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ORIGINAL RESEARCH
PAPER



Efficiency of adaptive cruise control in commercial vehicles

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ABSTRACT

The evolution of autonomous vehicles hinges significantly upon the advancements in driving assistance systems. Adaptive cruise control, a pivotal component of these systems, warrants continuous real-world examination to assess its operational efficiency. The study investigates these systems integrated into diverse commercial vehicles with a specific focus on the following distances they provide. The findings reveal that camera-based systems offer shorter following distances relative to ISO standards, while radar-based and combined camera and radar-based systems provide larger following distances. The study contributes to understand adaptive cruise control technology and its alignment with safety standards, thereby aiding in the on-going development of self-driving vehicles.

KEYWORDS

adaptive cruise control, camera-based, radar-based, following distance, commercial vehicles

1. INTRODUCTION

Over the past few decades, there has been ongoing development and refinement of Advanced Driver-Assistance Systems (ADAS) with the aim of improving driving comfort, minimizing driving errors, enhancing safety, boosting traffic efficiency, and mitigating fuel consumption [1]. Previous research in the field of ADAS has primarily centered on Adaptive Cruise Control (ACC) systems. These ACC systems have become readily available in numerous passenger vehicles and have garnered significant attention from researchers, automakers, governments, and consumers worldwide. Initially, luxury vehicle manufacturers and their suppliers introduced the first-generation ACC systems with the primary goal of improving driving comfort and convenience [2, 3], while also considering the potential safety enhancements that they could provide [4–7].

The ACC systems represent an advancement of Conventional Cruise Control (CCC) mechanisms [8]. They function by automatically adjusting a vehicle's speed to maintain a specific distance from the vehicle ahead, and they achieve this by controlling the throttle and, if necessary, the brake. A crucial component of ACC is the range sensor, which can be a radar, Light Detection And Ranging (LiDAR), or video camera. This sensor measures both the distance between the two vehicles and their relative speeds. However, each type of these mentioned sensors has its own features and ranging values [9–14]. Therefore, car manufacturers are constantly striving to develop their technological advancements in order to address challenges that hinder system operation. These challenges might typically revolve around the ability of range sensors to perform reliably in various weather conditions [15], reaction time and sensor height [16], as well as concerns related to driver distraction and impaired decision-making during emergency situations resulting from excessive reliance on

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automation and reduced attentiveness. Researchers have studied the efficiency of ACC systems from various perspectives. Regarding safety, Li et al. [5] have studied assessing the safety implications of vehicles equipped with ACC in congested traffic and demonstrated that these vehicles can notably decrease the incidence of accidents. Winter et al. [17] and Piccinini et al. [18] have confirmed that ACC reduces self-reported workload compared to manual driving in their studies. Along the same line, Eichelberger and McCartt [19] and Cicchino and McCartt [20] through their surveys indicated that ACC users hold favorable views regarding the convenience and comfort afforded by this technology. However, in a series of empirical tests, many other researchers diligently investigated the performance of ACC by manipulating various headway settings [21–24]. By systematically adjusting these parameters from the shortest to the longest headway, researchers were able to uncover crucial insights into the system's ability to enhance driving safety and convenience.

The study represents a comprehensive investigation into the effectiveness of adaptive cruise control systems, specifically focusing on their sensor types. This has been achieved through rigorous experimentation and analysis at ZalaZONE proving ground in Hungary. The study also aimed to shed light on the comparative advantages and limitations of different sensor technologies used in adaptive cruise control systems by comparing gap results of the tested vehicles with the standard one-second gap of ACC. This research contributes to the continuous improvement of ACC technology, helping to fine-tune its settings and optimize its functionality for a wide range of road scenarios, ultimately improving road safety and the driving experience.

2. AIM AND OBJECTIVES OF THE STUDY

The aim of this research is to comprehensively examine ACC systems implemented in a range of commercial vehicles, with a primary emphasis on evaluating and comparing the specific following distances they offer. The investigation specifically delves into the distances determined through radar-based systems, camera-based systems, and hybrid radar-camera ACC systems. Through rigorous testing and comparison of used ACC system at different levels of driving speed, the study aims to provide valuable insights into the performance and efficacy of these ACC technologies, contributing to a deeper understanding of their capabilities in enhancing vehicle safety and adherence to standardized following distances.

