

Platoon of SAE level-2 automated vehicles on public roads: setup, traffic interactions, and stability

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ABSTRACT

An increasing amount of the vehicles is equipped with driver assistance systems; many of the vehicles currently on the market can optionally be equipped with adaptive cruise control and lane centering systems. Using both systems at the same time brings the vehicle to SAE level-2 automation. This means a driver does not need to perform longitudinal and lateral operational driving, although the driver should be ready to intervene at any time. While this can provide comfort, the interaction between vehicles operated by these systems might cause some undesired effects. This becomes particularly relevant with increasing market penetration rates. This paper describes an experiment with 7 SAE level-2 vehicles driven as a platoon on the public road for a trip of almost 500 km. The paper discusses how the experiment was organized, the equipment of the vehicles. It also discusses the interaction of the platoon in traffic, as well as – in basic terms – the interaction between the automated vehicles. The experiences can be useful for other studies setting up field tests. The conclusion from this platoon test is: intentionally creating platoons on public roads is difficult in busy traffic conditions. Moreover, interactions between the vehicles in the platoon show that the current SAE level-2 systems are not suitable for driving as platoons of more than typically 3-4 vehicles, due to instabilities in the car-following behavior.

Keywords: Platoon, Adaptive Cruise Control, Field Test, Public Road Experiment, Platoon stability, SAE-level 2 vehicles.

1 INTRODUCTION

Vehicle automation has attracted considerable attention in recent years, since automated driving systems (ADSs) take over part or all of the driving tasks which may fundamentally change the way the current traffic system is operating (1, 2). Depending on the involvement of the driver in the tactical and operational driving tasks, ADSs can be classified into 5 levels of automation (3). Based on the use of communication technology, ADSs can be classified as autonomous and connected/cooperative systems. Autonomous automated vehicles (AAVs) rely solely on on-board sensors, such as radar and lidar (4, 5, 6, 7) and do not cooperate with other vehicles in the decision-making and control process. Connected/cooperative automated vehicles (CAVs) exchange (state and control) information with each other via Vehicle-to-Vehicle (V2V) communication or with road infrastructure via Vehicle-to-Infrastructure (V2I) communication to improve situation awareness and/or to maneuver together under a common goal (4, 8, 9, 10).

Adaptive Cruise Control (ACC) is the earliest autonomous vehicle system with level-1 automation, which is designed to enhance driving comfort (8, 11, 12). When there is no vehicle in front, the ACC system regulates the vehicle speed to match a user-specified desired speed. When constrained by a preceding vehicle, the system tracks the predecessor with a user-specified desired time gap. To be able to operate in full speed range, the system is often combined with a longitudinal collision avoidance system (13). This system has shown platoon instability property that increases the probability of traffic flow breakdown due to time delay (14, 15, 16).

ACC systems are becoming a standard equipment on med-price and high-end passenger cars. Integrating ACC system with a lane keeping system that takes over the steering from drivers to automate the lateral control of the vehicle leads to level-2 ADS (L2-ADS), which is available in premium passenger cars. With the reduction of cost of advanced sensors and technologies, L2-ADSs are expected to penetrate the market in the coming years to a broader vehicle population (17).

Parallel to the fast development of ADSs, concerns over their impact on traffic safety and traffic flow have been raised. Recent crashes involving ADSs in production vehicles or tested vehicles caused quite a stir the media concerning the capabilities of the systems. To understand and assess the impact of ADSs on traffic systems, field tests with ADSs are becoming increasingly necessary.

Several field tests have been conducted to prove the technical feasibility of individual AAVs. Notably, the DARPA Urban Challenge was organized to test whether highly automated driving systems developed by several universities can indeed maneuver under controlled urban scenarios (18). While acknowledging the effects of such tests on the development of individual AAVs, it is difficult to gain insights on the impact of such systems on the collective traffic systems.

Theory and simulation have shown the potential for CAVs to be beneficial collective traffic operations. Field tests with CAVs have attracted considerable attention. Back in the 1990s, research on Automated Highway System culminated in a demonstration of a platoon vehicles equipped with communication and magnetic sensors (19). There were concerns about the amount of funding to upscale this to a full-scale system, related to building separated lanes.

Multiple Cooperative ACC systems (level-1 automation) were built and tested as part of the Grand Cooperative Driving Challenge (GCDC) held in the Netherlands in 2011 (20). 9 teams from 11 universities and industry partners participated in the competition in controlled urban and freeway environment. This was followed by the iGAME challenge in 2016 to test cooperative

maneuvers in addition to longitudinal control (21).

From 2009 to 2012, the European Commission funded the Safe Road Trains for the Environment (SARTRE) project to study platooning in the mixed heavy and light vehicle case (22). The SARTRE project examined the potential impacts that platooning might have on infrastructure requirements. In 2016, the European Truck Platooning Challenge brought together several OEMs and industrial partners for long-distance truck platooning in public highway in light traffic conditions. Similar test have been conducted under the COMPANION project (23) and the Japanese Energy ITS project (24). These tests showed that infrastructure owners and operators have concerns on difficulties that cooperative CAV platoons could bring to other vehicles, especially at freeway entrance/exit sections.

