

Final evaluation report on vehicle data

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Document Information

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Preface

The work reported here is part of the research project 'Truck Platooning Trial' which is carried out by TNO on behalf of Rijkswaterstaat (the Ministry of Infrastructure and Water Management, RWS), as part of the Ursa Major neo program. The project involves the first real-life truck platooning trial on Dutch public roads, investigating the impact on motorway traffic, and assessing the expected impact on structural safety and service life of bridges and viaducts.

This report presents the "Final evaluation report on vehicle data" using measured data from the entire trial, collected between the 1st of June 2022 and the 30st of September 2022.

Executive Summary

This report presents the “Final evaluation report on vehicle data” using measured data from the entire trial, collected between the 1st of June 2022 and the 30st of September 2022. In the UMneo TPT, TNO used two EcoTwin3 CACC trucks. The platooning systems on these trucks are an evolution of the systems used in the European Truck Platooning Challenge (ETPC) in 2016. The functions that were assessed are Adaptive Cruise Control (ACC) and Cooperative Adaptive Cruise Control (CACC), both at different time gap settings. The trials were conducted on the public road between the city of Venlo and the Rotterdam harbour and partially overlaps with the Rhine-Alpine corridor within the Trans-European Transport Network (TEN-T). During the 20 test days no safety issues or near incidents occurred.

The data analysis was done in relation to the following Macro Topics:

- Vehicle and Traffic Impact on safety indicators
- Emission measurements
- Driver acceptance
- C-ITS infrastructure

The key findings in relation to the experiment described in this report are:

- ACC and CACC performed the driving task with less variation (in terms of gap variation and speed variation) compared to manual driving. Less variation in driving behaviour can qualitatively be interpreted as contribution to smoother traffic flow and improving traffic safety.
- For vehicle ET3 in trailer position, the test results showed a decrease in fuel consumption, CO₂ emissions and NO_x emissions with decreasing gap distance with respect to the leading vehicle, depending on the type of controller i.e. CACC or ACC. Due to the specific CACC controller, which was optimized on controller performance and on fail-safety, the trailing truck had speed variations, which increased the energy consumption rather than decreasing it.
- Acceptance of ACC by the drivers, measured as usefulness and satisfaction, was slightly higher for in the leading truck than in the trailing truck. Within the trailer, no effects of ACC versus CACC were found. Usefulness was on the positive part of the scale for both roles. Satisfaction score were slightly positive in the leading truck and neutral in the trailing truck. In terms of trust, there were some indications that CACC received slightly lower scores than ACC.
- The C-ITS allowed the roadside to detect platooning vehicles and to put constraints on platooning in relation to specific parts of the road network.

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List of Abbreviations

ACC	Adaptive Cruise Control
ADAS	Advanced Driver Assistance System
CACC	Cooperative Adaptive Cruise Control
CAM	Cooperative Awareness Message (ETSI EN 302 637-2)
CAN	Controller Area Network
CET	Central European Time
C-ITS	Cooperative Intelligent Transportation Systems
EB	Eastbound
EC	European Commission
ETPC	European Truck Platooning Challenge
EU	European Union
FCW	Frontal Collision Warning
FOT	Field Operational Tests
GPS	Global Position System
HMI	Human-Machine Interface
I2V	Infrastructure to Vehicle
ITS	Intelligent Transportation Systems
IVI	Infrastructure to Vehicle Information
IVIM	Infrastructure to Vehicle Information Message
MIO	Most Important Object
MT	Macro Topic
NWB	Nationaal Wegenbestand
OBU	OnBoard Unit
PI	Performance Indicator
RDW	Rijksdienst voor het Wegverkeer
RPM	Revolutions Per Minute
RSME	Rating Scale Mental Effort
RWS	Rijkswaterstaat
SAE	Society of Automotive Engineers
SEMS	Smart Emissions Measurement System
TEN-T	TransEuropean Transport Network
TKI	Topconsortium voor Kennis en Innovatie
TPT	Truck Platooning Trial
TTC	Time To Collision
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
WB	Westbound

1 Introduction

The Ursa Major neo Truck Platooning Trial (UMneo TPT in short) is the first real-life truck platooning trial on Dutch roads along the Rotterdam - Venlo corridor, investigating the impacts of truck platooning on motorway traffic, and assessing the expected impact on structural safety and service life of bridges and viaducts. The project is carried out on behalf of Rijkswaterstaat (the Ministry of Infrastructure and Water Management, RWS), by TNO as part of the Ursa Major neo program. This deliverable describes “Intermediate evaluation report on vehicle data”.

TNO has conducted the trials using “Eco-Twin3” trucks that were developed in 2016 in a TKI collaboration with DAF Trucks (Bijlsma et al., 2016). The project has identified the fields of investigation listed in Table 1-1, called Macro Topics (MTs). This report covers only Macro Topics that are related to data collected on the vehicles themselves, i.e. all except MT2 (Bridges and viaducts) which is covered in separate reports.

Table 1-1 Macro Topics (MTs) to be studied.

ID	Title	High-level description
MT1	Vehicle and Traffic Impact on safety indicators	Ego-vehicle safety, Platoon safety indicators, Other road user's safety indicators
MT2	Bridges and Viaducts	Impact on structural safety and service life of bridges and viaducts
MT3	Emission measurements	Impact of truck platooning on a typical trip with loaded truck
MT4	Driver acceptance*	User acceptance and impact of platooning on the truck drivers
MT5	C-ITS infrastructure	Showcase the potential benefit to mobility of Cooperative Intelligent Transportation Systems (C-ITS) by means of Infrastructure-To-Vehicle (I2V) and Vehicle-To-Infrastructure (V2I) communication

(*) Note that MT4 should be interpreted as “impact on drivers” more than “driver acceptance”: we decided however to keep the original notation (although possibly misleading) for consistency with the project proposal definition and with all previous documents

The evaluation approach of the field trial is based on the methodology described in the FESTA Handbook (FESTA, 2018), as depicted in Figure 1-1. The methodology originates from the EC-funded FESTA project, leading to the first FESTA Handbook in 2008, which has seen several revisions since then. The Handbook collects best practices for Field Operational Tests (FOTs), with the aim to ensure their quality and comparability. The UMneo TPT only covered a sub-set of this overall process. Specifically, traffic simulation (as part of the effect assessment), socio-economic analysis, and cost-benefit analysis were beyond the scope of the current project. Furthermore, the tests will be of a semi-controlled experimental nature (for instance, instructing drivers to use the systems with a pre-defined setting and follow pre-determined routes rather than letting them choose freely). Last but not least, the Umneo TPT implements some methodological changes with respect to the FESTA approach, for safety, legal and ethical reasons. These changes are similar as in the L3Pilot project (Innamaa et al., 2020), stemming from the fact that the platooning system should be considered a prototype rather than a production-type system, ready for an end user. This requires them to be driven by so-called safety drivers, rather than by any licenced (truck) driver. This has implications for the driver acceptance part of the project (MT4).

The left branch of the FESTA-V was covered in Deliverable 1.2 (Hogema, Van Weperen, Van Kempen, & Wissingh, 2022). It included the definition of the general project goals and the five Macro Topics (MTs), and the construction of the trial design. Starting from the research questions, the Performance Indicators (PIs) needed to answer these were identified, as well as the measures needed to obtain the PIs. These were all merged into the overall trial design, including the data logging requirements. During the trial operation, raw data were collected. To prepare for the analysis, data were enriched (amongst others by map matching and adding traffic flow data). The resulting pre-processed data are described in Deliverable 3.2A (Hogema, Van Weperen, Deschle, & Wedemeijer, 2022). This data set served as the basis for the analysis of each individual MT. This analysis is presented in the current report.

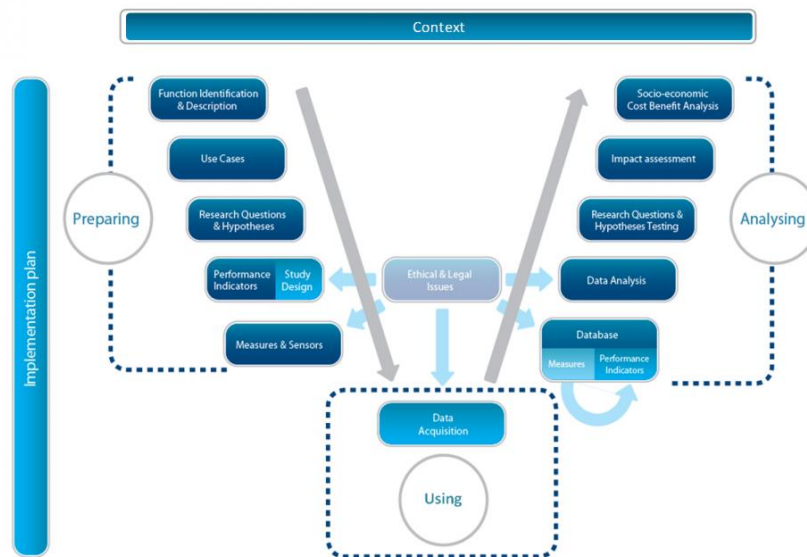


Figure 1-1 The “FESTA-V” (FESTA, 2018).

