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Cooperative adaptive cruise control and intelligent traffic signal interaction: a field operational test with platooning on a suburban arterial in real traffic

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Abstract: It is becoming increasingly important to gain real-life insights into the effects of vehicle automation with the continued introduction of cooperative and automated vehicles (CAV). This study reports on the findings of a field operational test (FOT) of cooperative adaptive cruise control (CACC) vehicles on an arterial corridor with other traffic. The FOT demonstrated that CACC vehicles can operate well under such conditions and can operate in platoons at lower time-headways than human driven vehicles. Platoon disengagement and cut-ins were analysed and showed that although many platoon break-ups are unavoidable, CACC operation was carried out without incident with frequent recoupling of platoons occurring. Most cut-ins occurred near to intersections, where vehicles are required to merge or need to change lanes to turn off the main corridor. It was not possible to derive potential traffic flow improvements from the FOT, due to a limited overall penetration rate and limitations of the intelligent traffic signals. The findings offer greater insights into the performance of CAV technology in a suburban environment and can aid road authorities to prepare infrastructure for the broader introduction of CAVs as well as the development of modelling tools to improve impact analysis of CAVs in urban environments.

1 Introduction

This paper reports on the findings of a field operational test (FOT) of cooperative adaptive cruise control (CACC) enabled vehicles on an arterial corridor with other traffic, which includes the presence and use of intelligent traffic signals (ITS) for platoon communication and prioritisation. As far as the authors are aware, this is one of the first FOTs to do this on such a scale on an open road in which interactions with other traffic occurs. The findings from the tests give greater insights into the performance of cooperative and automated vehicle (CAV) and allow road authorities to prepare infrastructure for a broader introduction of CAVs. The findings can also aid the development of modelling tools to improve impact analysis of CAVs in urban environments.

It is becoming increasingly important to gain insights into the effects of vehicle automation with the continued and gradual introduction of CAVs to public roads, also for (sub)urban roads. With increased on-road testing of concept vehicles, it is just a matter of time before the share of CAVs on roads will increase. The introduction of CAVs has led to road authorities, municipalities and researchers posing many questions on various issues related to traffic flow, vehicle interaction and safety, among many others. To allow these authorities to prepare for the wider introduction of CAVs and allow industry and science to develop technology and models to study their wider impact, ground-truths on the real impact of CAVs are required [1, 2]. Traditionally many driving simulator and closed road tests have taken place and have offered good initial insights [3, 4]. On-road testing in real traffic conditions, however, offers additional advantages to study interactions with other road users and infrastructure to a greater extent than closed road testing [5], as well as unearthing unexpected events. On-road testing on (sub-)urban roads is vital to be able to give insights into various yet unknown aspects of their performance and how (local) road authorities should react to their introduction. Up to now, very little on-road testing in real traffic conditions has been performed on sub(urban) roads with CACC technology.

The FOT described in this paper considers two main aspects of CAV technology: CACC enabled vehicles in platoons and the use of ITS. CACC has been in development for a few decades [6, 7]

and with increasing maturation of the automotive and communications technology is becoming available for on-road testing and implementation. CACC allows vehicles to follow each other with longitudinal automation with the added advantage of vehicle-to-vehicle (V2V) communication, which allows shorter time gaps between the vehicles due to very short delays in vehicles obtaining information about the driving states of the leading vehicles. Up to now, most research on CACC vehicles has rightly been focussed on freeway traffic, as this is where the greatest benefits are expected, at least in the short term. These benefits have been shown to include possible improvements in capacity [7–9], flow stability [10–12] and fuel consumption [13, 14]. However, the use of CACC in (regional) arterial traffic is not unheard of with various researchers proposing its use and finding potential improvements in traffic flow [15, 16]. It is especially in regard to active vehicle-to-everything communications and cooperation that CACC can play an important role on urban arterials [15]. At this point we do recognise the difference in the definition of CACC and platooning in some other literature, which defines CACC as using a constant time gap, while platooning can be defined as using a constant space gap [17]. We will describe groups of CACC-active vehicles in this paper as platoons, while acknowledging that they operate using constant time gaps and not space gaps.

Cooperative Intelligent Transportation System (C-ITS) technologies, such as green light optimal speed advisory, are all designed to improve traffic flow and reduce emissions through intersection with wireless communication [18, 19]. CACC with I2V works in a very similar way, possibly to a more effective extent. The wireless communications exist between vehicles (V2V), which is inherent to CACC technology, but also with infrastructure (V2I), such as ITS. ITS can receive information about approaching vehicles, such as a platoon of CACC vehicles, and can adjust the traffic signal phases such that a platoon (or any designated vehicle class, such as emergency vehicles) can be given priority at controlled intersections [20]. ITS can also be used to communicate information to approaching vehicles, such as time-to-green (TTG), so that vehicles can adjust their velocity to avoid arriving at the ITS during a red phase.

Speeds CACC, session 0180904-32

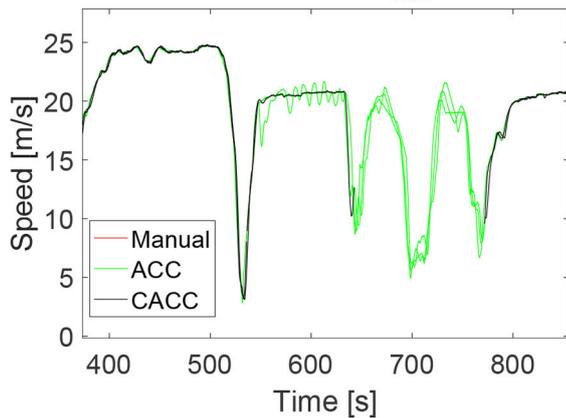


Fig. 1 Speeds of (C)ACC vehicles during run 32 (scenario E)

In this paper, we describe the conducted FOT and give the main findings from the FOT as well as discussing the implications. The main focus in the remainder of the paper will be on the performance of CACC during the FOT. The use of ITS in the FOT was operational, but its effectiveness was limited. This was mainly due to the traffic signal using a dynamic control strategy, which is very common in The Netherlands. This led to a changeable and therefore poorly reliable TTG indication for the vehicles. Furthermore, the test vehicles were often constrained by other road vehicles and almost entirely were never at the start of a queue at intersections. Therefore, the overall effectiveness of the ITS communication with the vehicles in regard to traffic performance was negligible. In future tests, the Province of Noord-Holland (PNH) has already indicated that it will strive to have static traffic signals controls available as a scenario option. Therefore, the main analysis and focus of the paper is on the CACC performance on the considered arterial corridor.