In recent years, PATH tested a four-vehicle platoon with ACC and CACC (Cooperative ACC) systems on the public roads(14). Based on the data collected from the test, the first calibrated car-following model for ACC and CACC systems was presented (14). CAVs have also been proposed in speed harmonization application (25). This concept was tested in real world (26), demonstrating the effectiveness of CAVs on improving traffic operations.

Despite the considerable efforts to prove the technical feasibility and concept of CAVs, there are uncertainties about the extent to which V2V/V2I communication will penetrate in the vehicle population. The scenario with increasing AAVs on public road without communication is still a likely future. It is of paramount importance to understand the collective impact of such systems on traffic flow and safety via field tests. In the spirit of this, a platooning test was conducted in 2015 on a closed test track in the Netherlands (27). This test showed that a platoon of modern ACC systems driving together on a highway does raise concerns over safety, caused by amplification of braking disturbance. Unfortunately, the measurements from this test are very coarse and the analysis remained mainly at a conceptual and qualitative level for level-1 automated driving systems.

The aforementioned literature review motivated the new test with a platoon of level-2 ADSs on public roads with interaction with surrounding traffic in naturalistic environment. The goal of the paper is to present the preparations for such a trip in general (section “preparations”), and to show the details on the trip we have been organizing in particular (from section “platoon trip of 13 June 2018”). The experiment consisted of 7 SAE-L2 vehicles driving (as much as possible) as a platoon on the public road for a trip of almost 500 km. The paper continues with sections on the interaction of a platoon in traffic and on the interaction between the automated vehicles. These analyses focus on the longitudinal operations of the automation, i.e. the car-following part. The paper ends with conclusions and discussion. The experiences can be useful for other studies setting up field tests. The data collected gives some insights into the potential impact of such systems on traffic dynamics.

2 PREPARATIONS

In this section, we describe the preparations for a field operational test. First, we describe the organizational efforts required for the organization of such a large-scale platoon test on public roads, then we comment on the vehicles and the data.

2.1 Organization

The organization of the test involved different parties. First of all, the drive had to be accepted by the road authorities and the police. The road authority itself, as well as the Netherlands Vehicle Authority, were eager to know the effects of vehicle automation systems, and were willing to cooperate.

With their help, exemptions were issued for various regulations, which all related to the way the platoon could stay together in one lane under the European directive of "keep right unless overtaking". This means that a driver is supposed to keep the rightmost lane, unless he overtakes its leader, after which he is supposed to go back to the right. This frequent lane changing of vehicles in the platoon will dissolve the platoon. Therefore, the desired situation was that the platoon could make use of the left lane (if the platoon was using the right lane, other drivers would cut into the platoon for entering or leaving the freeway). Driving in the left (fast) lane also justifies that the platoon would need to maintain a speed exceeding the speed limit, since otherwise, the platoon would block the (fast) traffic in the left lane.

Two exemptions were granted: (1) Exemption of the "keep right unless overtaking" rule, which means that the platoon could stay in the left lane, even in quiet traffic conditions. (2) Exemption of the speed limit within bounds. The platoon would drive typically 10 km/h over the speed limit. The police were informed on the planned test, the route, and the relevant exemptions.

The location of the platoon was included in the traffic reports (its dynamic location was tracked using the GPS units in the vehicle). Also the Waze traffic information app (in the Netherlands popular) notified other users were on the fact that a platoon was passing. The idea behind the information was that the platoon would stay more intact (less cut-in behavior) than without this publicity. Its effectiveness is hard to check: it is unclear what would have happened without this publicity. Subjectively, the participants in the platoon never got the impression that it was counter-productive: i.e., no observations were made about drivers cutting in on purpose and "testing" the platoon.

2.2 Vehicles and data

The test was carried out with passenger cars of various brands/types:

- 3 BMW 530i (2017 model, BMW code G30)
- 2 Mercedes E-class (2017 model, Mercedes code W213)
- 1 Audi A4 (2017 model, Audi code B9)
- 1 Tesla Model S (2017)

All cars are equipped with the most advanced systems of driver support that were at the time of production (optionally) available for customers on the market. In fact, the vehicles were selected based on their (advertised) relatively high level of driver support systems. All vehicles are up to level-2 SAE automation (3). The system is able to perform sustained longitudinal and lateral control of the vehicle under its operational design domain. That means that the vehicle can be driven "hands off" in some conditions (here we focus on freeway use), but the driver is supposed



FIGURE 1 A part of the platoon on the road

to monitor the traffic and the vehicle and performs the object and event detection and response (OEDR) He must be ready to take over the vehicle control immediately if the situation requires so.

In practice, we can identify two systems which take care of the vehicle control:

- Adaptive Cruise Control (ACC). A desired speed is set for the vehicle and the vehicle will drive at the set speed, but reduces speed for other vehicles ahead which drive at a lower speed.
- Lane centering systems (LCS). The vehicle observes the lanes on the road and steers the car to keep it within the lane.

The order of the platoon was varied a couple of times at breaks during the trip. In all cases, the Tesla was used as lead vehicle (due to its high-tech image the organisation choose so for media coverage). Vehicles of the same type were mostly running one after another. Figure 1 shows the platoon.