3. METHODOLOGY

The subsequent sections offer a comprehensive insight into the research methodology. Initially, a concise overview of the study location and testing circuit was furnished. Subsequently, a description of the used equipment has been explained. Then details about the test vehicles along with

their corresponding ACC systems were discussed, besides elucidating the scenarios and procedures employed, and finally, discussing data collection.

3.1. Field test location and site description

The field tests have been conducted in ZalaZONE Proving Ground, which is considered as a state-of-the-art testing and evaluation facility designed to rigorously assess and validate various technologies and systems, particularly those related to autonomous vehicles. ZalaZONE is located in a vast and controlled environment, the proving ground offers a wide range of testing scenarios and terrains, including urban, suburban, and off-road settings, allowing manufacturers and researchers to put their innovations through extensive trials (see Fig. 1). Motorway test track has been selected to carry out the tests as it provides a realistic environment, which is particularly important for testing and validating the ADAS system. The motorway track, which is in the left side of the map is shown in Fig. 2a consists of four divided traffic lanes with one safety lane in each side. It has been constructed with a length of 1,500 m, in which the road surface is mainly an asphalt flexible pavement. While an additional rigid concrete pavement also included to ensure variety of

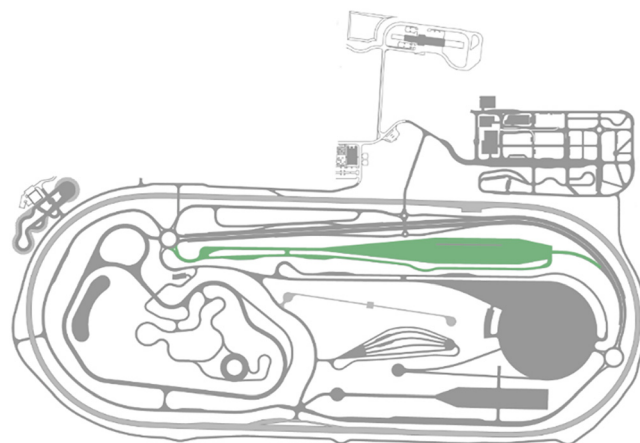
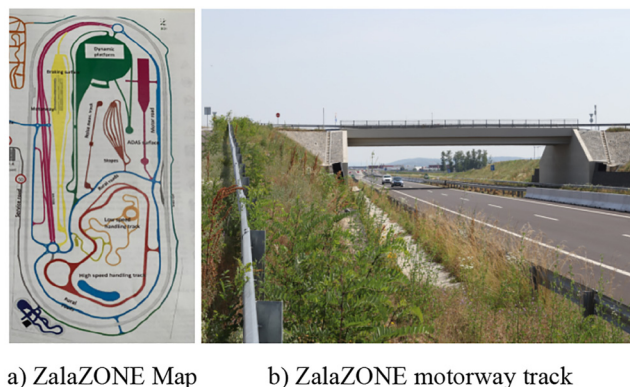


Fig. 1. ZalaZONE proving ground area (with the permission of ZalaZONE [25])



a) ZalaZONE Map

b) ZalaZONE motorway track

Fig. 2. ZalaZONE testing tracks (Source: Authors' photo)

motorway situations. The length of the straight section of the motorway is 960 m and the curved section is 540 m with a radius of 340 m. Furthermore, the separating elements installed on the median to separate different directions have various designs of single and double-row strip of guardrails as well as New Jersey barriers. These diverse elements help to test and challenge the functioning of autonomous vehicles and to evaluate their ability to navigate complex and real-world scenarios. On the other hand, the existence of the bridge over the motorway can be an ideal location for testing the functionality of built-in vehicle sensors and cameras (see Fig. 2b).

3.2. Setting up LiDAR equipment

RPLiDAR [26] has been used during the experiment to measure the following distances. The device provides a pioneering technological marvel that seamlessly fuses real-time location and mapping capabilities into a single, compact package. This standalone device boasts unparalleled versatility, requiring no external accessories or intricate setup procedures except turning it on and exploring a multitude of applications. RPLiDAR is the epitome of efficiency that provides an accuracy of ± 50 mm, resolution of 30 mm and speed of 10 kHz as per the device specifications [26]. This makes it the perfect choice for an array of diverse tasks, like robot localization and navigation, environmental mapping, and handheld measurements. With its integrated degree-of-freedom inertial navigation system, this device is engineered to operate effortlessly in both high and low undulating terrains, as well as inclined environments, all while in handheld mode. In addition to its remarkable performance capabilities, the device prioritizes safety. Compliant with Class 1 laser safety standards, as it emits laser light within an exceedingly brief timeframe, minimizing any potential harm to humans or pets. During our test, the LiDAR device was affixed to the rear bumper of each leading vehicle, and an examination was conducted to determine whether the readings were satisfactory as it is shown in Fig. 3.