The Truck Platooning Trial also provides insight in how well truck platooning can work on Dutch motorways, with its specific road and traffic characteristics. For a pair of trucks equipped with Adaptive Cruise Control (ACC) or Cooperative Adaptive Cruise Control (CACC), what percentage of time is it actually feasible to drive with these systems activated? Once activated, how long does a platooning phase typically last before it is terminated? Such practical questions dealing with platooning performance are also covered in MT1.

The remainder of this introduction provides a high-level overview of the overall approach. For details, the reader is referred to the following reports.

- The vehicles and their equipment are described in detail in Deliverable 2.1 (Goos, Wissingh and Van Kempen, 2021).
- The evaluation plan and methodology of the trials are described in detail in Deliverable 1.2 (Hogema, Van Weperen, Van Kempen, & Wissingh, 2022).
- An overview of the collected data is presented in Deliverable 3.2A (Hogema, Van Weperen, Deschle, & Wedemeijer, 2022).

Chapters 2 until 5 present the results of the Macro Topics 1 and 3-5. Appendix B gives an analysis of platooning impacts related to the context of traffic and road sections. This part of the report was authored by Simeon Calvert, Ali Nadi Najafabadi and Zhengliang Duanmu from TU Delft.

1.1 Trucks and platooning functions

In the UMneo TPT, TNO used two EcoTwin3 CACC trucks, whose main characteristics are presented in Table 1-2. The platooning systems on these trucks are an evolution of the systems used in the European Truck Platooning Challenge (ETPC) in 2016. The functions that were assessed are Adaptive Cruise Control (ACC) and Cooperative Adaptive Cruise Control (CACC), both at different time gap settings. In CACC, vehicle to vehicle (V2V) wireless communication is applied. Data received via this channel augmented the vehicle's own sensor signals. The ACC and CACC functions were developed by TNO, with emphasis on the platooning system's reliability and safety (Bijlsma & Hendriks, 2017). In vehicle following, the control objective of ACC and CACC was to keep the actual time gap equal to the intended time gap.

Lateral automation was part of the functionality of the EcoTwin3 trucks, but this was not used during the trials.

The trucks were equipped with Frontal Collision Warning (FCW) functions. This is a TNO developed functionality which used the same sensors as the platooning application. When driving above 40 km/h, an FCW alarm was triggered when the Time-To-Collision (TTC) with respect to an object in front dropped below 5 seconds. The warning consisted of a loud audio signal. The FCW system was functioning in all experimental conditions, including manual driving.

Table 1-2 Overview EcoTwin3 truck specifications

Aspect	Configuration in this platooning trial
Max combined train weight	Loaded trucks will weight up to 38t, thus obeying the regulations in the Netherlands (max 50t)
Time gaps (original)	CACC settings: 1.0, 1.2 or 1.4 s
	ACC settings: 1.5, 1.75 or 2.0 s
Time gaps (Truck Platooning Trial)	CACC settings: 1.0, 1.25 or 1.5 s
	ACC settings: 1.5, 1.75 or 2.0 s
Lateral automation	Present but not used in the UMneo TPT
Cooperative Adaptive Cruise Control	Longitudinal CACC capability in vehicles based on built-in sensor suite and V2V communication
Collision avoidance	Embedded in the TNO controller (full braking phase limited at 8 m/s ²). It is a function that runs parallel to ACC/CACC, but it can only be activated when ACC/CACC is active and not during manual driving.
Forward Collision Warning (FCW)	Embedded in the TNO controller by means of an audio and visual warning
Cargo load	Static, concrete bricks

The cockpit from the EcoTwin3 trucks is shown in Figure 1-2:

- ★ The DAF HMI was unchanged and contained the basic dashboard information as in a conventional truck.

- ★ The TNO HMI (see Figure 1-3 for a close-up) gave the driver the controls and displays information related to the platooning functionality. The TNO HMI from EcoTwin3 was used in the UMneo TPT. (Note that this implies there were some HMI elements present that were not used in the TPT: lateral control functions and the I2V traffic light information).
- ★ Part of the sensor suite of the trucks was a MobilEye camera-based system (MobilEye560) that provided data regarding lane and object detection. The MobilEye system came with an HMI that was mounted in the cockpit and provided headway information as well as warning functions.
- ★ The cockpit also contained a separate C-ITS HMI that was used to display C-ITS related information received from the infrastructure to the driver. There was no automatic actuation in response to this received information.



Figure 1-2 Cockpit of the trucks in EcoTwin-3, with the platooning HMI (user interface to (C)ACC functions) and an indicative location of the C-ITS HMI for the current project (Source: D1.2).



Figure 1-3 The TNO HMI in EcoTwin-3. 1) (C)ACC On/Off; 2) (C)ACC Set/Resume button; 3) Increase/Decrease set speed; 4) Increase/Decrease time gap; 5) Lane Keeping Assist On/Off button; 6) Active Lane Keeping On/Off button; 7) I2V communication On/Off (source: D1.2).

By means of the HMI, the driver could choose one out of three categorical time gap settings. These were automatically transformed into a time gap setting for the controller, using different values for

CACC than for ACC (Table 1-3). This implies that when a driver was in vehicle-following mode with ACC, and he changed from ACC to CACC, the time gap would be decreased. Likewise, switching from CACC to ACC would result in an increase of the time gap.

Table 1-3 Time gap settings for ACC and CACC.

Categorical setting	ACC setting [s]	CACC setting [s]
#1	1.5	1.0
#2	1.75	1.25
#3	2.0	1.5

The ACC function was available in both trucks. CACC was available only for the trailing truck, due to the dependency on the availability of V2V information from a leading vehicle. Starting with an activated ACC, the driver of the trailing truck could activate CACC using a button on the platooning HMI (a touch screen mounted in the cabin of the truck). An example of such a platooning activation phase is shown in Figure 1-4. In this example, both trucks started at a speed of around 40 km/h, driving in manual mode. While both trucks were accelerating, the driver of the trailing truck activated ACC at $t=9$ s, followed by transitioning to CACC at $t=15$ s. Meanwhile, the driver of the leading truck was still accelerating in manual mode: he activated ACC at $t=36$ s.

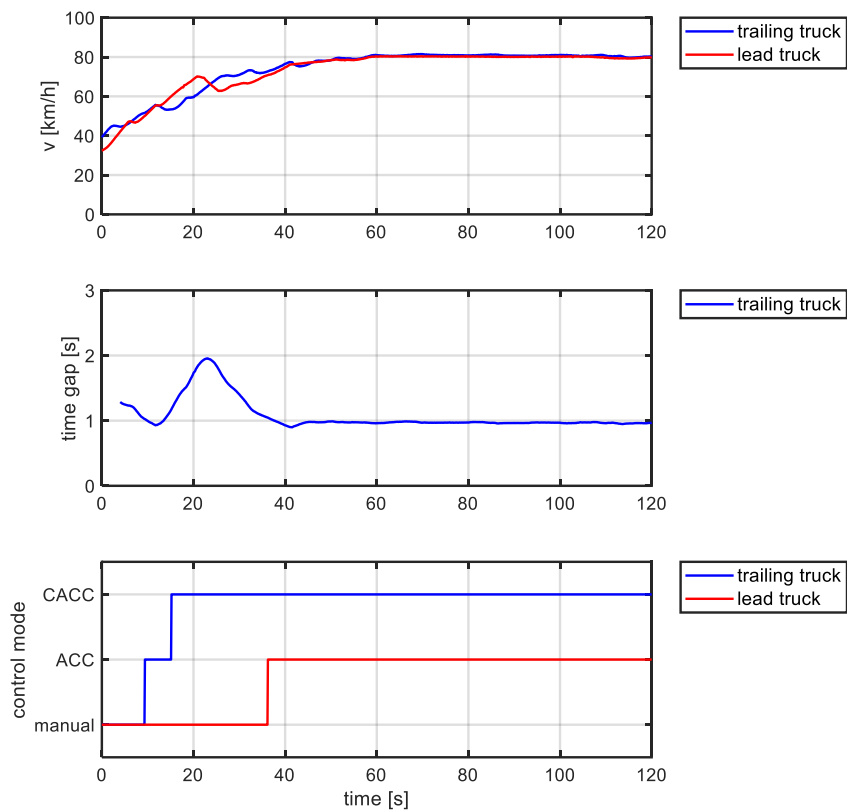


Figure 1-4 Example of platooning activation: leading truck using ACC, trailing truck using CACC.

The example in Figure 1-4 illustrates that various combinations of control modes can occur within a trip. Part of the analysis in Chapter 2 will deal with the percentages of time that the various control modes occurred during the trips. Other parts will investigate what kind of operational driving behaviour occurred, given that the system was in a certain control mode. All of this will be further detailed in Chapter 2.