2.3 Instrumentation

Apart from the OEM vehicle sensors, the vehicles have been equipped with further sensors; all of them are logged where ever possible. Retro-fitted instrumentation consists of a high-resolution Global Positioning System (GPS), and a Mobileye stereo camera. This Mobileye cameras provides data on objects in front of the vehicle (distance, speed) and on the own vehicle's lane position and the time and distance headway to the preceding vehicle. Moreover, there are 8 cameras looking inside and outside the vehicle, observing the driver, the dashboard and the surrounding traffic. The data logged from the CAN-bus varies for each of the different vehicle types. Broadly speaking, we sought CAN-bus data related to the status of the vehicle automation systems (settings and activation/deactivation), the vehicles movements (longitudinal and lateral; speeds and accelerations) and some additional signals such as the status of the indicator lights and wind shield wipers. The data fields which are available from the sensors are shown in table 1. Due to IT errors, some data are missing – sometimes a variable is missing for a few seconds or minutes; some data are missing for the whole day due to a loose connector. The latter causes by far most of the data loss. On average, we reckon at least 75% of the data are present. We looked into accuracy of positions and speeds. Positions seem to be accurate well within the order of vehicles in the platoon: we could

Sensor	Data	CAN bus field	Tesla model S	Audi A4	Mercedes E	BMW 530i
GPS	GPGGA					
GPS	GPGLL	ACC-Status				x
GPS	GPGSA	LIM-Status				x
GPS	GPRMC	SteerOverride	x			
GPS	GPVTG	acc-override		x		
GPS	datalogger-id	EnableAutosteer			x	
GPS	day	Lowbeam-Status			x	
GPS	elevation	acc-follow-distance			x	x
GPS	fix	acc-state		x	x	x
GPS	hour	acc-state-enum		x	x	x
GPS	latitude	acc-state-raw		x	x	x
GPS	logtime	acc-status		x	x	x
GPS	longitude	acc-status-enum		x	x	x
GPS	midnight	acc-status-raw		x		x
GPS	minute	brake-position			x	
GPS	month	cc-set-speed			x	x
GPS	msecond	engine-rpm			x	x
GPS	second	acc-follow-distance	x			
GPS	speed	brake-light-status	x	x		
GPS	synctime	brake-light-status-enum	x	x		
GPS	year	brake-light-status-raw	x	x		
		brake-position	x	x	x	x
IVCP	acceleration-x	button	x			x
IVCP	acceleration-y	button-enum	x	x		x
IVCP	acceleration-z	button-raw	x	x		x
IVCP	datalogger-id	gearbox-position	x			
IVCP	logtime	gearstick-position	x	x	x	
IVCP	midnight	gearstick-position-enum	x	x	x	
IVCP	synctime	gearstick-position-raw	x	x	x	
IVCP	voltage	indicator-left-status	x	x	x	x
		indicator-left-status-enum	x	x	x	x
MobilEye	datalogger-id	indicator-left-status-raw	x	x	x	x
MobilEye	logtime	indicator-right-status	x	x	x	x
MobilEye	midnight	indicator-right-status-enum	x	x	x	x
MobilEye	number-of-obstacles	indicator-right-status-raw	x	x	x	x
MobilEye	synctime	lks-state		x		x
		lks-state-enum		x		x
VCIL-TO-MOBILEYE	brake	lks-state-raw		x		x
VCIL-TO-MOBILEYE	datalogger-id	lks-status		x		x
VCIL-TO-MOBILEYE	left-blink	lks-status-enum		x		x
VCIL-TO-MOBILEYE	logtime	lks-status-raw		x		x
VCIL-TO-MOBILEYE	midnight	steeringwheel-angle	x	x	x	
VCIL-TO-MOBILEYE	right-blink	throttle-position	x	x	x	
VCIL-TO-MOBILEYE	speed	vehicle-speed	x	x	x	
VCIL-TO-MOBILEYE	synctime	wiper-status				x
VCIL-TO-MOBILEYE	wiper					

TABLE 1 The available data fields. The first column is available from external sensors and is present at all vehicles. The CAN bus data depends on the brand and make of the vehicle. Dynamic variables are typically recorded at 10Hz. The abbreviation LKS stands for Lane Keeping System, which has been used for the lane centering systems of the vehicles.

follow positions within the platoon. Moreover, we plotted the positions of a individual vehicle on a map positions every 0.1 second (repeated for various vehicles). From the trace (distance between the points and lateral deviations) we reckon we have an accuracy within a few meters. Speeds accuracy was derived from redundant speed loggings (CAN bus, and various GPS loggings), and is estimated to be accurate to approximately 1 km/h correct, with a time shift of several seconds depending on the logging device.

Some of the fields need further clarification. Unfortunately, not all data relevant for analysing

TABLE 2 Available data

Property	Tesla	Audi	Mercedes		BMW		
			1	2	1	2	3
ACC system (de)activation	No	Yes	No	No	Yes	No	Yes
Manual/automated throttling	Yes	Yes	No	No	No	No	No

**FIGURE 2 The route driven**

the status of the ACC system is logged for each vehicle. Table 2 indicates which data are available per vehicle. First, it shows whether the ACC status (on or off) is present. Even then, it is not clear whether ACC fully governs acceleration and deceleration. Namely, for some vehicles, the ACC status does not change if the driver overrules the ACC system with additional throttle. Moreover, the “throttle status” signal cannot always differentiate this additional throttle from ACC throttle action. Whereas other data (video footage of the dashboard and the drivers feet) can still be fused with the numerically collected data, this is a limiting factor with the data set currently available for analyses. The data set of the Audi is most complete and will be used to verify reported experiences of the participants in the test. Moreover, it means that the analyses being done in this paper will be limited to testing platoon effects at a basic level, based on the speed, which is present for all vehicles.

