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Platoon of SAE Level-2 Automated Vehicles on Public Roads: Setup, Traffic Interactions, and Stability

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Abstract
An increasing amount of vehicles are equipped with driver assistance systems; many of the vehicles currently on the market can be optionally 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 seven SAE level-2 vehicles driven as a platoon on public roads for a trip of almost 500 km. The paper discusses how the experiment was organized and 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 three to four vehicles, because of instabilities in the car-following behavior.

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 operates (*1, 2*). Depending on the involvement of the driver in the tactical and operational driving tasks, ADSs can be classified into five 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 (*4–7*) 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, 8–10*).

Adaptive cruise control (ACC) was the earliest form of autonomous vehicle system, designated as 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's speed to match a user-specified desired speed. When constrained by a preceding vehicle, the system tracks it 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 a platoon instability property which increases the probability of traffic flow breakdown because of time delay (*14–16*).

ACC systems are becoming standard equipment on premium—and even medium priced—passenger cars. Integrating the ACC system with a lane keeping system which takes over the steering from drivers to automate

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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 rapid 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 in 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 into the impact of such systems on the collective traffic systems.

Theory and simulation have shown the potential for CAVs to be beneficial in collective traffic operations. Field tests with CAVs have attracted considerable attention. In the 1990s, research on automated highway systems culminated in a demonstration of a platoon vehicles equipped with communication and magnetic sensors (*19*). There were concerns about the amount of funding needed 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*). Nine teams from 11 universities and industry partners participated in the competition in a 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 case of mixed heavy and light vehicles (*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 original equipment manufacturers (OEMs) and industrial partners for long-distance truck platooning on a public highway in light traffic conditions. Similar tests 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 about the difficulties that cooperative CAV platoons could create for other vehicles, especially at freeway entrance/exit sections.

In recent years, California Partners for Advanced Transportation Technology (PATH) tested a four-vehicle platoon with ACC and CACC (cooperative ACC) systems on 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 conditions (*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 the vehicle population. The scenario with increasing AAVs on public roads without communication is still a likely prospect. It is of paramount importance to understand the collective impact of such systems on traffic flow and safety via field tests. In this spirit, 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, because of 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 ADSs.

The literature review motivated a new test with a platoon of level-2 ADSs on public roads with interaction with surrounding traffic in a naturalistic environment. The goal of this paper is to present the preparations for the test in general (section "Preparations"), and to show the details of the trip organized, in particular (section "Platoon trip of June 13, 2018"). The experiment consisted of seven SAE level-2 vehicles driving (as much as possible) as a platoon on public roads for a trip of almost 500 km. The paper continues with sections on the interaction of the platoon in traffic and on the interaction between the automated vehicles. These analyses focus on the longitudinal operations of the automation, in other words, 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 provide insights into the potential impact of such systems on traffic dynamics.

Preparations

This section describes the preparations for a field operational test. First, the organizational efforts required for the organization of such a large-scale platoon test on public roads are described, followed by comment on the vehicles and the data.

Organization

The organization of the test involved different parties. First of all, the test had to be accepted by the road authorities and the police. The road authorities, 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, all of which related to the way the platoon could stay together in one lane due to national (and European) legislation of "keep right unless overtaking." This means that a driver is supposed to keep the rightmost lane, unless overtaking a vehicle in front, after which the driver is required to go back to the right. Frequent lane changing by the vehicles in the platoon would dissolve the platoon, however. 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 it when entering or leaving the freeway). Driving in the left (fast) lane also required 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 thus granted: (i) exemption from the "keep right unless overtaking" rule, which means that the platoon could stay in the left lane, even in quiet traffic conditions; and (ii) exemption from the speed limit, within bounds; the platoon would typically drive at 10 km/h over the speed limit. The police were informed of the planned test, the route, and the relevant exemptions.