The dependency of CACC on a V2V equipped lead vehicle has consequences when a cut-in scenario occurs in between the two platooning trucks. Part of the ACC functionality is to select, from the various objects detected by radar or camera sensors, the object that the controller should respond to: the Most Important Object (MIO). Most of the time this is the vehicle ahead of the ego vehicle, in the same lane. When a cut-in occurs, at some point the vehicle performing the cut-in manoeuvre will be assigned the role of MIO. When this happens in ACC mode, the ACC will adjust the acceleration such, that the reference time gap with respect to the new MIO is achieved and maintained. The combination of gap and relative speed determines the acceleration/deceleration level that is applied. ACC remains active unless the driver overrules or switches it off. When a truck is driving in CACC mode, it has several sources for the gap distance to the vehicle ahead. This is illustrated in Figure 1-5. First, the trailing truck has its on-board sensors (radar and camera systems), just like ACC. For the sake of simplicity, Figure 1-5 labels the gap data from these sensors as one measure Gap_{radar} . A second source of gap data is obtained via V2V. The leading truck communicates its GPS location, and by comparing that with the GPS location of the ego truck, the trailing truck can derive the resulting Gap_{V2V} . During regular platooning, these two gap measures will be approximately equal to each other. After a cut-in, however, once the cut-in vehicle has reached the stage of the Most Important Object, the platooning system will detect a large discrepancy between Gap_{radar} and

Gap_{V2V} . This implies that a cut-in has taken place and this will trigger an automatic transition from CACC to ACC. An example of this is shown in Figure 1-6.

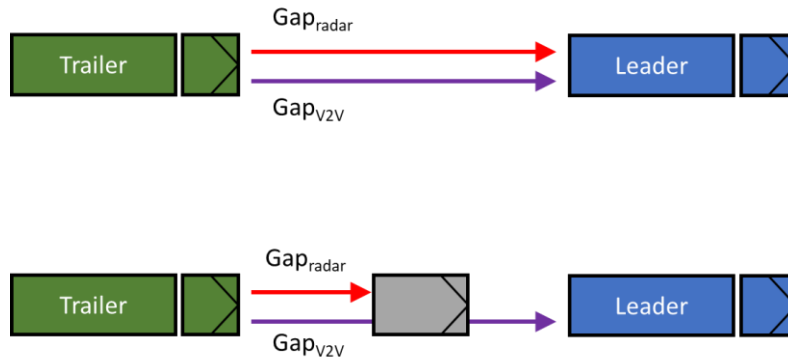


Figure 1-5 Different sources for the distance gap of the trailing truck in normal platooning (top) and after a cut-in (bottom).

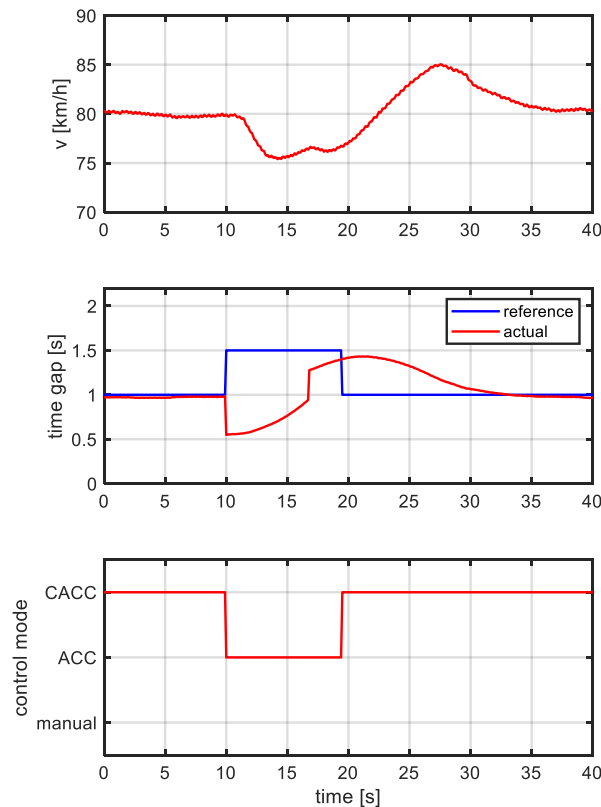


Figure 1-6 Example of a cut-in ($t=10$ s) and a cut-out ($t=17$ s) happening in front of the trailing truck (causing a transition from ACC to CACC and therewith an increase of the reference time gap). Switching back from ACC to CACC is done by the driver at $t=19.5$ s.

In the example of Figure 1-6, the trailing truck is initially following the lead truck in CACC mode, at an average speed of 80 km/h and at an actual time gap that is equal to the reference setting of 1 s. At $t=10$ s, a cut-in vehicle appears. This can be seen as the instantaneous reduction of the actual time gap, stepping from 1.0 to 0.55 s. At the same instant, the cut-in causes an automatic transition from CACC to ACC. This is accompanied by an increase of the reference time gap from 1.0 to 1.5

s, in line with Table 1-3. The controller responds by reducing the speed, thus starting to increase the time gap towards the setpoint. At $t=17$ s, there is another step on the actual time gap, from 0.9 to 1.3 s. This is the moment that the cut-in vehicle has moved to the adjacent lane (cut-out). The controller still remains in ACC mode and time gap is still being increased towards 1.5 s. At $t=19.5$ s, the driver of the trailing truck switched the control mode manually from ACC to CACC. This makes the setpoint change back to its original value of 1.0 s. The controller responds by temporarily increasing the truck's speed, thus making the actual time gap match the reference value again.

Part of the EcoTwin3 platooning concept was Driver State Monitoring. This consisted of the driver being prompted by an audio signal to respond by briefly pressing the throttle pedal. This was done every 2-4 minutes (random within this interval). If the driver did not respond within 5 s after the prompt, CACC would automatically revert to ACC, with a larger time gap as specified in Table 1-3.

This platooning system must be considered as a prototype system, not as production type system that has gone through type approval processes. Therefore, the trials can only be conducted if an exemption is granted by the authorities. In the Netherlands, assessment of an exemption requests is done by the Rijksdienst voor het Wegverkeer (RDW). On 8 June 2022, the exemption for the Truck Platooning Trial was granted (RDW exemption number: 2022TI002002).

In the exemption, allowed weights have been specified. The trailers were loaded with concrete blocks to meet these requirements. The allowed and actual weights are shown in Table 1-4; weighing was performed with full fuel and AdBlue tanks, without driver/passenger.

Table 1-4 Allowed and actual weight of the trucks.

Vehicle name	Vehicle licence	Allowed weight range (kg)	Actual weight (kg)
ET3	15-BJF-9	23.795 +/- 750	24.100
ET2	25-BFL-2	26.140 +/- 750	26.240

1.2 Route

The route selected for the trials partially overlaps with the Rhine-Alpine corridor within the Trans-European Transport Network (TEN-T). The route is shown in Figure 1-7, covering motorways between Rotterdam and Venlo.



Figure 1-7 The route selected for data collection: Rotterdam – Venlo over the A15 / A16 / A58 / A2 / A67 motorways (partially overlapping with the Rhine-Alpine corridor within the Trans-European Transport Network, TEN-T). Also indicating the C-ITS test site on the A16 and the two bridges that were instrumented.

1.3 C-ITS functions

C-ITS functions were realised by means of Infrastructure-To-Vehicle (I2V) and Vehicle-To-Infrastructure (V2I) communication. In the UMneo TPT, C-ITS functions were tested on a part of the experimental route over the A16. On this motorway, between Ridderkerk and Dordrecht, there was a trial site that has been used within multiple European projects (e.g. InterCor and CONCORDA). The V2I component informed the roadside system that trucks with platooning functions activated were approaching a specific part of the route. The I2V component enabled the roadside system to send specific instructions to the platooning vehicles. For this, two test cases were prepared (see Figure 5).

- When approaching the Drechtunnel, the C-ITS display instructs the drivers to disengage the platoon. This is done in both driving directions.
- When approaching specific weaving sections (one in the Northbound direction and one in the southbound direction), the C-ITS display instructs drivers to set the time gap to its maximum value.

Thus, C-ITS only presented instructions for the drivers on the HMI; there was no automatic actuation on the received information. The drivers were instructed to comply with the instructions given on the C-ITS display. After the trucks passed these specific locations, the instructions were revoked.



Figure 1-8 Locations on the A16 C-ITS test sites where test cases were conducted.

The C-ITS messages were presented to the drivers on a separate HMI. The display always showed one message out of a total set of three messages:

- “Platooning: no restrictions” (this is the default text)
- “Platooning: not allowed, disengage”
- “Platooning: use maximum time gap”

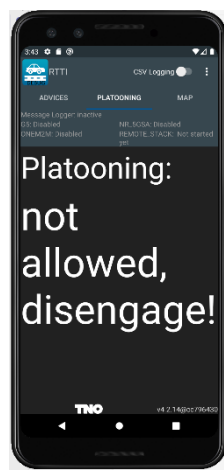


Figure 1-9 The C-ITS HMI (screen diagonal: 151.8 mm).