3 PLATOON TRIP OF 13 JUNE 2018

The route was a 465 km long stretch from the city of Groningen to Amsterdam, and then on to Eindhoven and Rotterdam; figure 2 shows the GPS trace on a map. The platoon testing focused on the freeway segments of the stretch. Only approximately 10 km of the trip consisted of non-

freeway driving. The trip took place on 13 June 2018, and started at around 7.30 am and ended around 5 pm in Rotterdam. Stops were made at the Amsterdam soccer stadium (“Johan Cruyff Arena”) and the Eindhoven/Helmond Automotive Campus. The average driving at freeways speed was similar to the other traffic (see also texts below). Different traffic conditions (congested, free flow) were encountered during the test drive. Weather conditions were good (no precipitation).

The vehicles are part of a larger test on naturalistic driving with SAE level-2 vehicles. In that test, individual drivers use the vehicles regular basis for a prolonged period of time (3 months per driver). Seven of these vehicles and drivers have been brought together for our test drive.

When the drivers began using their vehicle – typically several months earlier – the drivers have received training on how to use the assistance systems by *Prodrive*. The company is specialized in training drivers to drive with driver assistance systems. Their experience is that in 70% of the cases, owners of cars with drivers assistance systems do not use the assistance systems correctly. The drivers in the test drive have had training and have gained familiarity with the systems over a period of several months. Therefore, they could be expected to be able to use the systems safely and without any unfamiliarity which might hamper the operation of the car or systems.

Specially for this test drive, additional instructions to the drivers were to:

1. stay in the left lane, in order to keep the platoon intact and avoid that others make mandatory lane changes (from and to the off ramps) into the platoon;
2. switch on ACC and LCS, and let the vehicle determine the position in the lane, as well as the speed;
3. set the ACC to the closest distance setting in order to prevent as much as possible that other vehicles cut into the platoon;
4. set the desired speed of the ACC to a speed exceeding the leader’s speed to ensure that the vehicles would remain as a platoon.

To navigate through traffic with a 7-vehicle platoon requires special skills and driving techniques. This is not part of the usual driving behavior. To ensure the best platoon formation and to keep the platoon intact, a professional driving trainer from *Prodrive* was present in each car as co-driver.

All vehicles were equipped with portable radio transceivers (“walkie-talkies”). This allowed communication between people in the various vehicles up to a inter-vehicle distance of approximately 500-1000 m. Information on traffic situations or platoon forming and other actions could be communicated via the trainer. The information given over the radio would reach all vehicles simultaneously. In cases where the reach of the radio transceivers was insufficient, for instance from the first to the last vehicle, the message was passed on by one of trainers in the middle of the platoon. From there, the radio transceiver had sufficient reach to both ends of the platoon.

Behind the platoon was a vehicle of the organization, also equipped with a radio transceiver. The driver of this vehicle could instruct the drivers of other vehicles. He could report on relevant traffic events which become visible from the back. For instance, a police officer wanting to overtake and speed variations which became too severe were reported.

4 INTERACTION WITH OTHER VEHICLES

In this section, we discuss the interactions with the other drivers (i.e., not part of the platoon) during the trip. We first give general observations; the second subsection indicates the procedure followed to change lanes with a platoon.

4.1 General observations

The following was observed during the drive:

- The platoon needed to drive at least 10 km/h above the speed limit. If the speed of the platoon was lower, the platoon would form a moving bottleneck. Moreover, in quieter traffic conditions, other vehicles started to – unlawfully in the Netherlands – overtake the vehicles on the right.
- Other vehicles did cut in, even though the following distance was set to small (effective distance varies between vehicle brands). It should be noted that capacity values in the Netherlands are high, so drivers are used to small headways in normal conditions. (The Dutch Highway Capacity Manual (28) reports a capacity for a 2-lane freeway of 2150 veh/h/lane, equaling a average gross time headway, i.e. the time a vehicle takes to get to the same position as its predecessor, of 1.67 s.) The smallest ACC headway setting is hence not considered as very small headway.
- Even though there was an exemption of the keep right rule for the platoon, this was most likely not communicated to all officers. A military police officer on a motorbike directed all cars sequentially to the lanes further right. After he had passed, the platoon reclaimed its position on the left lane.
- It was undesirable that other vehicles would change lanes somewhere into the platoon; therefore all vehicles used the smallest headway setting available (the actual value might vary per brand). Even this small headway settings would not prevent cut-in. Cut-in lane changes could also be avoided by driving behavior. When it was expected that a driver in the adjacent lane (on the right) had a desire to make a lane change, the potential follower in the platoon would change its in-lane position. The driver overruled the LCS and drive to the right in its own lane; this would make the vehicle appear closer to the potential lane changing vehicle, and which could prevent a lane change in many cases.
- While drivers tried to rely the vehicle systems as much as possible, sometimes manual intervention was needed (for instance for lane changing, braking or catching up). This was very limited. For one vehicle (the Audi), we checked the amount of driving in each of the following situations: (1) ACC determines acceleration/deceleration, (2) ACC off, (3) ACC on, but overruled by throttle. Table 3 shows the time the system has been used. For the vast majority of time (98%) or distance (99%), the ACC system determined the acceleration and deceleration. The test drivers did not reveal any reason that considerably different values would be expected for other vehicles.