In the following section, we explain the setup of the FOT, the vehicle setup, the scenarios and the data that is collected. In Section 3, we give the analysis of the collected data from the FOT and summarise the main findings. These are discussed further in Section 4 and concluded thereafter.

2 Field operational test description

In this section, we describe the setup of the FOT. This includes the setup of the vehicles and their capabilities, the setup of the ITS, as well as describing the road corridor that is used. We also give a description of the scenarios that were applied during the FOT to test the CACC performance.

2.1 Vehicle and traffic signal setup

2.1.1 CACC vehicles: The test was carried out using seven Toyota Prius' with factory installed Adaptive Cruise Control (ACC) and after-market installed CACC system. The vehicles were unrecognisable as CACC equipped vehicles from the outside. This ensured that the experiment maintained a high level of validity. The default settings used, while in CACC mode for the vehicles during the experiment, is a gap time of 0.6 s increased by the nominal standstill distance of 5 m. This additional 5 m was a requirement for testing. This means that at a speed of 100 km/h, the distance between vehicles would be 22 m (17 m from the gap time increased by the 5 m safety buffer). The choice of 0.6 s was made to allow a short as possible time gap, while maintaining a sufficiently safe distance between vehicles. The applied CACC system is a system that was developed and fitted by Netherlands Organisation of Applied Scientific Research (TNO) and based on the work by Ploeg [21, 22] with the capability to communicate between the vehicles and with the road-side units, such as the ITS. The vehicles were fitted with Wi-Fi communication technology to allow them to communicate with each other and with the ITS. The applied system was pre-approved by the National Vehicle Approval

Authority in The Netherlands (RDW) after testing on their test circuit, as part of the concession application to carry out the FOT.

2.1.2 Drivers: The test drivers used during the FOT were exclusively certified and experienced test drivers who have followed specialised training to allow them to drive experimental vehicles in FOTs. The drivers were all familiar with the (C)ACC systems and many are also involved in their development. The use of certified test drivers was a requirement that was made in the FOT concession given by the PNH that had to be met to allow the FOT to commence. Therefore, the drivers cannot be considered to be a representative test group in this experiment. This, however, is not a problem, as the main focus of the FOT is not to evaluate the driver's performance, but the systems performance in interaction with the intersection infrastructure and other drivers. During testing, the order of the vehicles and the drivers for all scenarios and all tests was maintained. For example, the first driver and their vehicle were always the first driver in all scenarios, the second driver and their vehicle were always the second vehicles in all scenarios and so on. This also entails that the CACC vehicles did not perform overtaking manoeuvres of each other as one would expect in a platoon.

2.1.3 Traffic signals communications: The five intersections along the corridors are fitted with ITS with both 4G and WiFi-P communication technologies for direct I2V and V2I communication with approaching vehicles. The ITS are controlled by dynamic traffic signal control algorithms that can extend, shorten or cut-out various phases in the control cycle to give intersection priority to certain vehicles classes, such as emergency vehicles. During the experiment, both I2V and V2I communication is present between the traffic signals and the CACC equipped test vehicles. This made use of two different systems: green-time extension (GTE) and TTG communication. Depending on the scenario, the platoon of test vehicles would send out CAM messages which would be received by the ITS. When an ITS received at least two CAM messages from vehicles in the platoon, i.e. to indicate that platooning is being performed, a GTE request would be initiated within the signal controller. The TTG messages allow the platoon to adjust its speed to pass the intersection on the fly or alternatively prepare to stop if a green-phase extension cannot be given. As part of the safety procedure during the experiment, stationary test vehicles were not allowed to directly react to the communication given by the traffic signals, but had to be instructed by the driver to start driving. To facilitate this, each vehicle is fitted with a wireless device, which has an Android-based app installed that shows the information that is communicated by the traffic signals to the test driver. The test driver can then react to the information that is given, which was displayed as the TTG.

2.2 Road corridor and scenarios

2.2.1 FOT setup and corridor: The FOT was performed on a provincial arterial road that has been equipped by the PNH as a pilot corridor for C-ITS applications. The N205 road is located near the town of Hoofddorp and Schiphol airport to the South of Amsterdam, is ~12 km in length and includes five ITS intersections (see Fig. 1). The majority of the corridor is dual carriageway with two lanes per direction and additional lanes present in the approach to most intersections to assist turning traffic. These additional lanes lead to traffic interactions near intersections as vehicles change lanes to exit the road, either to the left or right, and often need to merge when the number of lanes returns to two after intersections. Furthermore, there are speed limit variations along the corridor; near the intersections, the speed limit is 70 km/h, while the speed limit between intersections is 100 km/h. In the southern part of the road, the speed limit is set at 80 km/h on the corridor as well as at the intersections. The speed limits and intersections are shown in the inset in Fig. 1.