An example of the C-ITS information on the actual HMI is shown in Figure 1-9. When the text on the display changed, a notification sound was played. As part of their pre-test training, the drivers were informed about all these C-ITS elements (message set and notification sound) that they might

encounter and what was expected of them. This was done to minimise their workload due to this HMI.

1.4 Study design and procedures

The study design was largely constructed as a controlled field experiment. This means that the platoon condition (condition of the entire platoon: manual/ACC/CACC) and the platoon time gaps and the route to follow were all pre-determined in the design of the study. The combination of manual driving with ACC or CACC at two time gaps leads to a total of five experimental conditions. The manual condition was without ACC, CACC or any other Advanced Driver Assistance System (ADAS). The only exception was the Forward Collision Warning (FCW) function as explained in Section 1.1, which was operational in all driving modes. The platoon had a fixed maximum size of two trucks. One truck was assigned the leading role and the second truck was assigned the trailing role.

Given the nature of the platooning system and the exemption conditions that allow it on public roads, special requirements held for the drivers of the trucks. These included: to have a valid CE truck driving license; having received instruction and briefing of how the platooning system works; having received additional TNO or external driving training, and at least 8 hours of driving with the platooning application per year of which the first 8 hours must be on a test track. In total, four drivers participated in the trials. The general instruction was to stay in the rightmost lane and to adhere to traffic rules. They fulfilled the role of so-called safety drivers rather than ordinary end users of a platooning system, meaning that their task was to monitor the correct functioning of the system at all times, to intervene when necessary, and to ensure that the platoon would not cause issues for surrounding traffic.

In addition to the drivers, there always was a third person present during the trials. This was the operator, who was responsible for monitoring the status of the platooning application and for logging. The operator sat in the passenger's seat of the trailing truck. During the trials, both drivers and the operator used a shared voice communication channel. Via this channel they continuously updated each other about presence and behaviour of nearby traffic participants, thus ensuring a common situational awareness. The operator also verbally guided the drivers about the route to follow.

The total number of days involved was 20, distributed between the 1st of June 2022 and the 30st of September 2022. During a typical test day, four different platooning conditions were tested in trips of approximately 90 minutes each. The order of the platooning condition was varied for different days to balance the road and traffic conditions, see D1.2 for further details. After each trip, drivers completed questionnaires to assess their workload, trust and acceptance.

In the trial design, trips were defined to be in a given platoon condition, being ACC or CACC (with a specific time gap setting), or in manual mode. The control modes as actually realised during the trips were logged and analysed. It should be noted that the actual control mode could not fully match the design control mode. First of all, the CACC function was only available for the trailing truck (see Table 1-5). This implies that in CACC trips, the leader would be driving with ACC (with possibly some manual driving as well). Furthermore, even for the trailing truck, CACC could only be activated after the driver had activated ACC. Thus, trips that were designed to be in CACC would involve some portions of manual and ACC driving as well. Similar, trips that were designed to be in ACC mode would also contain some portions of manual driving.

Table 1-5 Relationship between platoon condition and intended control mode per truck.

Platoon condition	Intended truck control mode	
	Leading truck	Trailing truck
Manual	Manual	Manual
ACC	ACC	ACC
CACC	ACC	CACC

The Operational Protocol that was defined as part of the exemption process contained several additional rules:

- All tests were conducted in daylight.
- Test were only conducted on working days (Monday – Friday).
- The platooning application was only used in favourable weather conditions:
 - o no heavy rain;
 - o no sleet/snow;
 - o no dense fog;
 - o no hard wind.
- There were several tunnels in the route. The drivers would always switch off CACC before entering the tunnel. After leaving the tunnel, the platooning system could be activated again.
- The platooning application was not used in exceptional situations, such as nearby emergency vehicles, accidents or road works.
- Drivers were instructed to anticipate to potentially merging vehicles from other lanes, and to increase their gaps manually if necessary.
- When the trucks had to execute lane changes, it was at the discretion of the drivers if they did this with ACC or CACC still activated, or by switching to manual driving.

With the instruction to strictly adhere to the traffic rules, they would under normal traffic conditions aim to drive at their legal speed limit of 80 km/h. It should be noted that trucks on Dutch motorways typically drive a bit faster than this. Dicke-Ogenia et al. (2020) reported average truck speeds of typically around 90 km/h on various locations in the Dutch motorway network.

To incorporate traffic flow data into the analysis, GPS data and the corresponding time stamps were exported for an enrichment process. Based on the GPS coordinates and the heading of the trace, the vehicle was projected on the Dutch road network. The network that was used was based on the Nationaal Wegenbestand (NWB). This resulted in average traffic volume and traffic speed data (one-minute averages) becoming available in the vehicle data. How these data were used in the analysis will be covered in Section 2.5.

1.5 Data validation

The process of data validation that was conducted prior to the analysis is described in Deliverable 3.2A (Hogema et al., 2022). The various data sources have been checked independently from each other as well as in cross-checks. A few trips had to be excluded from the analysis because of technical issues. These were exceptional: the vast majority of data were marked as suitable for analysis. In the GPS data, missing data occurred systematically in and near the tunnels on the route. Measures were taken to ensure that the analysis would not be affected.

The validation phase included marking parts of the data that were not on the route described in Section 1.2: these were excluded from the analysis. The total amounts of data suitable for analysis are shown in Table 1-6 and Table 1-7, distributed by platoon condition and truck role. Both tables are copied from D3.2A.

Table 1-6 Total number of kilometres on the experimental route by platoon experimental condition and by truck role, see ref D3.2A.

Platoon condition	Leader [km]	Trailer [km]
ACC (1.5 s)	1103	1105
ACC (2.0 s)	898	1010
CACC (1.0 s)	1187	1194
CACC (1.5 s)	1073	1039
Manual	982	988
Total	5243	5335

Table 1-7 Total driving time (minutes) on the experimental route by platoon experimental condition and by truck role, see ref D3.2A.

Platoon condition	Leader [min]	Trailer [min]
ACC (1.5 s)	888	889
ACC (2.0 s)	694	803
CACC (1.0 s)	926	929
CACC (1.5 s)	873	846
Manual	801	806
Total	4183	4274

2 Vehicle and Traffic impact on safety indicators (MT1)

2.1 Methodology

As described in Deliverable 3.2A (Hogema et al., 2022), the raw vehicle data were synchronised and stored at a uniform 10 Hz sampling frequency. Various derived measures were calculated from the logged measures. Specifically:

- The *distance gap* was defined as the distance [m] between the ego vehicle's leading surface and the trailing surface of the lead vehicle (SAE, 2014). This measure was obtained as a direct measure in the log data from the radar and camera sensors (see D2.1: Goos, Wissingh & Van Kempen, 2021).
- The *time gap* was defined as the time interval [s], needed for the ego vehicle's leading surface to reach the current location of the trailing surface of the lead vehicle assuming a constant speed of the ego vehicle. It was calculated as a time series by dividing the current distance gap by the absolute speed of the ego vehicle [m/s].
- The *Time to Collision (TTC)* was defined as the duration [s] required for the ego vehicle to strike the lead vehicle, assuming that the relative speed remains unchanged (SAE, 2014; Van der Horst, 1991). It was calculated in each sample by dividing the distance gap by the relative speed [m/s].
 - When the sign of the relative speed was such that the gap was opening, TTC was infinite or not defined.
 - When the sign of the relative speed was such that the gap was closing, TTC was calculated as explained above. TTC values above 60 s were truncated at 60 s.

2.1.1 Levels of analysis and Performance Indicators

The analysis of this Macro Topic 1 was performed on two main levels, as shown in Figure 2-1.

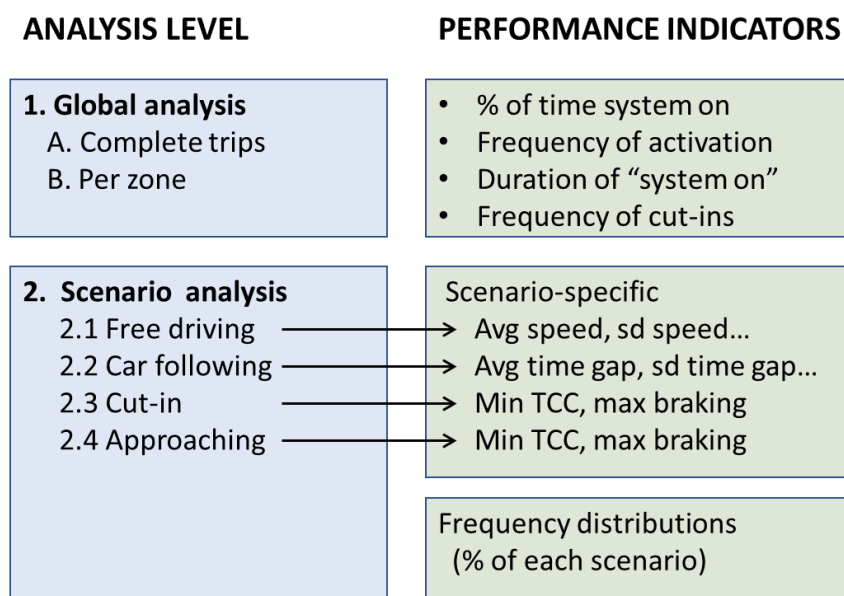


Figure 2-1 Macro Topic 1 analysis overview.