The location of the platoon was included in traffic reports (its dynamic location was tracked using the GPS units in the vehicles). The Waze traffic information app (popular in the Netherlands) also notified other road users of the fact that the platoon was passing. The purpse of providing this information was that the platoon would remain more intact with less cut-in behavior. The effectiveness of this publicity is difficult to determine, as there is no evidence of what would have happened without it. Subjectively, the participants in the platoon never gained the impression that it was counter-productive, that is, no observations were made about drivers cutting in on purpose and "testing" the platoon.

Vehicles and Data

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

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

Figure 1. A part of the platoon on the road.

All cars are equipped with the most advanced systems of driver support that were (optionally) available at the time of production for customers on the market. In fact, the vehicles were selected based on their (advertised) relatively high level of driver support systems; all achieved SAE level-2 automation (*3*). These systems are able to perform sustained longitudinal and lateral control of the vehicle under its operational design domain. This means that the vehicle can be driven "hands off" in some conditions (here focused on freeway use), but the driver is supposed to monitor the traffic and the vehicle and to performs object and event detection and response (OEDR). The driver must be ready to take over control of the vehicle immediately if the situation requires it.

In practice, two systems take care of the vehicle control:

- *ACC*. A desired speed is set for the vehicle and the vehicle will drive at the set speed, but reduces speed when constrained by other vehicles ahead which drive at a slower speed.
- *Lane centering system* (LCS). The vehicle observes the lanes on the road and steers the car to keep it within its lane.

The order of the platoon was varied a couple of times at breaks during the trip. At all times the Tesla was used as the lead vehicle—a choice guided by its "high-tech" image, with a view to media coverage of the operation. Vehicles of the same type were mostly grouped together. Figure 1 shows the platoon.

Instrumentation

Apart from the OEM vehicle sensors, the vehicles were equipped with further sensors; all of them were logged wherever possible. Retro-fitted instrumentation consisted of a high-resolution global positioning system (GPS), and a Mobileye stereo camera. The Mobileye camera provides data on objects in front of the vehicle (distance, speed) and on the vehicle's own lane position and the

Table 1. Available Data Fields

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

Note: The first column lists external sensors present in all vehicles. Availability of CAN-bus data depends on the brand and make of the vehicle. Dynamic variables are typically recorded at 10 Hz. lks = lane keeping system, referring to the LCSs of the vehicles; x = available; NA = not available.

time and distance headway to the preceding vehicle. Moreover, there were eight cameras looking inside and outside the vehicle, observing the driver, the dashboard, and the surrounding traffic. The data logged from the Controller Area Network bus (CAN-bus) varied for each of the different vehicle types. Broadly speaking, CAN-bus data related to the status of the vehicle automation systems (settings and activation/deactivation), the vehicle's movements (longitudinal and lateral; speed and acceleration), and some additional signals such as the status of the indicator lights and windshield wipers. The data fields which are available from the sensors are shown in Table 1. Because of equipment failure, some data are missing—sometimes a variable is missing for a few seconds or minutes. Some data are missing for a whole day because of a loose connector, which caused by

Table 2. Available Data for ACC System

			Mercedes		BMW		
Property	Tesla	Audi	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

Note: ACC = adaptive cruise control.

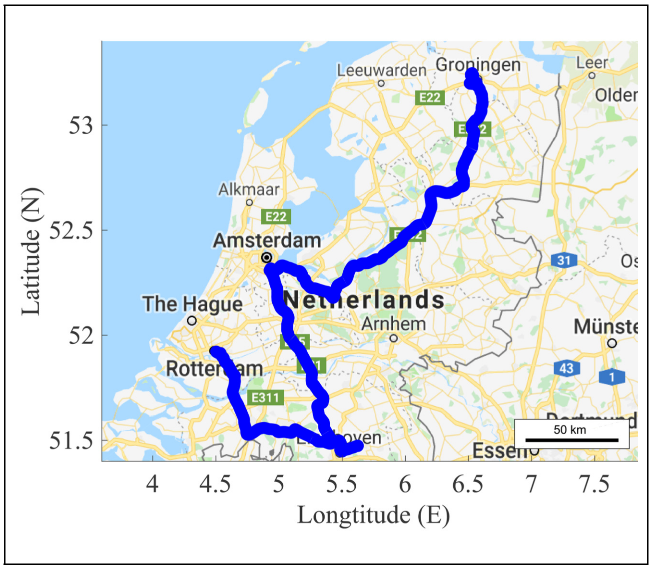


Figure 2. The route driven.