2.2.2 FOT scenarios: The FOT was performed during a working week, in which five different scenario types were carried out based

on two variables: the default vehicle mode and the type of traffic signal communication. The three vehicle modes are: manual driving, ACC mode and CACC mode. (C)ACC modes indicate that (C)ACC is enabled and should be used when possible (e.g. safe and viable). The three different traffic signal communication settings for the communication with the ITS are: regular (non-communicative), green recognition and green recognition with green-phase extension. These different modes and settings are combined to give the following five scenario types:

- (A) Manual driving with regular traffic signal settings
- (B) Manual driving with green recognition
- (C) ACC mode with green recognition
- (D) CACC mode with green recognition
- (E) CACC mode with green recognition and green-phase extension

Each of these scenario types is carried out up to a maximum of eight times during the FOT: four with a three vehicle platoon and four with a seven vehicle platoon. For manual driving only four runs were performed in total, and for CACC with platoon recognition with three test vehicles, two runs were carried out. This results in 10 unique cases and a total of 34 runs over the corridor. A FOT run is considered as a complete 'circuit' of the corridor in which the vehicles have continuously driven once in both directions. The vehicles first drove in a southbound direction. At the end of the corridor they performed a U-turn at a roundabout and proceeded back along the road on the opposite northbound carriageway. Regardless of the scenario, the vehicles drove on the right most lane when multiple lanes were available for their route and were not permitted to overtake each other or other vehicles. While driving in CACC mode, the vehicles follow each other at the pre-set gap (0.6 s plus 5 m) and react immediately, with only the communications delay, to changes in speed of the leading test vehicle. While in ACC mode, the vehicles remain in a peloton, but now rely only on their own sensors. While in ACC mode, the vehicles resort to a gap of 0.8 s plus 5 m as safety becomes more critical without cooperative information. While driving in manual mode, the test drivers were instructed to keep a safe but regular distance to the vehicle ahead, similar to what might be expected while driving in normal traffic. When an entire circuit was completed, the vehicles would proceed back to the holding bay and prepare for the next run. The test runs per scenario are spread over different times of the day so that each scenario is applied in different traffic conditions (e.g. AM or PM peak period, or between peak periods). The runs took place between 7:30 and 18:15 on four consecutive days workdays in September 2018 and each lasted for ~20–30 min. The full list of performed runs and times can be requested from the authors.

During scenario runs, cut-ins from other vehicles were possible and did occur. This means that if a platoon is split up and the test vehicles revert to ACC or even manual mode, the scenario remains a CACC scenario. Obviously for the analysis of the data, we do consider which mode is currently in operation and not the default mode. For cut-ins, the platoon continues to proceed in CACC mode, but with fewer vehicles, while the following vehicle behind the cut-in would revert back to ACC mode, therefore effectively resulting in two shorter platoons. Once the cut-in vehicle moves out of the platoon, the platoon will not automatically try to reconnect, although reconnection does occur if the following vehicles catch up again with the leading test vehicles, such as at intersections or if the platoon is stuck behind slower traffic. In ACC mode or manual mode, the test vehicles continue as instructed in ACC or manual mode. This approach allows us to investigate how a platoon interacts with surrounding traffic. It should also be noted that the experiment was kept secret and not made publically known prior to its execution to prevent other road users being aware of the tests and/or attracting unwanted attention or effects from other road users other than their natural interactions and reactions. This allows the FOT to be representative of CACC platooning under normal traffic conditions and was also a prior requirement for testing.

3 Performance analysis based on data

In this section, we present the results of the FOT. The applied approach for the analysis is firstly given with thereafter details on platooning performance, platoon break-ups and cut-ins, and traffic performance along the test corridor. This is considered both quantitatively and qualitatively.

3.1 Analysis approach

The collected data is available per vehicle for all the applicable sensors and is time stamped to allow cross-comparison between the outputs of the different sensors. Some of the data is time based, while other data is event based. To be able to analyse the data per FOT run and scenario, data transformation was carried out to combine the different sources from the different vehicles into a consistent dataset per FOT run. In short, this consisted of the following steps:

- Transform all sensor output to the same time-based intervals (0.1 s)
- Derive desired vehicle/traffic variables from sensor data
- Combine individual vehicle data together for a single run

A full list of the data fields contained within the raw vehicle data can be accessed through the author. The derived vehicle variables from the data after processing are:

- Time stamp
- Vehicle ID
- Leader ID
- Ego-speed
- Ego-acceleration
- Space headway to leader
- Vehicle mode state [(C)ACC-active and/or enabled]
- Brake pedal use
- Throttle pedal use
- Leader speed
- Leader acceleration

With the processed data, analyses of various aspects of the FOT and CACC driving can be performed. We have focussed the analysis in this contribution on the platooning performance of CACC, as this was the main purpose of the FOT. Quantitatively, we consider the time-headways of the test vehicles in their different modes, how long the vehicles were able to platoon, how often platoons were interrupted by cut-ins and where this often occurred. Qualitatively, we also consider phenomena found from analysing trajectory plots from test runs for platooning capability for the different scenarios as well as viewing specific occurrences of cut-ins and other disturbances to the platoons.

3.2 Platooning performance

Effective CACC platooning entails the ability of vehicles to follow each other at short time-headways with high homogeneity, i.e. minimal deviation between speeds and time-headways. Shorter headways mean that platoons can offer the potential advantages of higher road capacity, while homogeneity also promotes greater string stability within a platoon. The combined time-headways of all scenarios per active vehicle mode and for the traffic state are shown in Fig. 2. Stable traffic is defined as traffic in which the acceleration and deceleration of vehicles remains within the bandwidth of 0.5 m/s^2 to -0.5 m/s^2 . Traffic is considered to be in a state of acceleration or deceleration if the acceleration exceeds these values.

Comparison is made using the median to avoid the effects of outliers. The standard deviation is used to indicate the spread of observations. Negligible differences were present based on the same driving modes over the scenarios for time-headways, therefore grouping of results can be performed to give a larger dataset to perform this analysis.