Fig. 3. Setting up RPLiDAR device (Source: Authors' photo)

3.3. Test vehicle types and following scenarios

In this study, an evaluation was conducted to assess the efficacy of ACC systems. To achieve this objective, three distinct vehicle brands were employed, each equipped with its unique ACC system. The vehicles under investigation were the Subaru Levorg, Volvo XC40, and Volkswagen (VW) e-golf, as it is shown in Table 1. The Subaru Levorg's ACC system, known as "Eyesight," relies on vision-based sensors, specifically stereo cameras positioned near the rearview mirror to enhance road monitoring capabilities. In contrast, the Volvo XC40 utilizes a combination of radar and camera technologies as an alternative ACC sensor type, offering a comprehensive perspective of the road and traffic conditions. The VW e-golf, on the other hand, exclusively employs radar-based ACC sensors. This investigation seeks to analyze and compare the performance of these ACC systems in terms of their ability to maintain safe following distances. In order to ensure the neutrality of field data acquisition, the selected vehicles were subjected to various car-following scenarios under identical daytime and weather conditions as it is shown in Fig. 4. The first scenario involved utilizing a Subaru as the following vehicle, followed by a second scenario in which a Volvo was employed in the same circumstances. The third scenario featured a WV as the following vehicle. It is noteworthy that the specific make and model of the leading vehicle in each scenario was not of significant importance; rather, the primary focus of the study was to investigate the following distances achievable through the operation of different types of ACC systems.

3.4. Data collection

To comprehensively assess the operational efficiency of the ACC systems within the context of this study, the selected vehicles have been subjected to a series of controlled tests. These tests spanned a range of constant speeds, starting at 30 km h^{-1} and extending up to 110 km h^{-1} with 10 km h^{-1} incremental intervals. Following distances were meticulously recorded, which reflect the actual clearances between consecutive vehicles within each test scenario, corresponding to the specified driving speeds. Although all ACC systems operate at several distance or time following settings as explained earlier in Table 1. The shortest setting (setting 1) has been selected for all test runs to better investigate the riskiest driving situations that might occur during the operation of ACC systems at the minimum allowable distances, especially at high speeds (see Fig. 5).

The data acquisition process was executed with an emphasis on precision, facilitated by using RPLiDAR and the measurement program that features an interface allowing lateral and longitudinal limits on the measurement range. Users can specify the location and file name during recording. Pressing START automatically records the longitudinal and lateral distances of the nearest object within the set range to a file, displaying the detected points in real time. Pressing STOP ends data recording. During the recording phase, the work team inside the follower vehicle maintained constant vigilance over RPLiDAR device's

Table 1. Tested vehicle brands and corresponding ACC characteristics (Online Sources [27–29])

Vehicle Brand	ACC type	ACC adjustable settings	ACC following time/distance Setting	Source
Subaru Levorg	Vision-based	Speed and following distance	Four distance settings	Subaru Official Website
Volvo XC40	Combined Vision and radar-based	Speed and following time	Five time settings	Volvo Official Website
VW e-golf	Radar-based	Speed and following distance	Five distance settings	VW Official Website



Fig. 4. Tested vehicles with the applied following scenarios, a) first following scenario, b) second following scenario, c) third following scenario (Source: Authors' Photo)

operation. They achieved this by continuously monitoring the laptop screen to confirm that the follower vehicle consistently tracked the leader vehicle, which was operating at a slower speed than the test speed of the follower vehicle, as it is shown in Fig. 6. The Python-based software interface manages the above-mentioned functionalities. It activates a C++ driver in the background during measurement initiation, processing raw LiDAR data through serial communication, and applying data filtering. Filtered data is then transmitted to the Python program, which displays and saves the nearest object's data, including time, longitudinal distance, and lateral distance.