far the majority of the data loss. On average, the authors estimate that at least 75% of the data are present. The accuracy of positions and speeds was assessed. Positions seem to be accurate within the order of vehicles in the platoon; it was possible to follow positions within the platoon. Moreover, the positions of an individual vehicle were plotted on a map every 0.1 second (repeated for various vehicles). From the trace (distance between the points and lateral deviations), the accuracy was approximately within a few meters. Speed accuracy was derived from redundant speed loggings (CAN-bus and various GPS loggings), and is estimated to be accurate to approximately 1 km/h, 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 analyzing the status of the ACC system was 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; 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 driver's feet) can still be fused with the numerically collected data, this a limiting factor with the data set currently available for analysis. 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 presented in this paper will be limited to testing platoon effects at a basic level, based on the speed, which is present for all vehicles.

Platoon Trip of June 13, 2018

The route was a 465 km long journey 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 journey; only approximately 10 km of the trip consisted of non-freeway driving. The trip took place on June 13, 2018; it started at around 7.30 am and ended around 5:00 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 below). Different traffic conditions (congested, free flow) were encountered during the journey. Weather conditions were good (no precipitation).

The vehicles used in this study are part of a larger test of naturalistic driving with SAE level-2 vehicles. In that test, individual drivers use the vehicles regularly for a prolonged period of time (three months per driver). Seven of these vehicles and drivers were brought together for this test drive.

When the drivers began using their vehicles—typically several months earlier—they received training on how to use the assistance systems from Prodrive, a company specialized in training drivers to drive with driver assistance systems. Their experience is that, in 70% of cases, owners of cars with driver assistance systems do not use them correctly (personal observations of one of the authors, Mark Maaskant). The drivers in the test drive thus 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, to keep the platoon intact and avoid other road users making 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 to prevent other vehicles cutting into the platoon, to the extent possible;
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 seven-vehicle platoon requires special skills and driving techniques which are not part of 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 an intervehicle distance of approximately between 500 m and 1000 m. Information on traffic situations or platoon formation 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 range to reach both ends of the platoon.

Behind the platoon was a support vehicle, also equipped with a radio transceiver. The driver of this vehicle could instruct the drivers of the other vehicles in the platoon. 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.

Interaction with Other Vehicles

This section discusses the interactions with the other drivers (i.e., not part of the platoon) during the trip. First general observations are presented; the second subsection indicates the procedure followed to change lanes with a platoon.

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—unlawfully in the Netherlands—to overtake the vehicles on the right.
- Other vehicles did cut in, even though the following distance was set to be 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 the capacity of a two-lane freeway of 2,150 veh/h/lane, equaling an average gross time headway, that is, the time a vehicle takes to get to the same position as its leader, of 1.67 s.) The smallest ACC headway setting is hence not considered as very small headway.
- Even though the platoon was exempt from the "keep right" rule, this was most likely not communicated to all traffic enforcement officers. On one occasion, a military police officer on a motorbike directed all the cars sequentially to the lanes further right. After he had passed, the platoon reclaimed its position on the left lane.
- It was undesirable for other vehicles to change lanes somewhere into the platoon; therefore all vehicles used the smallest headway setting available (the actual value might vary per brand). Even these small headway settings would not prevent cut-in. Cut-in lane changes could also be avoided by driving behiavor. When it was expected that a driver in the adjacent lane (on the right) had desired to make a lane change, the potential follower in the platoon would change its in-lane position. The driver overruled the LCS and drove to the right in its own lane; this would make the vehicle appear closer to the potential lane-changing vehicle, and would prevent a lane change in many cases.
- While drivers tried to rely on the vehicle systems as much as possible, sometimes manual intervention was needed (for instance, for lane changing, braking, or catching up). This intervention was very limited, however. For one vehicle (the Audi), the amount of driving in each of the following situations was checked: ACC determines acceleration/deceleration; ACC off; ACC on, but overruled by throttle. Table 3 shows the time the system has been used. For the vast majority of