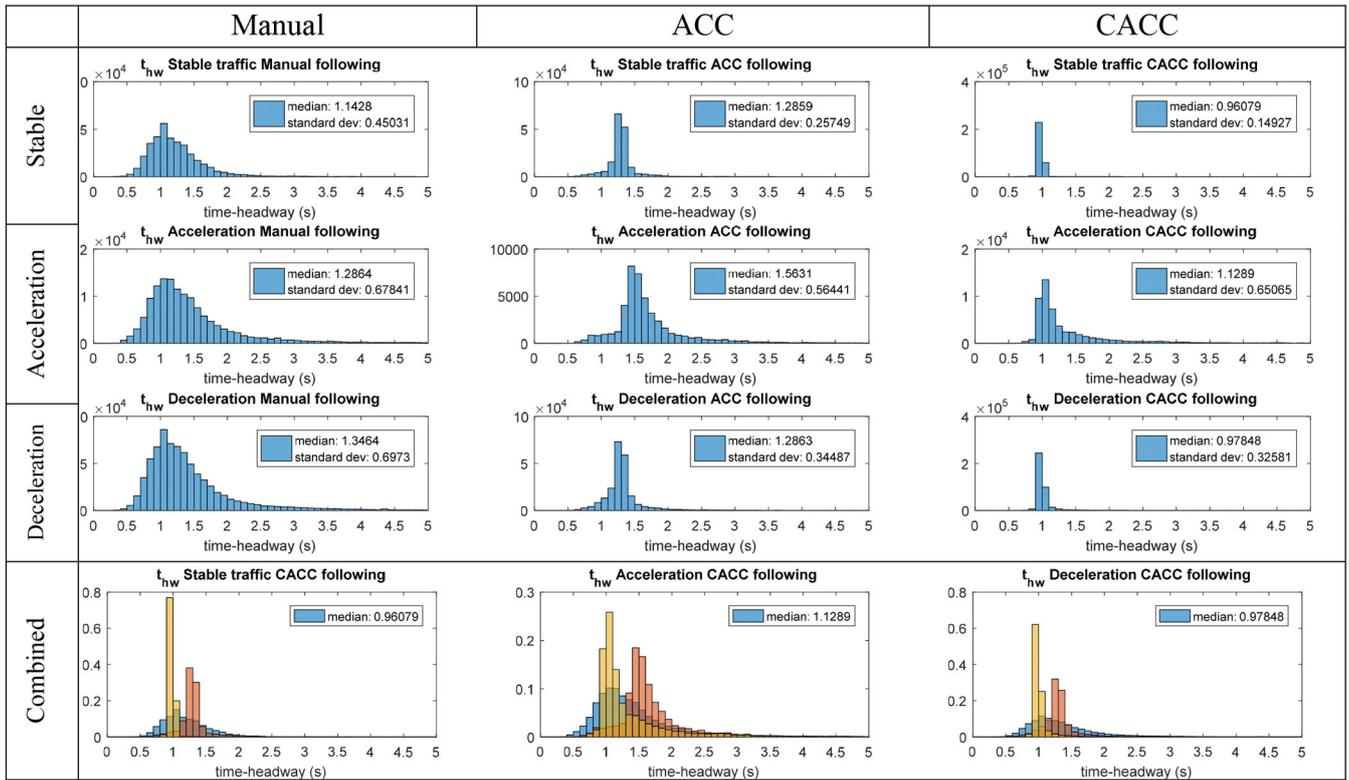


Fig. 2 Time headway distributions of manual, ACC and CACC active vehicles during the FOT

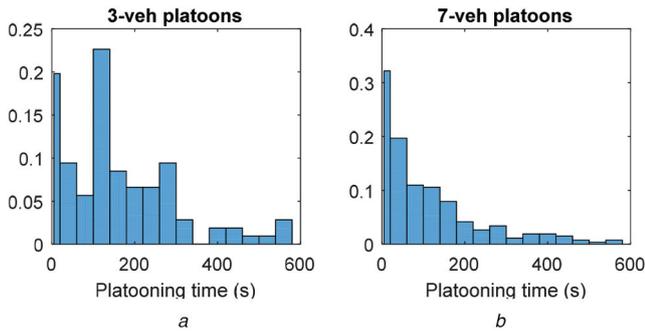


Fig. 3 Distribution of platooning time (normalised) for (a) Three-vehicle platoon runs, (b) Seven-vehicle platoon runs

In stable traffic, CACC vehicles have a significantly lower median time-headway than in manual mode, while ACC has a higher mean value than manual mode. The standard deviation for ACC is found to be much smaller than manual mode, while CACC mode yields an even smaller standard deviation. A similar pattern is also found for acceleration and deceleration of the vehicles, although the standard deviation is higher for all three modes out with stable driving, even though the standard deviation remains the highest for manual mode driving. Recall that the activation of (C)ACC took place manually when departing from a red traffic signal due to restrictions in the concession, which will have resulted in higher median time-headways for ACC and CACC when accelerating. The overall findings from the time-headways are therefore that driving with CACC active leads to shorter and more stable (less deviation) time-headways compared to manual driving. ACC on the other hand leads to longer time headways, although the spread of time headways is smaller. During acceleration and deceleration, there is a greater spread in values although the general trend in median values is pretty consistent between the three driving modes.

3.3 Platoon break-ups and cut-ins

3.3.1 Quantitative analysis: Qualitative analysis showed that most platoon break-ups occurred due to cut-ins from other vehicles. These other vehicles either momentarily cut-through a

platoon to then move on to a further lane, or were involved in a merge into a platoon and broke up a platoon over an extended period. Another reason for platoon break-ups was stopping for red signals at traffic lights, although these were much fewer. On occasions, manual disengagement is applied by the driver if a situation is deemed unsafe, which only occurred for the ACC scenarios.