Fig. 5. Applying shortest following ACC setting (setting 1) (Source: Authors' Photo)

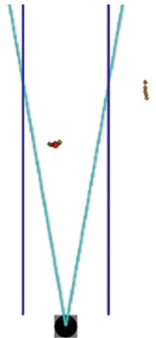


Fig. 6. Monitoring the leader vehicle track by RPLiDAR (Source: Authors' Photo)

4. RESULTS AND DISCUSSION

In this section, the collected data from ZalaZONE field test including clearances between every two following vehicles for each scenario have been presented and comparatively analyzed to understand the operational effectiveness of the studied ACC systems. The application of different constant driving speeds using the selected vehicles was also very important in the experiment to indicate how setting 1 of ACC systems adjusts the shortest distances between the following vehicles to ensure safety aspects. Figure 7 illustrates the distribution of clearances along each corresponding driven constant speed by the tested vehicles for the whole motorway section. Although there is smooth rippling of the lines representing the clearances for Subaru, the difference between minimum and maximum clearance at any driving speed seems to be in reasonable range. Except for the highest speed of 110 km h^{-1} where the divergence reached approximately 5 m. In similar vein, VW experiences difficulties when generating readings from the clearance distribution data collected during tests at different speeds. These readings exhibit an unsettling degree of instability, characterized by sharper and more pronounced ripples. Furthermore, this trend bears resemblance to the observations made with Subaru's data, as the gap between detection measurements widens significantly as the vehicle's speed increases, especially at 100 and 110 km h^{-1} . This phenomenon implies

that at higher speeds, the accuracy, and precision of the clearance distribution readings from both VW and Subaru become increasingly compromised, posing challenges for their data analysis and interpretation. On the other hand, Volvo's ACC system excels in maintaining more consistent and reliable following distances when compared to its counterparts. The generated lines representing these following distances exhibit a higher degree of linearity and consistency, delivering a smoother and more predictable experience for drivers. However, it is worth mentioning that at lower speeds, around 30 km h^{-1} , the ACC system in Volvo still exhibits some minor fluctuations in the following distance. While it remains significantly improved compared to other systems, the occasional deviations in distance maintenance at these slower speeds might be noticeable. This nuanced performance difference between higher and lower speeds underscores the complex engineering challenges in achieving seamless control across a wide range of driving conditions, with Volvo's ACC system offering a generally superior experience in maintaining steady following distances, particularly at higher speeds.

Subsequently, an analysis was conducted to determine the average following distances maintained by the vehicles during the series of test drives. These distances were then compared to the ISO 15622:2018 [30], which define safe clearances equivalent to a one-second time gap for different driving speeds. The results revealed a noteworthy contrast among the vehicles tested as it is shown in Fig. 8, which