TABLE 3 Usage of the ACC system on the freeways

	ACC determines acceleration/deceleration	ACC off	ACC on, overruled by throttle
Time	4h12min	5 min 20 sec	6 seconds
Fraction of time	98%	2%	0.04%
Fraction of distance	99%	1%	0.03%

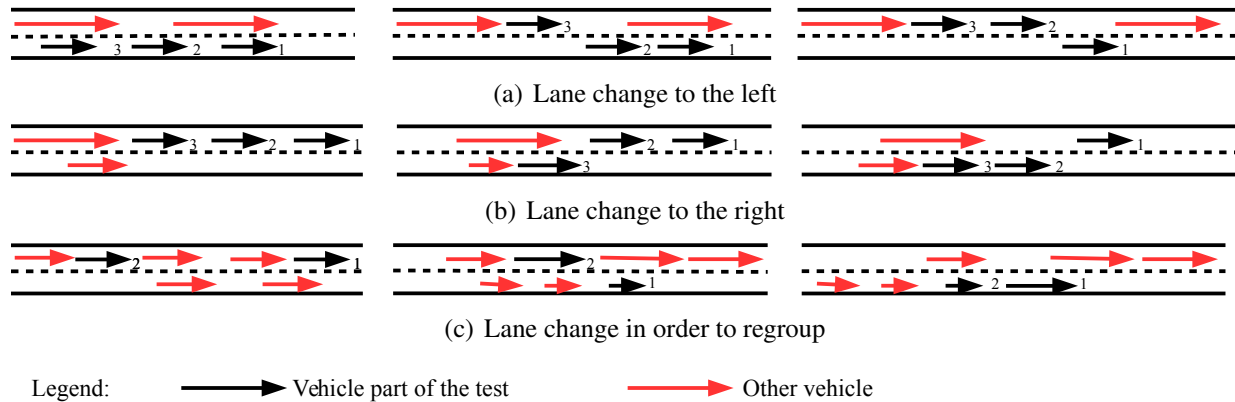


FIGURE 3 Schematic overview of the lane change manoeuvres. The size of the arrows represents the speed of the vehicle. Within a subfigure, the numbers indicate the same vehicle at different time instances.

Studies by the Netherlands Vehicle Authority showed that motor bikes were not always detected by ACC systems when they were driving close to or on the lane markings (29). This has been further tested during the drive. Two motor bikers from the national biking association joined the platoon for a part of the drive and tested the vehicle's ability to detect them in various positions on the road. In short, all vehicles detected the bikes in all positions. When releasing the throttle, a motor bike yields a higher deceleration than of a car due to its lower mass. This would yield an acceleration which was amplified throughout the platoon. A speed reduction without braking from 100 to 80 km/h would yield speeds of 40 km/h for the last vehicle in the platoon (see also section "Interaction between the vehicles").

4.2 Lane changing of the platoon

Changing lane with the platoon as one entity to another lane requires special attention. Note that this was seldom needed, since the platoon used the left lane. However, when entering the freeway from the onramp (at the right), or when leaving, it was needed. Here, we discuss the ways used to change lanes.

The following procedure was used to change to the left (see figure 3a). First, the last vehicle in the platoon would make a lane change to the left. He would continue driving until he reached the next vehicle (seen from the upstream end of the platoon), which then merged in front. For lane changes to the leftmost lane, this works well, since no-one is expected to overtake on the right and no-one should hence be able to cut-in between. For lane changes to the right, a similar procedure was followed (see figure 3b). First, the last vehicle in the platoon would change to the right lane.

Then, the second to last vehicle would slow down as much as necessary to merge right in front the last vehicle, etc.

Lane changing was also sometimes needed to regroup the platoon. This would be the case if there were (too many) vehicles which merged into the platoon, possibly drivers with a higher desired speed which would cut into the platoon and which would afterwards not leave the left lane. If this was the case, the platoon would regroup in another lane (see figure 3c), using an inversed lane change manoeuvre. This means that the first vehicle in the platoon would first move one (or more) lanes to the right. The second one stays in the faster left lane until it has reached the position right behind the first one and changes lanes to obtain the position right behind the first one. This is done sequentially for all vehicles in the platoon until the platoon is complete. Then, the platoon would change back to the left lane. If there are many vehicles in between, the best is to regroup in the rightmost lane, it is possible to drive there at a considerable lower speed than traffic, which would make it unattractive for other vehicles to merge in. Besides, at low speeds, it is easier to catch up because speed differences are higher if the vehicles that need to hold back drive at a lower speed in the rightmost lane.

5 INTERACTION BETWEEN THE VEHICLES

In this section we discuss the platoon stability, followed by the fuel consumption.

5.1 Platoon stability

Pueboobpaphan and van Arem (30) defines different levels of stability. Platoon stability indicates whether disturbances (speed fluctuations) would increase or decrease when moving from one vehicle to the next in a platoon (also known as string stability). Note that different quantifications and definitions exist, see Ploeg et al. (7). For the sake of simplicity, and to limit the influence of missing (visible by appearing and disappearing lines) and noisy data, in this paper we follow the definition of Pueboobpaphan and van Arem (30). We hence only consider fluctuations in speed, on which we apply a basic, largely qualitative, analysis. We acknowledge that there are more elegant ways to analyse the string stability properties of the ACC and CACC controllers, e.g. (31).