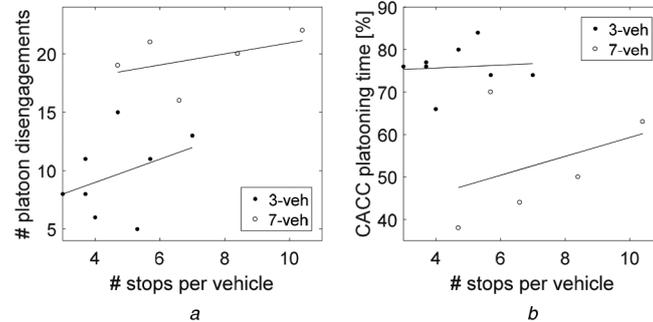
Comparison between FOT scenarios D and E [with(out) GTE] showed no significant difference in platooning time distribution. We define platooning time as the percentage of time during which vehicles are recorded as being in active CACC mode with a leading vehicle, which it is following. An average is taken over all applicable vehicles. In Fig. 3, the distribution of platooning time for the CACC enabled scenarios (D and E) for three- and seven-vehicle platoons are shown. Note that the platooning time of only the following vehicles are included, as the leader does not have the ability to drive in CACC-active mode (as there is no CACC leader). The platooning time for three-vehicle platoons is greater than for the seven-vehicle platoons. As a consequence of the longer platoon size, cut-ins occurred more regularly, which meant that platooning time was restricted in comparison.

Table 1 shows data on the time platooning percentage and the number of disengagements during the FOT for the ACC and CACC scenarios for both three- and seven-vehicle platoons. Again, this shows that vehicles in shorter platoons can maintain a longer time in CACC and ACC active mode, respectively, compared to the longer seven-vehicle platoons. The seven-vehicle platoons also incurred a higher number of disengagements per vehicle and were on average not able to platoon as long in between disengagements. The results from Table 1 are consistent and significant between scenarios, although there were differences found between individual FOT runs from the same scenarios resulting from differing traffic conditions and random arrivals at different traffic signal phases.

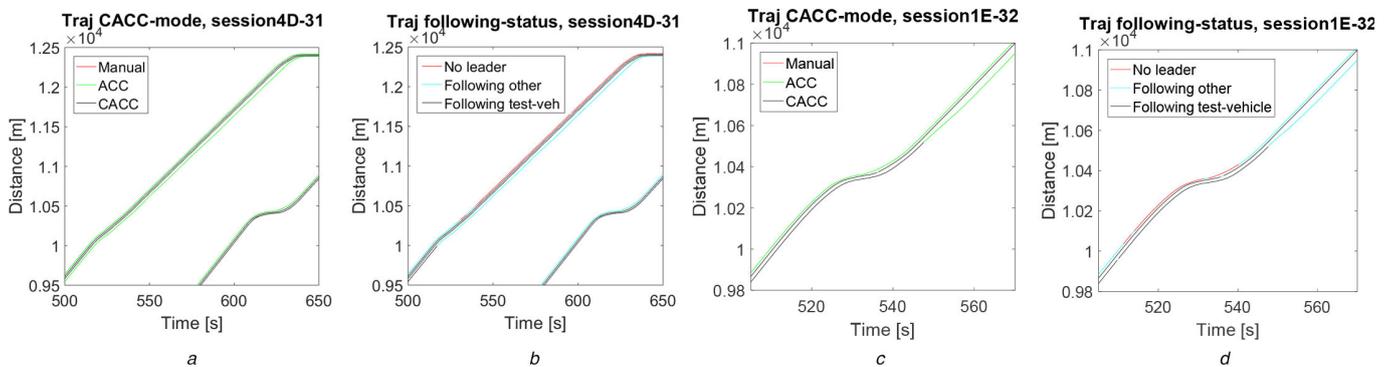
Comparison of the platooning time and the number of disengagements versus the number of vehicle stops in a run is shown in Fig. 4. A vehicle stop is counted if a vehicle is stationary for at least 1.0 s. The total number of vehicle stops in a run is divided by the number of test vehicles to get the values shown in the figure. This was tested to see if a greater number of vehicle stops (at intersections) influences the ability of the vehicles to

Table 1 Platooning time and number of disengagements per vehicle driving mode

Scenarios	No. test vehicles	time ACC, % time CACC, %	No. total disengagements	No. disengagement per veh	average platoon time, s
ACC	3	77	n/a	n/a	n/a
ACC	7	64	n/a	n/a	n/a
CACC	3	23	76	151	122
CACC	7	46	52	630	49

**Fig. 4** Platoon disengagements and platooning time versus average number of stops per run

(a) Platoon disengagements, (b) Platooning time

**Fig. 5** Trajectory plots of individual FOT runs

(a) Traj CACC-mode, session 4D-31, (b) Traj following status, session 4D-31, (c) Traj CACC-mode, session 1E-32, (d) Traj following status, session 1E-32

remain in a CACC platoon. The results show a slight trend that more disengagements are found when vehicles stopped more often during a run (Fig. 4a). This was the case for both the three- and seven-vehicle platoon runs. Interestingly, the platooning time appears to be slightly higher when more stops occurred during the FOT (Fig. 4b). This may be down to the test vehicles not becoming stretched out and having the opportunity to regroup at enforced stops.

3.3.2 Qualitative analysis: Analysis of the trajectory plots of the FOT scenario runs gives further insights into various phenomena that occurred during the FOT. This was especially the case with regard to platoon break-ups. We will run through a number of the most relevant insights from the qualitative analysis here and refer to Figs. 5–7 for the accompanying trajectory plots.

Most platoon break-ups occurred due to cut-ins. However, these occurred in different ways and had different consequences for platooning ability. Run 31 gives a very good example of this (see Fig. 5a). In this seven-vehicle platoon run, an early cut-in meant that the platoon had split early in the run and that the second group of test vehicles had missed a green phase that the first group had made, which meant that the test vehicles would not reconnect for the remainder of the run. Fig. 5b shows that a further cut-in occurred after a merge (see location 10,000 m), however the vehicle that is cut-in on remained only a single vehicle away from the rest of the platoon and was later able to re-join the platoon (not shown in the figure). Early split-ups occurred in a number of the seven-vehicle runs, often due to similar circumstances, which will have affected the platooning time of the test vehicles in these runs. This was rare in the three-vehicle runs, although cut-ins were still

observed, again often at merges, as was found for example in run 32 (see Figs. 5c and d) for a cut-in at a lane drop from 2 to 1 lanes. At this merge, one can also see that traffic slows at the merge before returning to their desired speed.