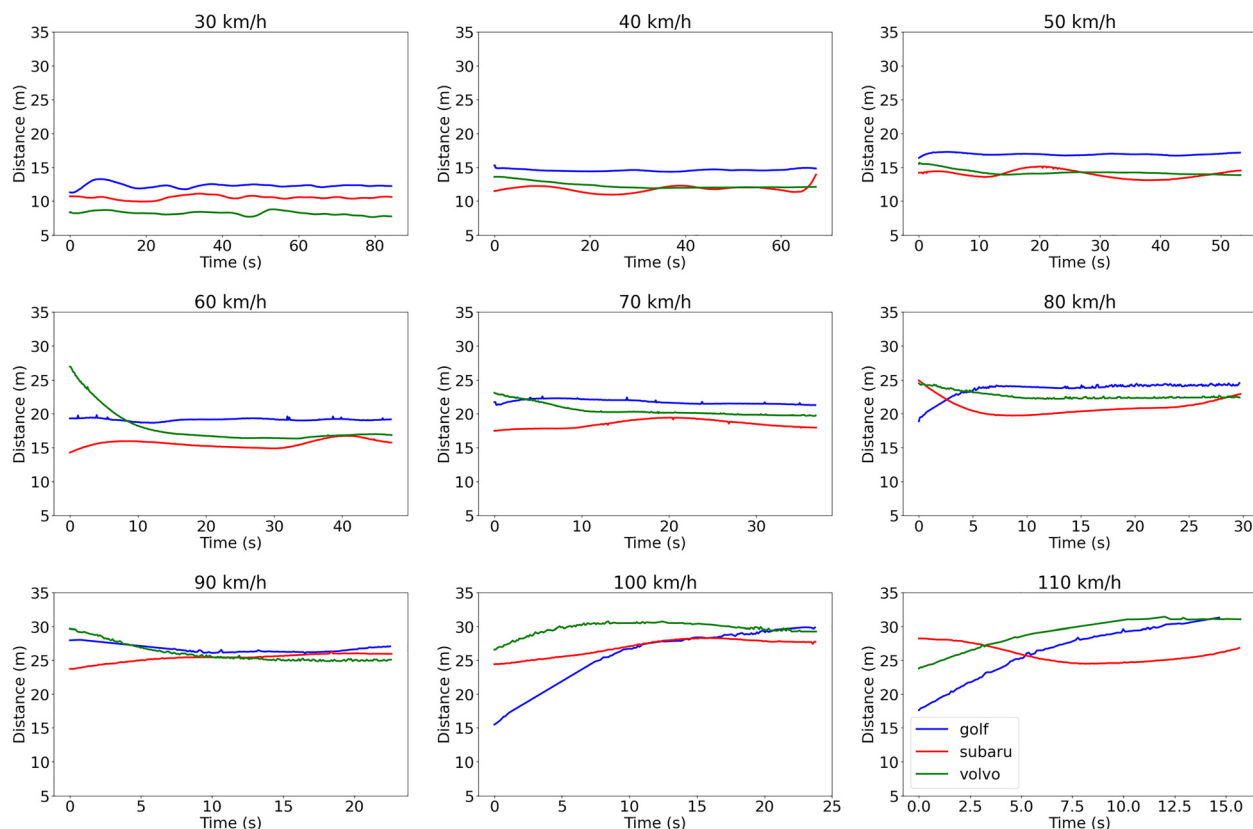


Fig. 7. Following clearances by all tested vehicles' ACC systems (Source: Authors' result)



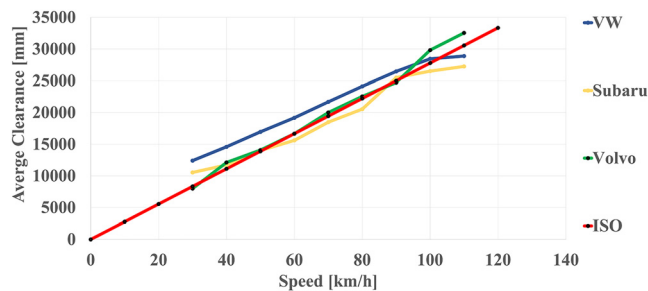


Fig. 8. Average following clearances vs. driving speeds (Source: Authors' result)

visually demonstrates the findings. It becomes evident that both Volvo and, to a certain extent, VW, consistently maintained following distances that exceeded the ISO 15622:2018 [30]. This suggests that the ACC systems in these vehicles err on the side of caution when it comes to safety, offering drivers a more conservative approach to distance management. On the other hand, the Subaru vehicle showcased distinct driving behavior, characterized by shorter following distances for the majority of the tested driving speeds. This observation implies that Subaru's ACC system exhibits a more assertive or proactive approach to maintaining safe distances between vehicles. The proactive nature of Subaru's system may be perceived as aggressive in comparison to the other vehicles, but it also means that it provides drivers with a closer and more responsive interaction with traffic flow, which could have implications for both safety and driving experience. Nevertheless, the analysis of following distances in the context of different ACC systems has overlooked the critical aspects of vehicle acceleration and deceleration. This oversight could lead to a skewed conclusion when comparing these systems and their compliance with ISO 15622:2018 [30].

5. CONCLUSION

This empirical study focused on assessing the efficiency of ACC systems in recent commercial vehicles, with a specific emphasis on their ability to maintain optimal following distances. While the study's test speed was limited to a particular motorway section at ZalaZONE proving ground, the results obtained reflect a comprehensive exploration of ACC systems. The findings revealed that vision-based ACC systems consistently provided shorter following distances compared to ISO standards. This suggests potential benefits in terms of increasing traffic capacity within road networks. However, it also raises safety concerns, particularly at high driving speeds. Conversely, radar-based ACC systems and combined camera and radar-based systems demonstrated higher following distances than ISO standards, while this enhances traffic safety, it diminishes capacity, which may hinder the evolution of autonomous vehicles. In light of these outcomes, it becomes evident that further research,

encompassing a broader range of ACC settings, is imperative. This approach will be instrumental in gaining a deeper understanding of how these advanced driving assistance systems operate and their real-world impact on driving conditions.

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