Table 3. Usage of the ACC System on Freeways

	ACC determines acceleration/deceleration	ACC off	ACC on, overruled by throttle
Time	4 h 12 min	5 min 20 s	6 s
Fraction of time	98%	2%	0.04%
Fraction of distance	99%	1%	0.03%

Note: ACC = adaptive cruise control.

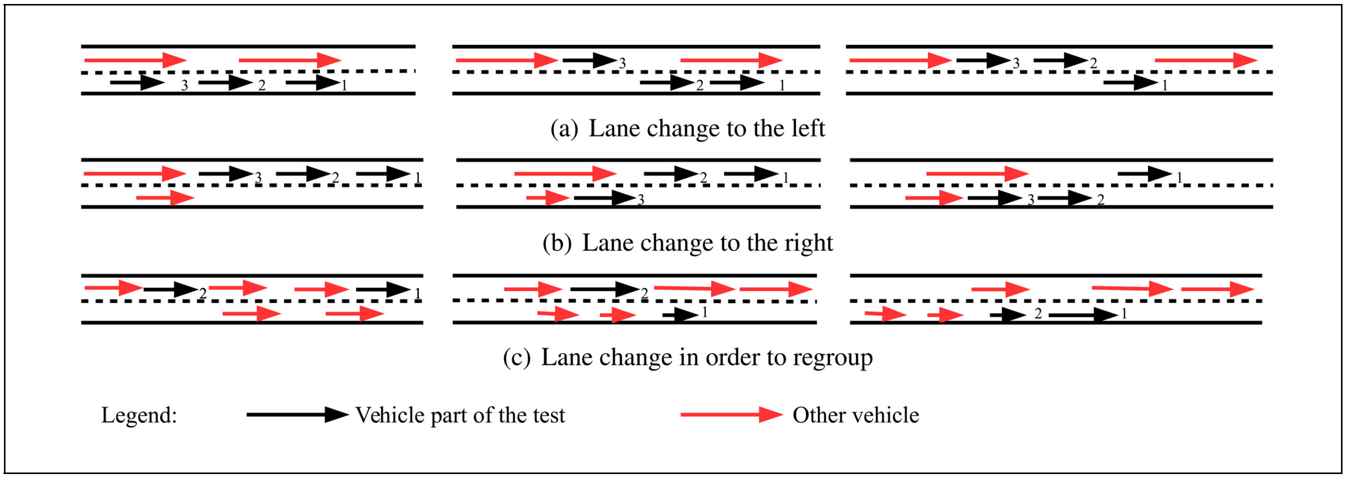


Figure 3. Schematic overview of the lane change maneuvers. The size of the arrows represents the speed of the vehicle. Within each part of the figure, the numbers indicate the same vehicle at different time instances.

time (98%) or distance (99%), the ACC system determined the acceleration and deceleration. The test drivers did not reveal any reason why considerably different values would be expected for other vehicles.

Studies by the Netherlands Vehicle Authority showed that motorbikes were not always detected by ACC systems when they were driving close to or on the lane markings (*29*). This was further tested during the present platoon test. Two motorcyclists from the national motorbike association joined the platoon for a part of the drive and tested the vehicles' ability to detect them in various positions on the road. In short, all vehicles detected the bikes in all positions. When the throttle is released, a motorbike yields a higher deceleration than a car because of its lower mass. This would yield a deceleration would be amplified throughout the platoon. A speed reduction without braking from 100 km/h 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").