The first was the **global analysis level**. This analysis level covers Performance Indicators (PIs) that can only be obtained over a longer period, such as the percentage of time in a given control mode or the frequency of events. This global analysis was conducted at two geographical sublevels. The first was the **trip level**, covering the entire trips of approximately 90 minutes of driving in one experimental condition (as explained in Section 1.4). The second sublevel was the **zone level**. The following three geographical zones were defined: (see also depicted in Figure 2-2)

- ★ Zone 1: the A67 near Venlo until Junction Leenderheide
- ★ Zone 2: Junction Batadorp (A58) until exit nr 20 ('s-Gravendeel) on the A16
- ★ Zone 3: exit nr 20 ('s-Gravendeel) until A16 (end of the route).

These zones cover most of the entire route. The only exception is the beltway around Eindhoven which was excluded. It should be noted that one trip may cover one or more zones or parts thereof, depending on where the trip was started and stopped. The zones were expected to vary in terms of complexity of driving, due to differences in road and traffic conditions. Zone 1 was relatively straightforward: a two-lane motorway with an occasional on-ramp or off-ramp. Zone 3 was relatively complex: it was characterised by more on-ramps, off-ramps, weaving sections, and tunnels. These zones were analysed without making a distinction between the driving directions. Zone 2 was analysed per driving directions. Driving westbound (Venlo towards Rotterdam), the zone was relatively simple, similar to Zone 1. Driving eastbound, (Rotterdam towards Venlo), the trucks had more weaving sections to negotiate. In total, this classification resulted in 4 zones in the analysis: Zone 1, Zone 2 westbound, Zone 2 eastbound, and Zone 3.



Figure 2-2 The three zones within the overall route.

Performance Indicators for the global analysis level were the following:

- a. The percentage of time that ACC or CACC was active.
- b. The frequency of ACC or CACC activations.
- c. The frequency of cut-in manoeuvres that the trucks were confronted with.

This global analysis also covered platooning performance in terms of:

- a. The distribution of time that ACC/CACC remained active after activation (which is closely related to the frequency of activations mentioned above).
- b. A classification of how ACC/CACC was deactivated. For instance, by manual deactivation by the driver, due to a cut-in, etc.

The second level of analysis was the **scenario-based analysis**. Here, the trip data were first separated into scenarios, and next, a set of PIs was calculated for each individual scenario. These processes are further explained in the following sub-section.

2.1.2 Scenario definition and detection at the single vehicle level

The process of scenario detection was initially conducted at the level of individual trucks. This was done generically for an 'ego vehicle', which could be either the leading or the trailing truck and was independent of the truck condition. In a second step, these truck-based scenarios were extended to the level of platoon-based scenarios. This will be detailed further in Section 2.1.3; the current section deals with scenarios at the level of an individual vehicle.

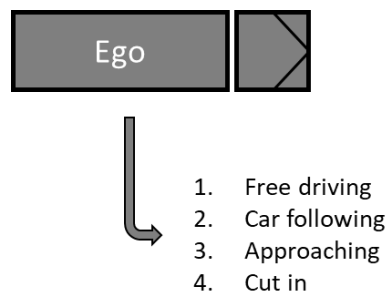


Figure 2-3 Scenarios at the single vehicle level.

On the individual vehicle level, the following four scenario types were distinguished:

1. Free driving
2. Car following¹
3. Approaching
4. Cut-in.

The overall approach is similar to scenario detection as applied in projects like L3Pilot (Weber et al., 2021). Parameter values that were used in the definitions below were also based on earlier work. The process of scenario detection is based on the assumption that only one scenario can be active at any instant. The scenario set used in this report did not cover all driving situation. For example,

¹ "Vehicle following" would be a more generic term, more appropriate when a truck is being followed instead of a car. However, given the widespread use of the term *car following* in research, this term will be used throughout this report.

when the trucks were performing a lane change or were approaching a traffic jam. When none of the four scenarios applied, the label 'other' was applied.

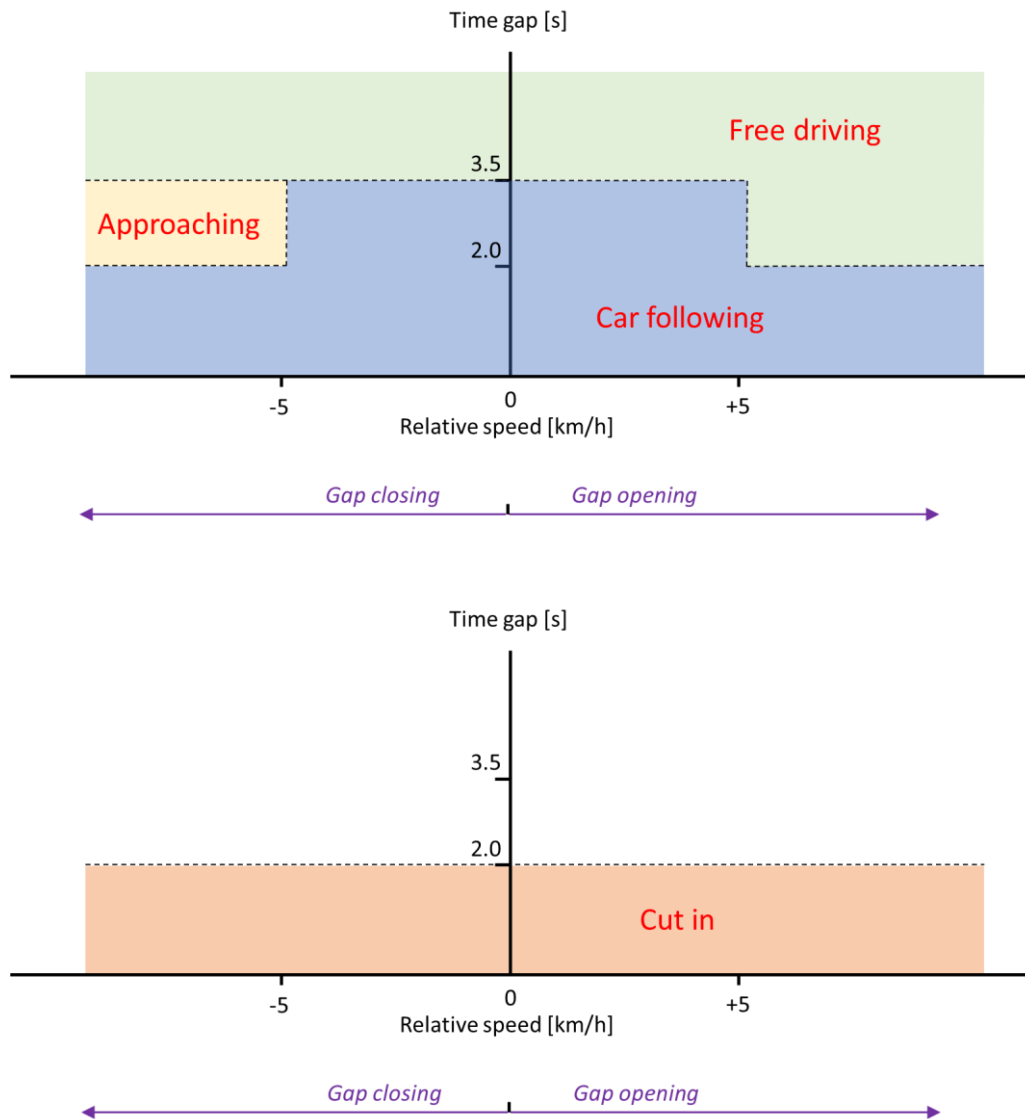


Figure 2-4 Phase plane representation of time gap versus relative speed in scenario detection for a single individual vehicle. Top: free driving, car following and approaching. Bottom: cut-in.

The classification rules are visualised in Figure 2-4 in a phase plane representation, with the time gap on the vertical axis and the relative speed on the horizontal axis.

- During the **free driving** scenario, the truck was following its lane without being influenced by other vehicles ahead in its lane. The truck was detected to be free driving when the time gap between the truck and the lead vehicle was larger than 3.5 s, or when the lead vehicle was driving at least 5 km/h faster than the truck while the time gap was larger than 2 s, or when no lead vehicle was present in the ego lane.
- The **car following** scenario was detected when the truck was following a lead vehicle at a time gap smaller than 2 s, or if the time gap was smaller than 3.5 s time gap while the absolute relative speed was less than 5 km/h.
- The truck was **approaching** a slower lead vehicle in its lane when the relative speed between the slower vehicle and the truck was larger than 5 km/h. In this case the gap size between

the vehicles was decreasing. The lead vehicle had to be driving within 2 s and 3.5 s time gap to the truck.