In another interesting run, the flexibility of having vehicles CACC-enabled without always being CACC active was shown. In run 28 (see Figs. 6c and d), the platoon had been split and the vehicle groups were now traversing the corridor in two different traffic signal phases. A single test vehicle from the second group made a green phase, while the rest of the test vehicles did not and that vehicle managed to catch up with the first set of test vehicles that were constrained in their free driving by a slower non-test vehicle. The test vehicle was able to recouple to the leading set of test vehicles and revert to CACC mode.

An interesting comparison between scenarios D and E and for busier and quieter traffic circumstances can be seen between run 23 (D and quieter) and run 33 (E and busier) in Figs. 6a and b. In both cases, the platoons approach the same intersection at which the traffic signals have turned to green. In run 23, the platoon is almost entirely unhindered and only needs to slow before the intersection as it approaches another vehicle, but after the intersection can proceed in free non-following mode with all test vehicles platooning. In run 33, the platoon stops for a short time at the end of the queue at the traffic signal. As vehicles merge after the intersection, at least two cut-ins occur and only two test vehicles can remain in CACC mode following a test vehicle. Also, the platoon is constrained by a non-test vehicle ahead and cannot proceed freely at its desired speed.

Finally, we consider the performance of ACC-active test vehicles. In general, similar cut-in behaviour was observed in

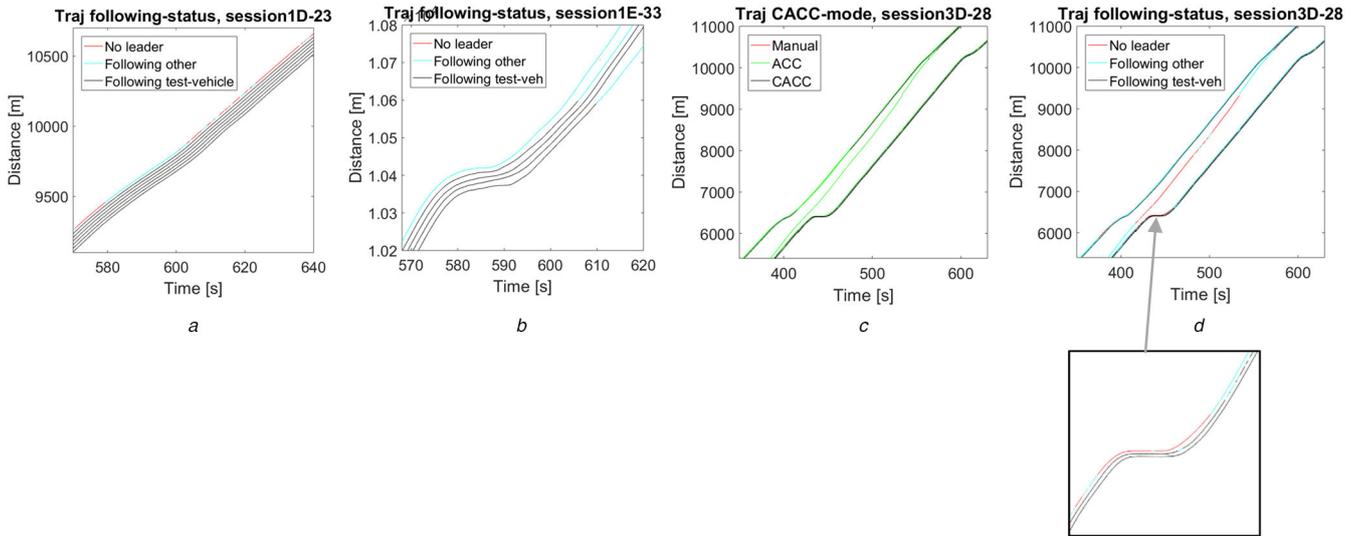


Fig. 6 Trajectory plots of individual FOT runs

(a) Traj following status, session 1D-23, (b) Traj following status, session 1E-33, (c) Traj CACC-mode, session3D-28, (d) Traj following status, session3D-28

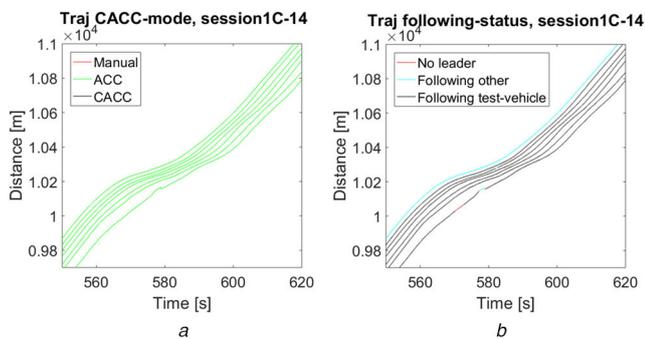


Fig. 7 Trajectory plots of individual FOT runs

(a) Traj CACC-mode, session1C-14, (b) Traj following status, session1c-14

comparison to the CACC scenarios (D and E). One marked difference we observed was a greater degree of instability in trajectories for the ACC scenarios. This can be seen in run 14 in Figs. 7a and b. Before, during and after the merge location, the car-following behaviour of the test vehicles shows oscillations that are not visible in the CACC trajectory data and shows a lesser degree of string stability for ACC compared to CACC mode driving. This behaviour is consistent for most of the ACC runs as well as more stable behaviour for the CACC runs.

Fig. 1 graphically demonstrates the string stability findings. It shows a scenario in which CACC enabled vehicles are driving in a platoon (the ACC vehicle prior to $t=550$ is the leading vehicle) and at a certain time ($t \sim 550$), one of the following vehicles reverts to ACC mode and starts to show string unstable behaviour. This in turn leads to the entire platoon reverting to ACC mode (for safety reasons). Especially during $t=700-780$, increasing speed oscillations can be viewed when all vehicles were in ACC mode prior to them returning to CACC mode. This same behaviour was viewed for the majority of ACC scenarios.

