert users (Average = 6 sec; SD = 2.3; $p < 0.04$) [32].

The PRT analysis with the Off system (Figure 3b) confirms the tendency of skilled users to have longer times (AVERAGE = 2.9; SD = 0.6; $p < 0.01$), with an average difference of 1 second (AVERAGE = 1.9; SD = 0.7; $p < 0.01$). Although there are no dangerous braking events, which record low TTC (TTC skilled = 7 sec; TTC Inexpert = 6 sec), it is possible to highlight how the TH in for Inexpert is below the limit (Average = 0.9; SD = 0.07; $p < 0.01$).



(**a**)



(**b**)

Figure 3. Statistic evaluation of PRT. (**a**) Results with ACC On; (**b**) results with ACC Off.

The statistical comparison of PRT between the On and Off conditions of the system shows very different maximum and minimum values when the system is On; a trend that decreases with ACC Off. This substantial difference between autonomous and manual driving behavior is not very compatible with a road occupied by both autonomous and manual vehicles [20].

4. Discussion

The trial showed relevant results of analysis of the ACC considering the combined use of the ME and the V-Box. The synchronization and subsequent overlapping of the data, allowed to define of a detailed picture of the operation of CAVs, in relation to controlled braking events, comparing it with manual driving.

The combined analysis methodology has made it possible to evaluate the perception-reaction time. It represents the range that elapses between the moment when the individual looks at the LED stop of the car in front of him (T_F), to the instant he starts braking. Although the litearture debates the reaction time (T_L-T_B), that is the time that starts with the previous vehicle's (V1) brakes, to when the

vehicle V2 also begins the braking maneuver, the reaction-perception time (T_F-T_B) represents a step forward in the analysis of driving behavior. In fact, it allows the kinematic data of the vehicle to be linked with human perception. An innovative analysis point is added to the braking reaction interval, extrapolated from the speed and acceleration trend, namely the first visual perception of the previous braking vehicle (T_F). T_F represents a crucial point of analysis because it makes a quick comparison between experienced and inexperienced users; indeed they are located in very different time points, thus defining intervals of greater and lesser extent.
With the system on, ACC-Skilled tends to look at the vehicle braking first; the opposite situation for inexperienced drivers who are watching it late. Indeed Inexperts, not knowing the functioning of the system, fix mainly the dashboard to check the correct function of the ACC.

When the system is switched Off, the trend is confirmed, however, showing a decrease in the average values of PRTs. This result denotes a decrease in perception-reaction time when the system is turned Off, thus a faster response to dangerous situations. This factor, therefore linked to the manual driving of vehicles, underlines a first substantial difference in traffic flows; in car-following conditions, the control of the system entails wider deceleration curves, compared to the behavior recorded with manual driving.

In relation to these results, a further assessment was made, namely whether driving the vehicle first with the system On or Off led to variations. It has emerged that users who have driven first with the system operative and then with the system turned Off, kept longer minimum distances. This driving behavior shows how the use of the system had instructed them to have greater respect for the rules of the road, therefore increasing driving safety.

The TH and TTC underline another important behavioral element i.e. the tendency of experienced users to change lanes during braking, so as to reduce the discomfort related to the change in speed. Both analysis factors record averages above critical values, except for Inexpert when the system is shut down. Only in this case, in fact, a time headway is recorded just below the limit, as the time interval between the passage in the same point of two successive vehicles is equal to 0.9 seconds. However, having no low TTC, it is possible to define such a situation without possible collisions.

The ACC is confirmed as a driver assistance system that holds the record in the first level of automation.

It allows a profound change in driving behavior, especially in braking events. It is noticeable that it tends to increase the perception-reaction times of drivers, having deceleration intervals wider than manual driving. It also defines higher TH and TTC, so as to reduce the risk of accidents between vehicles. These factors, therefore, highlight a substantial behavioral difference on the road between autonomous and manual driving.

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