- The analysis of **cut-in** manoeuvres was restricted to cut-ins that were experienced by the trucks ('passive cut-ins'); cut-ins that were conducted by the trucks ('active cut-ins') were beyond the scope of our analysis. Thus, when this report mentions cut-in scenarios, this always refers to passive cut-ins. Cut-ins were detected when a vehicle changed lanes directly in front of one of the ego vehicles, into the lane of the ego vehicle, within a time gap of 2 s. This threshold was chosen to prevent detection of cut-ins which do not influence the behaviour of the truck, since they were too far away. Cut-ins were independent of the speed of the vehicle or whether the lane change was from left to right or vice versa. The starting point of the cut-in was the point at which the vehicles' centre was closest to lane marking and the vehicle was moving towards the trucks' lane centre.

In the data it may occur that the combination of time gap and relative speed fluctuated around the thresholds shown in Figure 2-4. This typically resulted in frequent switching between approaching and car-following scenarios. This was eliminated by removing approaching scenarios between two car-following scenarios if the distance gap between the vehicles did not decrease more than 30% in the approach scenario

Slices of constant situational and design variables

Before the scenario PIs were calculated, the data were sliced into time periods where both the scenario and the platooning parameters (control mode and time gap setting) were constant. This is illustrated in Figure 2-5.

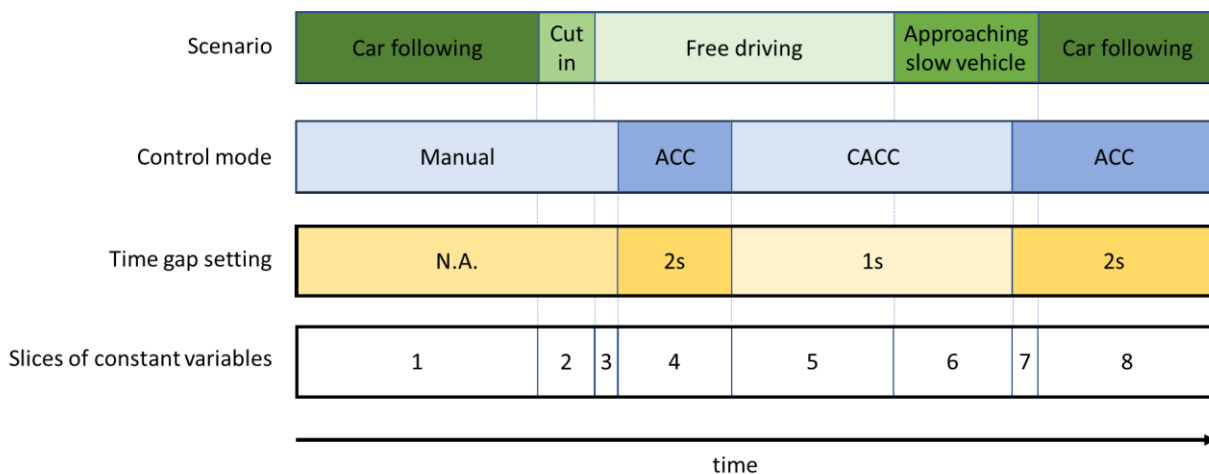


Figure 2-5 Visualization of slicing data into constant situational and design variables.

Two scenarios can show a wide variation in duration: free driving and car-following. At the same time, several performance indicators of these scenarios are influenced by the duration of scenarios (for instance, minimum/maximum and standard deviation / variance). To prevent the scenario duration from confounding the results, the slices from these two scenarios were sliced further into sections of 10 seconds. Basically, this is the same approach as suggested by Dozza, Bärgrman, and Lee (2013). The largest possible number of 10 s slices fitting into the original slice was determined.

The starting point for the first slices was chosen at random, such that at the begin and end of the initial slice a portion smaller than 10 seconds remained (see Figure 2-6). These remnants were disregarded in the analysis, as illustrated in Figure 2-6.

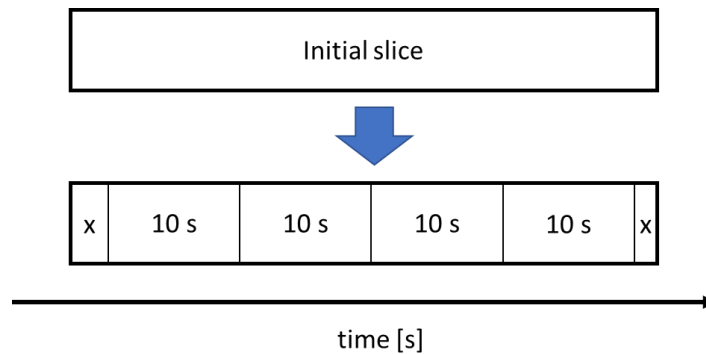


Figure 2-6 The process of slicing car-following or free driving sections into 10-s portions (the 'x' sections are removed from analysis).

The process above resulted in a list of slices, for each trip, with the start time, the end time and the scenario type of the slice. Based on this list, the Performance Indicators from Table 2-1 were calculated for each slice. As this table shows, there were four measures involved: speed, time gap, deceleration, and Time-To-Collision. For each slice, the PI calculations were done in the following steps.

- First, the time series of the four measures were retrieved for the slice under consideration.
 - When a measure is called x , and there are n samples in the slice, the time series consists of samples x_i with i ranging from 1 to n .
- Next, the mathematical operators specified in Table 2-1 were applied to these time series.
 - The *Average* operator consisted of taking the arithmetic average of the measure. Thus, the average $\bar{x}$ is defined as:

$$\bar{x} = \frac{\sum_{i=1}^n x_i}{n}$$

- The *Standard deviation* operator calculated the sample standard deviation, to obtain an unbiased estimation of the standard deviation (see e.g. Aron & Aron, 2003):

$$sd = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n - 1}}$$

In this way, the PIs were obtained for each individual slice. This data set was used as input for the statistical analysis that will be explained in detail in Section 2.1.5.

In the analysis only slices of data where the actual truck condition matched the targeted control condition were considered. This means parts of the trip in which CACC temporarily fell back to ACC or manual driving were disregarded.

Table 2-1 Scenario-based Performance Indicators for MT1 (source: D1.2).

Performance Indicator	Measure	Operator	Units	Relevant scenarios
Average speed (km/h)	Speed	Average	km/h	Free driving
Standard deviation of speed	Speed	Standard deviation	km/h	Free driving
Average time gap	Time gap	Average	s	Car-following
Maximum deceleration	Deceleration	Maximum	m/s ²	Approaching slower lead vehicle
Minimum Time-To-Collision	Time-To-Collision	Minimum	s	Approaching slower lead vehicle
Maximum deceleration	Deceleration	Maximum	m/s ²	Cut-in
Minimum time gap	Time gap	Minimum	s	Cut-in
Minimum Time-To-Collision	Time-To-Collision	Minimum	s	Cut-in

2.1.3 Platoon level versus truck level: scenarios

In Section 2.1.2, the scenarios detection at the level of a single vehicle has been presented. In the context of the Truck Platooning Trial, scenarios are also considered for the leader and the trailer truck at the same time. This leads to the possible combinations shown in Figure 2-7.

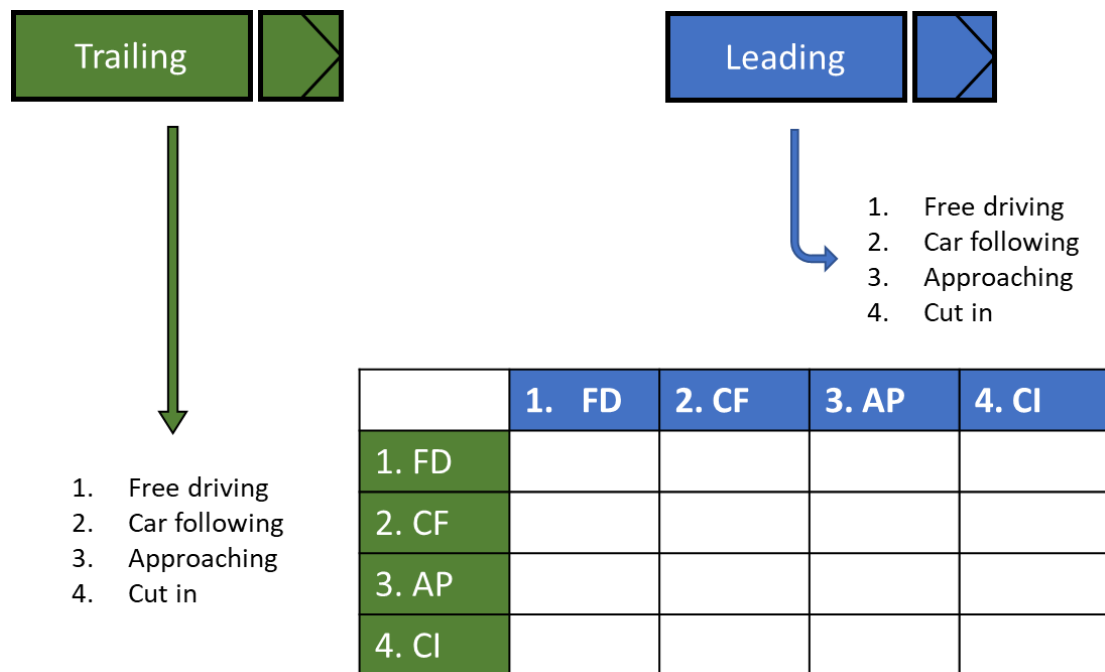


Figure 2-7 From scenarios at the single vehicle level to the platoon level.