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 on ramp (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 3*a*). First, the last vehicle in the platoon would make a lane change to the left. It would continue driving until it 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 road user is expected to overtake on the right and hence no one should be able to cut-in between. For lane changes to the right, a similar procedure was followed (see Figure 3*b*). 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, and so forth.

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 who would cut into the platoon and who would afterwards not leave the left lane. If this was the case, the platoon would regroup in another lane (see Figure 3*c*), using an inversed lane change maneuver. This means that the first vehicle in the platoon will first move one (or more) lanes to the right.

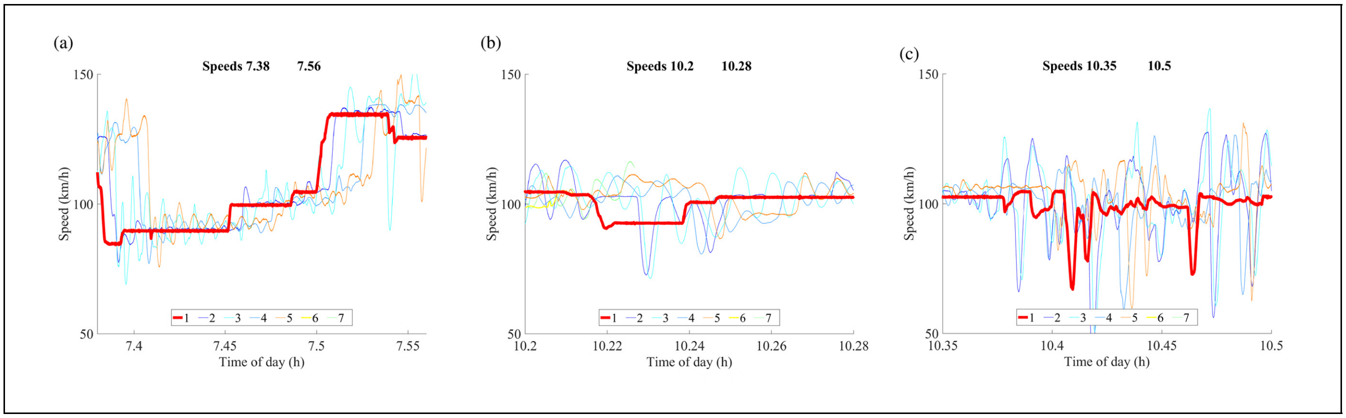


Figure 4. Fluctuation of speeds for various vehicles in the platoon for various time intervals. The number is the position of the vehicle in the platoon; the platoon leader is plotted in bold. The same color denotes the same vehicle. (a) 7h23-7h34; (b) 10h12-10h17; (c) 10h21-10h30.

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 tactic is to regroup in the rightmost lane, where it is possible to drive at a considerably lower speed than other 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.

Interaction between the Vehicles

This section discusses platoon stability, followed by fuel consumption.

Platoon Stability

Pueboobpaphan and van Arem (*30*) have defined different levels of platoon 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 (*7*). For the sake of simplicity, and to limit the influence of missing (visible by appearing and disappearing lines) and noisy data, this paper follows the definition of Pueboobpaphan and van Arem (*30*). Hence only fluctuations in speed are considered, to which a basic, largely qualitative, analysis is applied. The authors acknowledge that there are more elegant ways to analyze the string stability properties of ACC and CACC controllers, for example, the work of Treiber and Kesting (*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 represent different vehicles. The speed of the platoon leader is shown as a bold line. Figure 4*a* 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 3. Where the leader reduces its speed from approximately 105 km/h 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 unstable according to the definition of Pueboobpaphan and van Arem (*30*).