Figure 4 shows the speed of various vehicles over time for different time windows. The time windows have been selected to illustrate typical effects; these patterns can be considered representative for the whole road trip. Different colors are different vehicles. The speed of the platoon leader is shown as bold line. Figure 4a shows that the platoon leader has almost constant speed for longer periods of time, which changes every now and then – when the cruise control is set to another speed. Obviously, the other vehicles follow later. More importantly, there are fluctuations around the set speed for the following vehicles. This later and amplified response to a change to a new set-point for the speed of the leader is also seen in figure 4b. Where the leader reduces his speed from approximately 105 to 95 km/h, two vehicles in the platoon reduce their speed to around 75 km/h before settling to a higher speed again. This shows that the platoon is platoon unstable according to the definition of Pueboobpaphan and van Arem (30).

A more extreme example of this is shown in figure 4c. There is a reduction of speed by the leader from 100 to around 70 km/h. The followers reacted more strongly, such that the minimum speed of the last vehicle in the platoon of the followers drops to approximately 40 km/h. These low speeds are the consequence of a multiple times amplified reaction by each of the vehicles

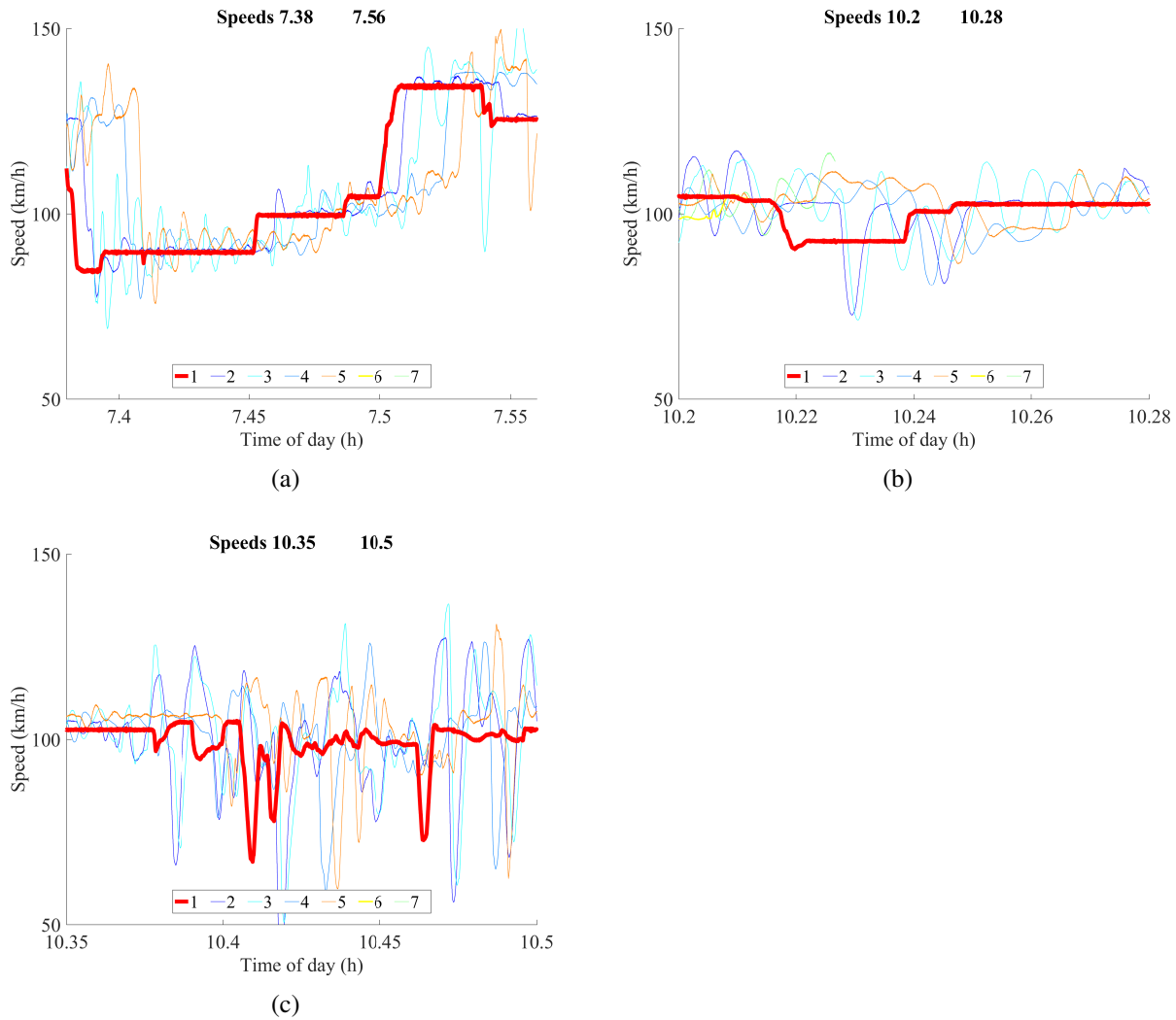


FIGURE 4 Fluctuation of speeds for various vehicles in the platoon. The number is the position of the vehicle in the platoon; the platoon leader is plotted in bold. The same color denotes the same vehicle.

in the platoon. This could cause dangerous situations on the freeway, since other drivers do not expect these low speeds in free flow conditions. The same situation has happened at another location where a vehicle in front of the platoon reduced speed to 80 km/h when entering a tunnel. Following vehicles would reduce speeds further and further, such that the last vehicle drove less than 40 km/h. This happened in free-flow traffic conditions. The follower behind the platoon was not expecting this speed decrease, which provided a dangerous traffic situation especially given that it was happening in a tunnel. Clearly, the effects caused with this 7-vehicle platoon are undesirable, for safety and comfort. Judged by the speeds and reported comfort level of drivers in the vehicles during the test, platoons of more than 3-4 vehicles become undesirable.