2.1.4 Platoon level versus truck level: control modes

The experimental conditions as specified on the study design (Section 1.4) were manual driving, ACC and CACC. These were defined on a trip level, and as a condition for the entire platoon. However, one level deeper, this setting has different implications for the leader than for the trailer (see Table 2-2). For manual and ACC driving, both trucks can use the control mode as specified by the platoon condition. The CACC function, on the other hand, can only be activated by vehicles that are driving behind another platoon member, because this function depends on the availability of V2V. Thus, in trips where the platoon condition was CACC, only the actual control mode of the trailer was CACC, whereas the control mode of the leader was ACC.

Table 2-2 Relationship between platoon conditions and truck conditions (study design level).

Platoon condition	Intended truck condition	
	Leading truck	Trailing truck
Manual	Manual	Manual
ACC	ACC	ACC
CACC	ACC	CACC

These conditions on the study design level, defined as the intended control modes of an entire trip. At the same time, within the actual trips, there will always be portions with manual driving, even if the intended control mode is ACC or CACC. Similar, when the intended control mode is CACC, even the trailer will also be using ACC driving part of the time (because CACC can only be activated from the ACC mode). The actual control mode is one of the Performance Indicators that will be investigated. This control mode was initially logged on the level of individual trucks: the *truck control*

mode. In the analysis, the control modes of both trucks are combined into a *platoon control mode*. How this was done is illustrated in Figure 2-8. The classification rules were as follows:

- If the trailing truck was in CACC mode and the leading truck in ACC mode, the platoon mode was labelled CACC;
- Else, if both vehicles were in ACC mode, the platoon mode was labelled ACC;
- Else, the platoon mode was labelled as Manual.

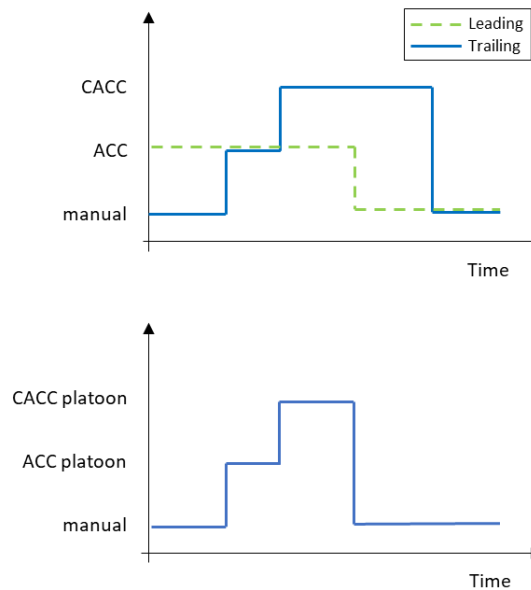


Figure 2-8 Relationship between of leader and trailer longitudinal control modes (top figure) with resulting platoon mode (bottom figure).

2.1.5 Statistical designs

Overviews of available data for the analysis were presented in Deliverable 3.2A (Hogema et al., 2022). For the condition driving with ACC, data were available for three time gap settings for the trailer as well as the leader. Thus, the statistical analyses were covered with two designs, illustrated in Figure 2-9. The statistical tests conducted were linear mixed-effects models with designs as explained below. In addition to the description below, driver ID was used as a random factor. These designs were applied both at the trip level and at the scenario level. The zone based analysis was of a more exploratory nature; here, no statistical tests were conducted.

- In Design A, there were two independent variables: the truck role (leader or trailer) and the truck condition (with four levels: ACC at three different time gap settings as well as the manual condition). The interaction effects (truck condition X truck role) was also included in the model.
- In Design B, only the trailing truck is involved. One independent variable 'truck condition' was used, with six levels: ACC with three time gap settings, CACC with two time gap settings, and the manual condition.

Design A

Truck condition	Leader	Trailer
ACC (1.5 s)	x	x
ACC (1.75 s)	x	x
ACC (2.0 s)	x	x
CACC (1.0 s)		x
CACC (1.5 s)		x
Manual	x	x

Design B

Truck condition	Leader	Trailer
ACC (1.5 s)	x	x
ACC (1.75 s)	x	x
ACC (2.0 s)	x	x
CACC (1.0 s)		x
CACC (1.5 s)		x
Manual	x	x

Figure 2-9 Designs in the statistical analysis. Crosses indicate cells in the matrix where data are available; the coloured parts show conditions included in the designs.

- Design A: ACC at three time gap settings and manual, including role (L, T) as a factor; this design uses the cells marked green.
- Design B: ACC, CACC and manual (only for the trailing truck); this design uses the cells marked blue.

In the results, marginal means from the statistical models will be presented broken down by the various experimental conditions. These are the means of the respective conditions, after accounting for the variation caused by the other factors. Due to different drivers distributions in Design A and Design B, minor deviations of the results can occur between these two designs.

2.2 Trip-based results

This section presents the results on the trip-based level. The total amounts of data used in the analysis were summarised in Table 1-6 and Table 1-7 in terms of time and distance travelled. The distribution of trip durations is shown in Figure 2-10; the median trip duration was 74 minutes.

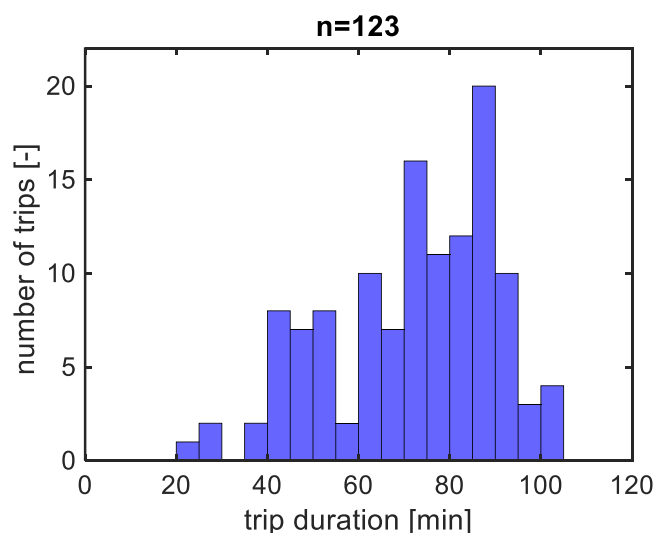


Figure 2-10 Distribution of trip duration.

2.2.1 Percentage of trip time with ACC/CACC active

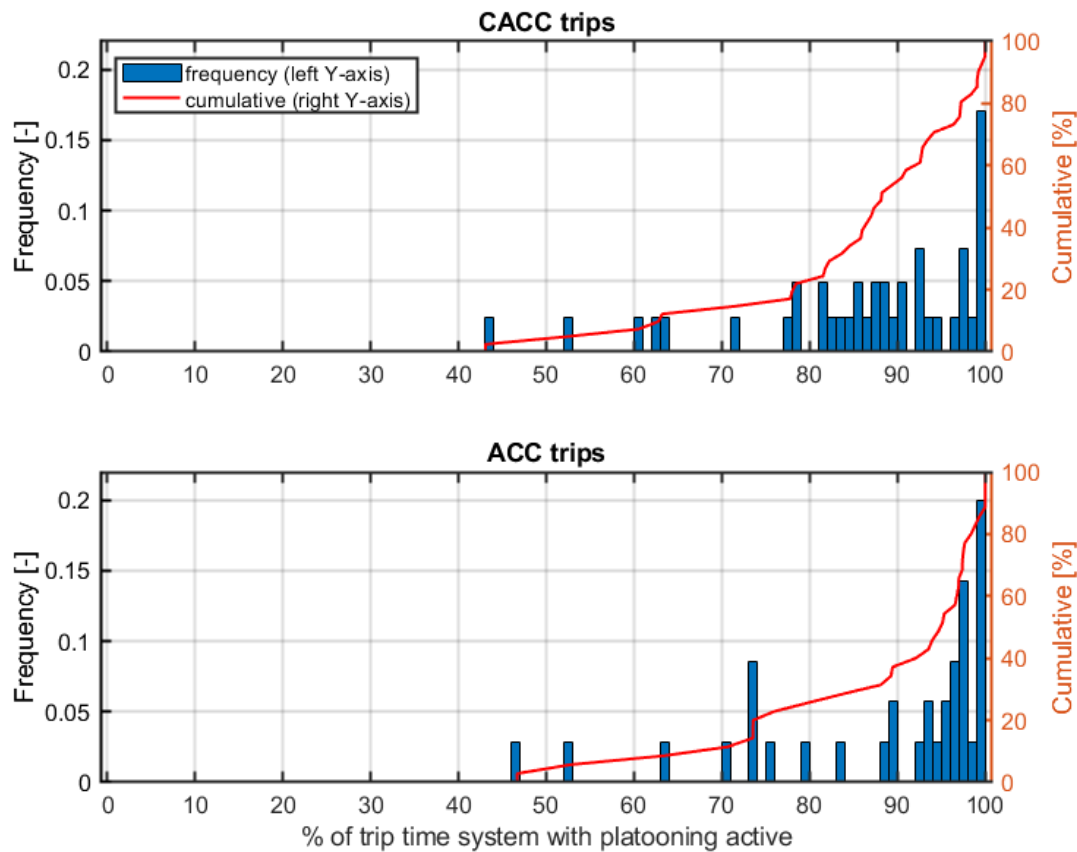


Figure 2-11 Distribution of % of trip time with platooning active (i.e., functions active in both trucks at the same time).