A more extreme example of this is shown in Figure 4*c*. There is a reduction of speed by the leader from 100 km/h to around 70 km/h. The followers reacted more strongly, such that the minimum speed of the last vehicle in the platoon dropped to approximately 40 km/h. These low speeds are the consequence of a reaction amplified multiple times by each of the vehicles in the platoon. This could cause dangerous situations on the freeway, since other drivers do not expect such low speeds in free flow conditions. The same situation occurred at another location where a vehicle in front of the platoon reduced speed to 80 km/h when entering a tunnel. The following vehicles reduced their speeds further and further, such that the speed of the last vehicle was less than 40 km/h. This happened in free-flow traffic conditions. The follower behind the platoon was not expecting this speed decrease, which created a dangerous traffic situation especially given that it was happening in a tunnel.

Clearly, the effects caused by this seven-vehicle platoon are undesirable, for both safety and comfort. Judging by the speeds and reported comfort level of drivers in the vehicles during the test, platoons of more than three or four vehicles become undesirable.

The most dangerous situations occurred when the leader changing speed, in particular if the leader reduced speed, accelerated, and reduced speed again. The consequence was that the vehicles in the platoon would reduce speed more than the leader, and to catch up they would accelerate to higher speeds than the leader (in line desired speed set in the ACC, which exceeds the speed limit). Because of the delayed reaction (and perhaps lacking engine power), the following vehicles would still be accelerating when the leader (and direct followers) already braked. This braking action was not always detected in time by the ACC systems, and the drivers 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.

Fuel Consumption

Stability also has an effect on the acceleration of the vehicles, which in turn affects the fuel consumption. Cruise control is known to reduce fuel consumption because it decreases speed variations. Let us 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 the effects on fuel consumption are explored using a simple fuel consumption model.

The fuel needed for the first and the last car in the platoon over the same stretch of road are compared. Some vehicles inherently use more fuel than others (depending on size, weight, fuel type, streamlining, etc.), and therefore the actual fuel consumption does not reflect the effect of the accelerations. Therefore, the amount of fuel needed for these two vehicles is not simply compared. Instead, the trajectories are used and the fuel consumption computed using a standardized fuel consumption. To this end, the model devised by Akcelik (*32*) is used. The model describes fuel consumption as a polynomial function of speed and acceleration:

$$F = \max(0, b_1 + b_2 v + b_3 v^2 + b_4 v^3 + c_1 va + c_2 v(\max(0, a))^2) \tag{1}$$

In this equation, v is the speed in m/s and a is the acceleration in m/s^2, yielding a fuel consumption F in ml/s. The parameters are also taken from Akcelik (*32*).

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

(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 almost three decades since the publication of Akcelik (*32*), vehicles have become more efficient, but using this model provides a relative comparison between the first and last vehicle in the platoon.