The most dangerous situations occurred with changing speeds of the leader, in particular if the leader would reduce speed, accelerate, and reduce speed again. The consequence was that the vehicles further in the platoon would reduce speed more than the leader, and in order to catch up

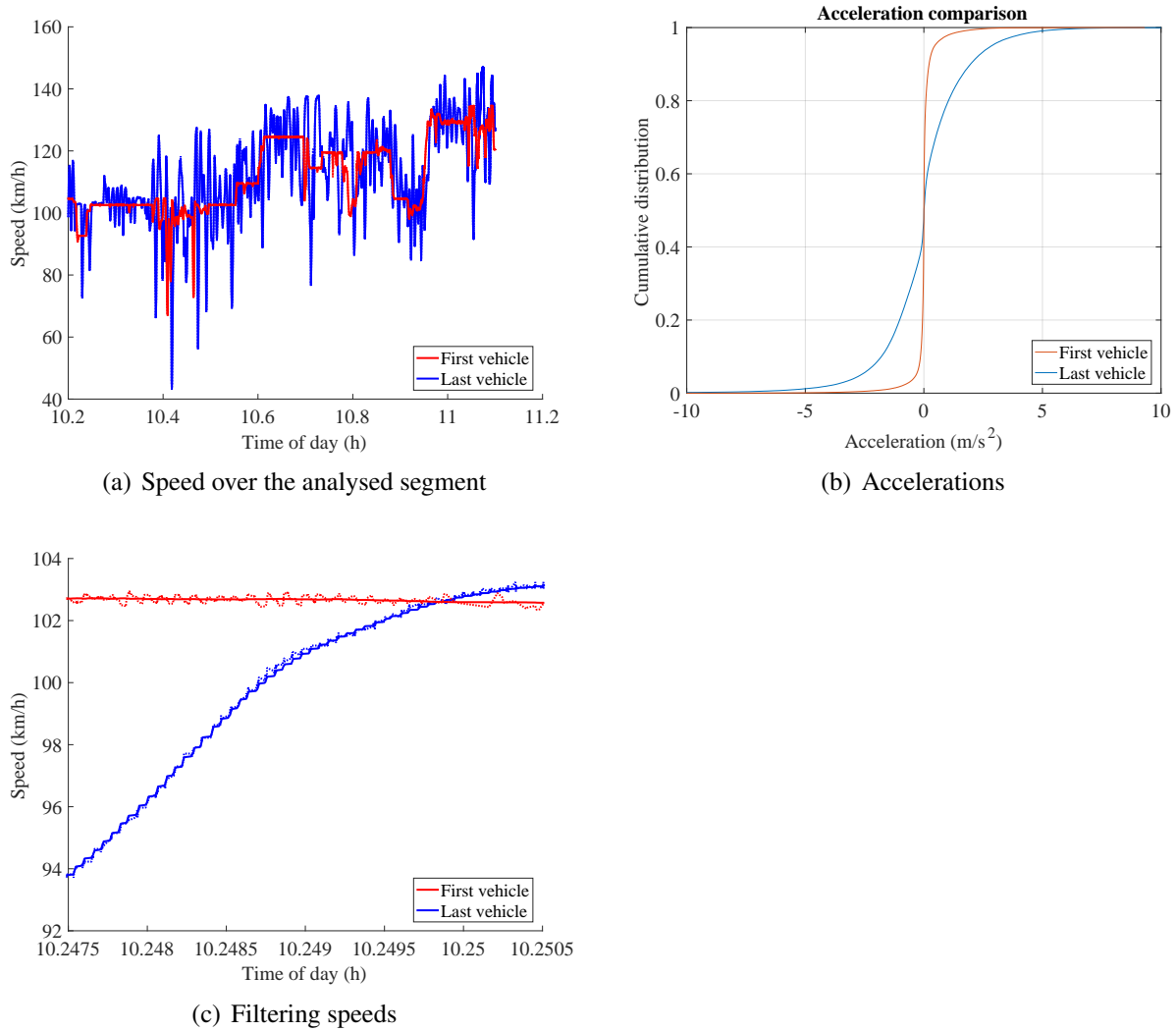


FIGURE 5 The speed profile of the first and last vehicle of the platoon

accelerate to higher speeds than the leader (in line desired speed set in the ACC, which exceeds the speed limit). Due to the delayed reaction (and perhaps lacking engine power), the following vehicles would still be accelerating while the leader (and direct followers) already braked. This braking action was not always detected in time by the ACC systems, and the driver deemed manual intervention necessary to avoid a collision. A hypothesis could be formulated that this situation is most likely to occur with less powerful cars and/or aggressive settings for the following vehicle. This hypothesis is to be tested by a quantitative follow-up research.