3.3.3 CACC disengagement locations: Although disengagement and platoon cut-ins occurred at many different locations, there were certain locations where this occurred more often. Fig. 1 shows a heat map of the geographical locations where this happened most. The locations with the highest numbers are those in the vicinity of the intersections, both before and after the intersections. These locations are where other vehicles perform a cut-through to get to a specific lane to turn off the main road prior to the intersection, and the merge locations after intersection when a lane drop occurs, forcing other vehicles to merge into the platoon.

3.4 Influence on traffic performance

Although the main focus of the FOT was on platooning performance, we also consider the effects on the traffic performance during the different scenarios to see if the experiment had any effect on the traffic throughput. Although the different scenario runs are performed during different peak periods, we cannot claim that each situation is identical, therefore, the results are indicative rather than definitive. The traffic performance is given as the mean and median travel time by all vehicles in all runs of a specific scenario (Fig. 8).

The results of the travel times are given in Fig. 9. Scenario E (CACC mode with GTE and TTG) shows a consistently shorter travel time compared to manual driving, however this result is not significant. From the other scenarios, it would not be objective to draw conclusions based on the results and we leave the results as an initial indication of potential effects without going any further. Further experiment using a far greater penetration rate of CACC vehicles would be required to find and draw conclusive conclusions on this point.

3.5 Summary of main findings

The FOT demonstrates that the use of CACC platooning on an urbanised arterial can be performed with shorter time-headways than under manual driving and that the vehicles can traverse the arterial homogeneously with minimal headway variation. This may be unsurprising as the CACC headway settings are also set lower than the average human driver would maintain, although the influence of other traffic and the infrastructure could have severely influenced this, however this seems to have been limited. In ACC mode, the vehicles showed a larger time-headway compared to manual driving, even though the spread of measurement values was narrower than manual driving. This is a likely consequence of a greater time delay from the controller in comparison to the shorter communications delay that is present for the CACC controller. A further finding from qualitative analysis is that the string stability of ACC driving was obviously and visually much poorer than that of CACC driving, a fact that was also indicated by the test drivers during the debriefing.

Although shorter headways could be achieved with CACC, we cannot conclusively derive conclusions from the FOT on the potential to improve traffic flow as the penetration rate of the test vehicles on the road was very limited. Also on such suburban arterials, the capacity through intersections rather than between intersections is the critical factor for traffic throughput, but this would also rely on a greater penetration rate to give conclusive results.

The ability to remain platooning differed based on the number of test vehicles in a FOT run. On average, vehicles in the seven-

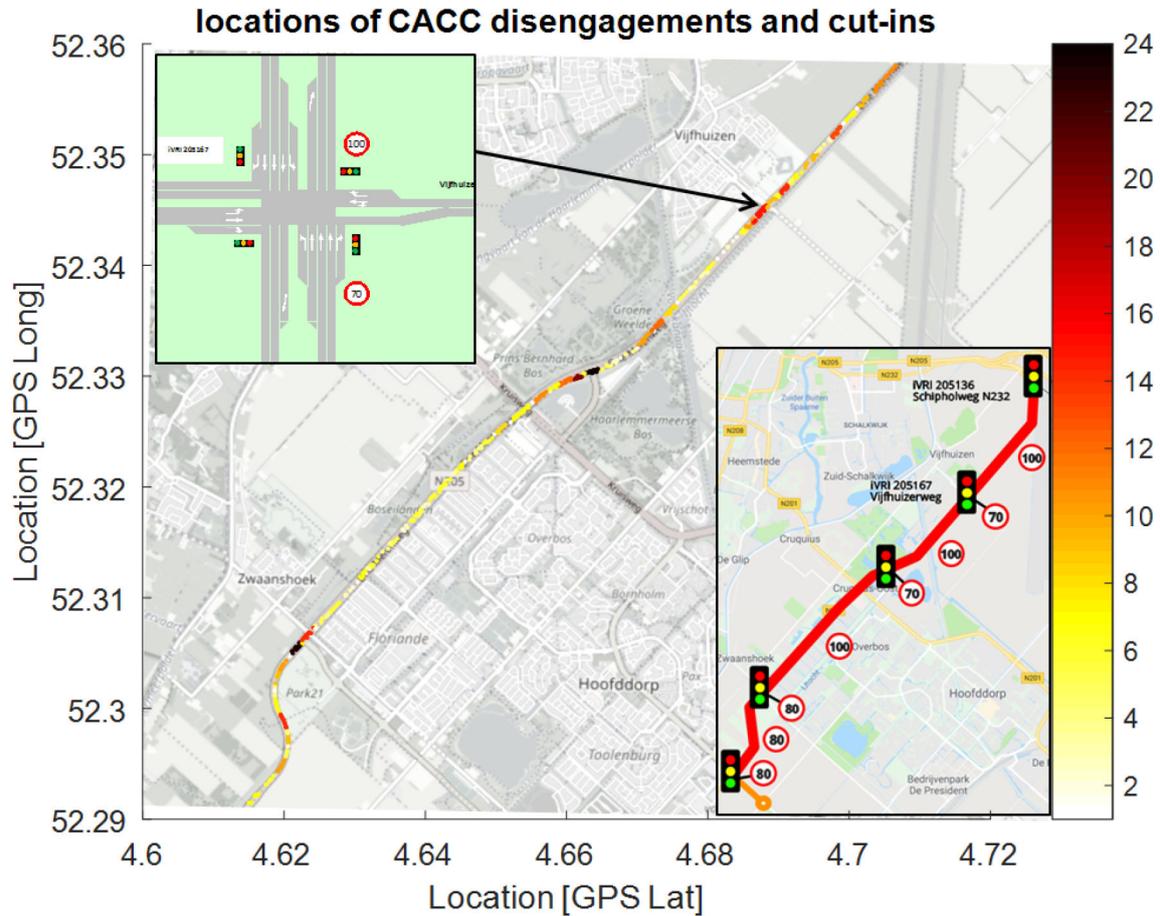


Fig. 8 Heat map of locations of CACC disengagements with additional corridor information (insets)