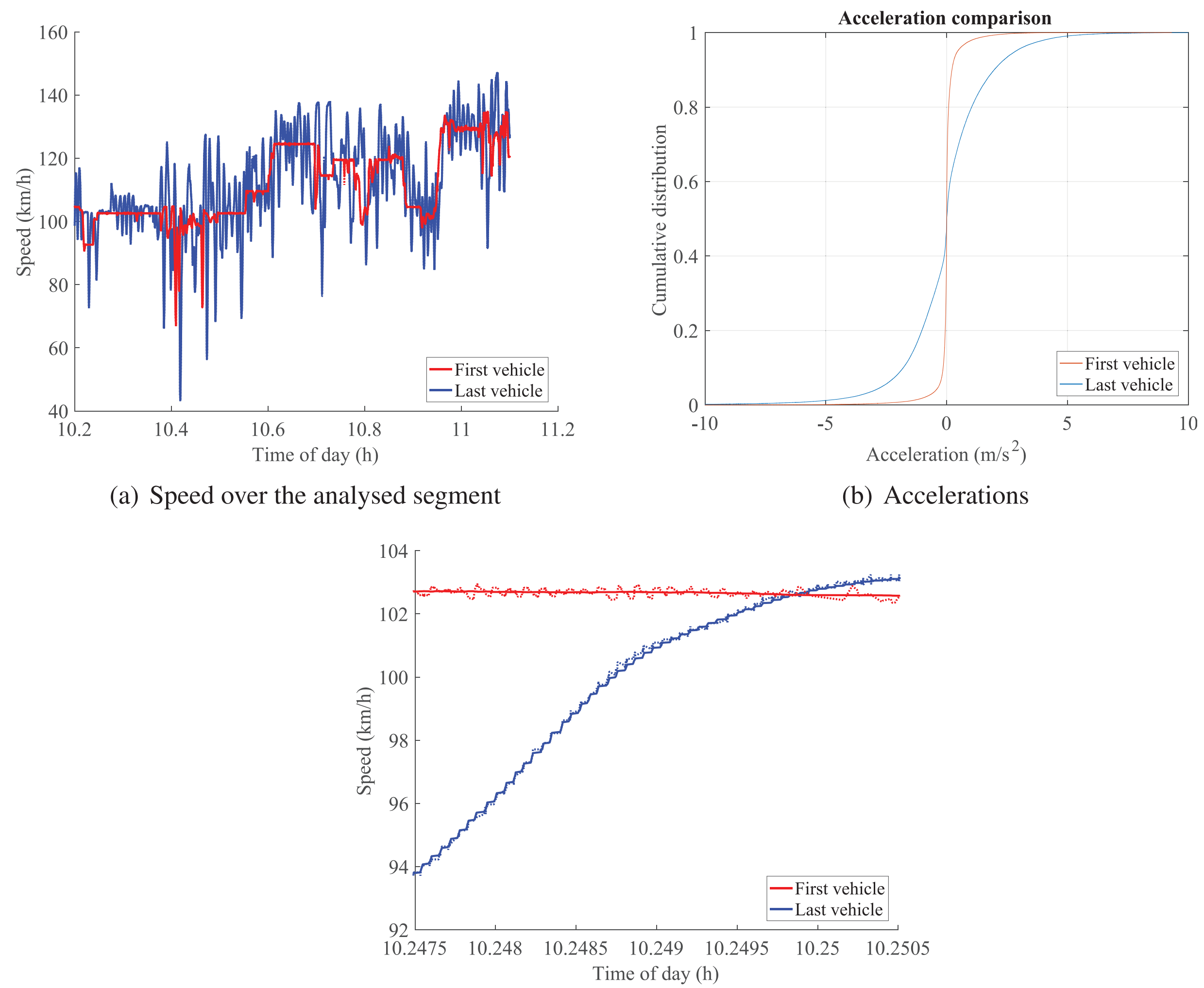
The model requires the speed and the acceleration. A period of 54 minutes of freeway driving was chosen, for which the speeds of both the first and the last vehicle of the platoon are known, see Figure 5*a*. From the figure, it is obvious that the speed of the last vehicle in the platoon is more volatile.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

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

Conclusions and Discussion

This paper has 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 for the test vehicles 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. Other vehicles would cut into the platoon, partially because some drivers really wanted 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 when all



(a) Speed over the analysed segment
(b) Accelerations
(c) Filtering speeds

Figure 5. The speed profile of the first and last vehicle of the platoon.

vehicles are driven with ACC activated. There are (sometimes severe) variations in speed which lead to discomfort and even risks of rear-end collisions. The most dangerous situations occurred when the lead vehicle had to oscillate its speed (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. The results will be used eventually to develop guidelines for regulating the maximum platoon size of AAVs or develop stabilizing algorithms for traffic streams using more advanced sensing and communication systems.

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Author Contributions

VLK is the main author of the paper, the initiator of these traffic engineering analyses, and performed the analyses. MW wrote several sections and was, jointly with VLK, involved in the research conception. IW described the vehicles' sensing devices. DMH supervised the project of equipping the vehicles and observing the driving behavior. MM conceived the strategies for the operational driving of the platoon. E-JvdM organized the field operational test. All authors contributed to the writing and reviewed the manuscript prior to its final submission.

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