5.2 Fuel consumption

Stability also has an effect on acceleration of the vehicles, which in turn affects the fuel consumption. Cruise control is known to reduce the fuel consumption because it decreases speed variations. Let's reflect on the fuel consumption of ACC vehicles, and particularly the ones in a platoon. The platoon of ACC vehicles is unstable, so there is a larger variation in speeds for the last vehicle than

the first vehicle in the platoon. In this section we explore the effects on fuel consumption using a simple fuel consumption model.

We will compare the fuel needed for the first and the last car in the platoon over the same stretch of road. Some vehicles inherently use more fuel than others (depending on size, weight, fuel type, streamline, etc.), and therefore the actual fuel consumptions do not reflect the effect of the accelerations. Therefore, we will not simply compare the amount of fuel needed for these two vehicles. Instead, we will be using the trajectories and compute the fuel consumption using a standardized fuel consumption. To this end, we use the model by Akcelik (32). The model describes the fuel consumption as polynomial function of speed and acceleration:

$$F = \max(0, b_1 + b_2v + b_3v^2 + b_4v^3 + c_1va + c_2v(\max(0, a))^2) \quad (1)$$

In this equation, v is the speed in m/s and a the acceleration in m/s², yielding a fuel consumption F in ml/s. We also take the parameters from Akcelik (32).

$$b = \begin{bmatrix} 0.666 \text{ [ml/s]} \\ 0.072 \times 0.269 \text{ [ml/m]} \\ 0.072 \times 0.0171 \text{ [ml s/m}^2\text{]} \\ 0.072 \times 0.000672 \text{ [ml s}^2\text{/m}^3\text{]} \end{bmatrix} \quad c = \begin{bmatrix} 0.072 \times 1.68 \text{ [ml s}^2\text{/m}^2\text{]} \\ 0.472 \times 1.68 \text{ [ml s}^4\text{/m}^3\text{]} \end{bmatrix} \quad (2)$$

(For completeness, units have been added; the principle is that the units are aligned with the units of the variables mentioned above.) One can argue that in the past almost 3 decades since the publication of Akcelik (32), vehicles have become more efficient, but by using this model we aim to provide a relative comparison between the first and last vehicle in the platoon.

The model requires the speed and the acceleration. We choose a period of 54 minutes of freeway driving for which we have the speeds of both the first and the last vehicle of the platoon, see figure 5a. From the figure, it is obvious that the speed of the last vehicle in the platoon is more volatile. We are using the raw speeds from the CAN bus. These speeds are slightly noisy, hence we add a moving average smoothing filter which does not affect the pattern of speed variations, but removes the noise at the level of individual measurements – see figure 5c. Computing the accelerations for the 54 minute section already show that there are much more and stronger accelerations for the last vehicle in the platoon, confirming the volatility (figure 5b).

The standardized model gives a fuel consumption of 15.2 l for first vehicle and 41.2 l for last vehicle. Indeed, these values are both too high for an approximately 100 km trip (as expected with increasing fuel efficiency of modern vehicles). However, the comparison on the two numbers shows that the instabilities do not only cause discomfort, but also considerably increase fuel consumption.

6 CONCLUSIONS AND DISCUSSION

In this paper we have described the setup for and experiences from a field operational test with a platoon of SAE level-2 automated vehicles. To achieve driving conditions in which platoon effects could be studied, exemptions were granted to drive in the left lane and at speeds exceeding the speed limit. Nonetheless, it was found impossible to keep the platoon intact for all of the 465 km of driving. There were vehicles cutting into the platoon, partially because some drivers really want

to change lanes, and partially because even the closest distance setting of the ACC systems gives longer headways than Dutch drivers regularly maintain on freeways.

With increasing penetration rates of ACC equipped vehicles, it is more likely that platoons of these vehicles will be formed by chance (rather than by design, as in this experiment). The traffic dynamics in this experiment showed that the platoon becomes unstable with all vehicles driving with ACC activated. There are (sometimes severe) variations in speed which leads to discomfort and even risks of rear-end collisions. The most dangerous situations occurred when the leader had to oscillate his/her speeds (i.e., deceleration followed by acceleration and deceleration).

It is concluded that current ACC systems should not be seen as adequate tools to enable fully automated driving on a large scale. As comfort enhancement system it works well for individual drivers, but for large penetration rates, the platoon stability (also known as string stability) should be improved.

Further research will be needed to quantify car-following behavior and the way the instabilities propagate through the platoon. Results on this will be used to eventually develop guidelines for regulating the maximum platoon size of autonomous automated vehicles or develop stabilizing algorithms for traffic streams using on more advanced sensing and communication systems.

STATEMENT OF CONTRIBUTION

V.L. Knoop is the main author of the paper, the initiator of these traffic engineering analyses and performed the analyses. M. Wang is writer of several sections and is jointly with V.L. Knoop involved in the research conception. I.R. Wilmink described the vehicles' sensing devices. D.M. Hoedemaeker supervised the project of equipping the vehicles and observing the driving behavior. M. Maaskant conceived the strategies for the operational driving of the platoon. E-J. van der Meer organized the field operational test. All authors have seen the paper, and have (in decreasing amount with increasing author number) contributed to the writing of the paper.

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