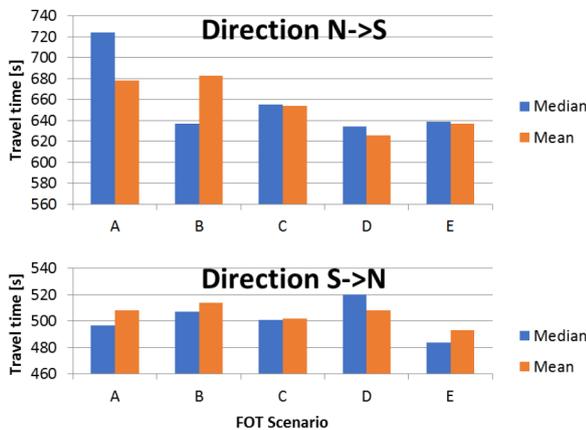


Fig. 9 Travel times of test vehicles per FOT scenario in both driving directions

vehicle platoons were not able to platoon as long as the three-vehicle platoons due to an increased chance of a platoon break-up. That being said, in many cases the seven-vehicle platoon would break-up into two smaller platoons that would often be able to continue to platoon. With the test vehicles remaining CACC-enabled, it would sometime be possible for the test vehicles to reconnect to a platoon, which demonstrates a certain degree of flexibility of the system.

The break-up of platoons occurred primarily due to cut-ins from other vehicles. These cut-ins occurred most frequently at the merge sections at lanes drops following an intersection and in many cases would result in a prolonged platoon break-up. Short-lasting break-ups also occurred prior to intersection due to other vehicles getting into their desired lanes, as the non-test vehicles would continue onto another turning lane. More disengagements were found in runs in which the platoon had fewer stops at intersections. If a platoon has to stop at an intersection, other traffic can gather

around it and the time required to traverse the intersection is also higher, which in turn seems to also increase the likelihood of cut-ins. However, stops at intersections also allow the test vehicles to regroup if traffic is not too heavy.

4 Discussion

The ability for vehicles to traverse a road in close proximity has been shown in other literature on motorways to lead to higher capacities [23, 24], while the speed of communication and vehicle reaction to changing traffic conditions has also been demonstrated as a potentially safe addition [25]. On the considered urban arterial road, we found that the use of CACC was feasible and made it possible for the CACC-enabled test vehicles to platoon over extended stretches of the corridor. Compared to motorway traffic, increased platoon break ups and cut-ins must be expected, nevertheless maintaining a flexible ability to platoon in CACC formation means that the use of CACC does not need to rely on maintaining a rigid platoon formation to see potential benefits that may occur from shorter time headways and faster inter-vehicle reaction times. From debriefing of the test drivers, indications were that they felt happy with the CACC performance and general overall safety as well. On a side note, this was very much in contrast to the use of ACC in the test. The test drivers indicated that they did not feel that the system was safe and effective when platooning in ACC mode, which resulted in manual deactivation in certain cases. Also when the data was reviewed, extensive oscillations were found indicating diminished string stability. ACC was never developed for urbanised road or arterials and therefore the outcomes should be no surprise and road authorities may want to consider the permission of ACC on arterials or urban roads, which is given as a recommendation for further research.

While the use of CACC is feasible, its benefits for traffic flow on urban arterials based on the FOT remains inconclusive. The main reasons behind this are the characteristics of arterials with controlled intersections that mean that it will often be the

intersections that dictate traffic throughput rather than the free driving sections, which is where CACC has its greatest positive effects on motorways. The penetration rate of the CACC in the FOT was very low, which does not allow any conclusive results to be gained on the influence on traffic flow. The travel times of the CACC-active vehicles also do not give any indications in this regard as they are also constrained by other non-CACC vehicles on the corridor. Additional experiments using a far greater penetration rate of CACC vehicles would be required to find and draw conclusive conclusions on this point.

Although testing of the use of ITS was also part of the FOT, its effectiveness was limited and therefore also the conclusions that could be reached. As previously stated, this was mainly due to the traffic signal using a dynamic control strategy, which led to a changeable and therefore poorly reliable TTG indication for the vehicles. Test vehicles also being constrained by non-test vehicles played a role in this too. With intersection capacity playing a dominant role in the traffic throughout, these issues would need to be addressed if improved traffic throughput is to be the main goal. Further research into the required levels of CACC penetration as well as consideration of practical application of ITS with CACC is required to give greater clarity. How to setup and properly account for non-CACC vehicles using ITS such that the entire traffic system benefits also requires addition thought and testing in future research.

5 Conclusions

A unique FOT of CACC enabled vehicles on an arterial corridor with other traffic was performed to give insights into the feasibility and performance of the use of CACC on (sub)urban arterials. The findings from the FOT found that CACC on such an arterial is feasible and that CACC vehicles can operate well under such conditions. They are able to platoon at lower time-headways than human driven vehicles and, even when platoon break-ups occur, are able to reconnect and proceed platooning. Many platoon break-ups are unavoidable and especially took place near to intersections, where vehicles are required to merge or need to change lanes to turn off the main corridor. It was not possible to derive potential traffic flow improvements from the FOT, in part due to a limited overall penetration rate, and in part due to no recognisable improvements in intersection capacities, which are dominant on urban road for traffic throughput. Further research is required on ways to effectively implement ITS to communities with CACC vehicles to improve intersection and traffic throughput. Much of this will depend on finding a good balance between prioritisation of CACC versus manual driven vehicles and clear communication. A further finding was that ACC vehicles are not suited for such arterials and some consideration should be given to their potential prohibition in (sub)urban road.

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