Distributions of the percentage of trip time that functions (ACC or CACC) were active simultaneously in both trucks are shown in

Figure 2-12. This is done separately for trips where ACC was to be used and trips where CACC was to be used. The horizontal axis shows the percentage of trip time that the platoon was in ACC platoon mode or in CACC platoon mode, as defined in Section 2.1.4. A Kolmogorov-Smirnov test showed that these difference between these distributions was marginally significantly [$p=0.079$]: the percentage of time with platooning active typically reached somewhat higher levels in ACC trips than in CACC trips. Medians were 88.2% for CACC and 95.1% for ACC trips.

Summing over all trips, per platooning function, the overall results in terms of platooning control modes are shown in Table 2-3. For the relationship between these modes on platoon and truck level, see Section 2.1.4.

Table 2-3 Percentage of trip time in the different control modes on the platoon level, as a function of intended platooning condition.

Intended platoon condition	% of time platoon ACC	% of time platoon CACC	% of time no platoon	% of time total
ACC	90.1	0 (N.A.)	9.9	100.0
CACC	13.8	71.6	14.6	100.0

Table 2-4 Percentage of trip time functions were active on a truck level, as a function of truck role and platooning condition.

Truck role	Intended platoon condition	% of time ACC active	% of time CACC active	% of time manual	% of time total
Leader	ACC	93.3	- (N.A.)	6.7	100.0
	CACC	87.5	- (N.A.)	12.5	100.0
Trailer	ACC	93.3	- (N.A.)	6.7	100.0
	CACC	14.2	76.2	9.6	100.0

2.2.2 Activation duration

The distribution of system activation phases on the trip level is shown in

Figure 2-12, for CACC as well as ACC. A Kolmogorov-Smirnov test showed that these distributions differed significantly [$p < 0.001$]. The medians were 0.52 minutes for CACC and 4.63 minutes for ACC, showing that ACC platooning phases typically to last longer than CACC platooning phases. Durations longer than 10 minutes are rare for CACC (4.3% of the activations), but still common for ACC (34.6% of the activations).

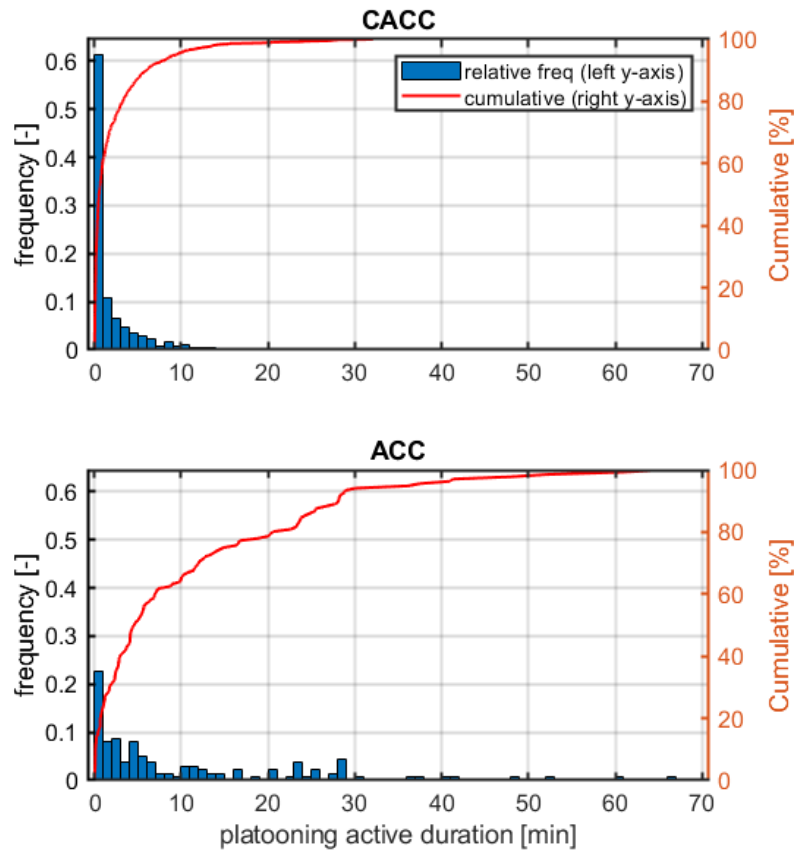


Figure 2-12 Distribution of duration of platooning phases. Histograms with frequencies (left y-axis) and cumulative distributions (right y-axis).

Looking at the large peak of the CACC distribution for durations that lasted shorter than one minute, one might wonder if these very short activations are really to be considered as true activations, or perhaps rather as unsuccessful attempts to activate the system. From the logged data this distinction cannot be made. However, to get some idea about the sensitivity of the results with respect to the ‘very short’ activations, it was investigated how the median of the activation durations varied if durations below a threshold were ignored. The results are shown in Table 2-5: the first row (threshold =0) shows values that match the medians reported above). As the table shows, when introducing such a threshold, an increase of the median activation durations can be observed. This is the case for ACC as well as for CACC; for any threshold choice, the ACC durations remain longer than the CACC durations.

Table 2-5 Effect of a lower duration threshold (for excluding data in the computation) on the median of activation durations, for ACC and CACC trips.

threshold [min]	median duration ACC [min]	median duration CACC [min]
0.00	4.63	0.52
0.25	6.20	1.50
0.50	6.66	2.37
0.75	7.10	2.88
1.00	7.30	3.35

Having seen how the activation durations are distributed, a next question is how the activation was ended, or what caused it to end. This is not explicitly logged, but various possible termination reasons could be identified from the data. These are the following:

- A brake overrule action by the driver (of the leading truck or of the trailing truck).
- A cut-in occurring between the two trucks (i.e., in front of the trailing truck). This would automatically trigger a transition from CACC to ACC mode.
- When driving with CACC, the Driver State Monitor required the driver to respond to an audio prompt that was presented at random intervals (as explained in Section 1.1). Failing to do so would cause the CACC to switch off.
- A 'status_vehicle_longitudinal error':
- A 'nominal gateway error': this occurred if a failure of any of the onboard systems was detected. These are: V2V, GPS, camera, radar, steering actuator, brake actuator, throttle actuator, the HMI, and the CAN connection with the EcoTwin3 truck. When this happened, the driver was alerted by means of an audio warning and an error message on the HMI. At the same time, ACC and CACC actuation were disabled, putting the truck in manual control mode.

For each termination event it was checked if one or more of the reasons listed above were present. If none of these were found, the event was labelled as 'other' (or 'unclassified').

The reasons for the termination of a platooning phase is shown in Table 2-6.

Table 2-6 Relative frequencies of reasons for termination of platooning phases (% of the termination events). (Note: multiple reasons can occur in each termination, therefore the sum of the rows is > 100%).

Reason for termination of platooning phases	Intended platoon condition	
	ACC	CACC
Other (= unclassified)	39.0 %	59.3 %
Cut-in in front of Trailer	16.2 %	16.2 %
Brake overrule Leader	23.5 %	1.2 %
Brake overrule Trailer	14.0 %	4.4 %
Driver failed to react to the Driver State Monitor	n.a.	14.7 %
Status vehicle longitudinal error	11.8 %	2.1 %
Nominal gateway error trailing truck	2.9 %	3.2 %
status_hw_arbiter error	2.9 %	3.2 %

Table 2-6 shows that the relative number of platoon terminations due to the nominal gateway error is higher for the CACC platoon than the ACC platoon. This is expected since platooning requires more components which can potentially fail.

2.2.3 Frequency of cut-in scenarios

The frequency of cut-in manoeuvres experienced by the trucks was expressed as the number per hour. Results are shown in Figure 2-13.

Design A showed a significant effect of Role [$p < 0.001$] showing that the leader had a higher cut-in frequency than the trailing truck (averages 69 and 12 per hour, respectively). Planned comparisons showed that the difference between leading and trailing truck was significant in all conditions [all $p < 0.001$], with the exception of ACC at a 1.5 s time gap [$p = 0.19$]. Within both roles, no significant differences occurred among the four conditions (manual + 3x ACC) [all $p > 0.16$].

Looking at results of Design B (comparing all conditions, only within the trailing truck), no significant differences were found among the conditions in planned comparisons [all $p > 0.8$].

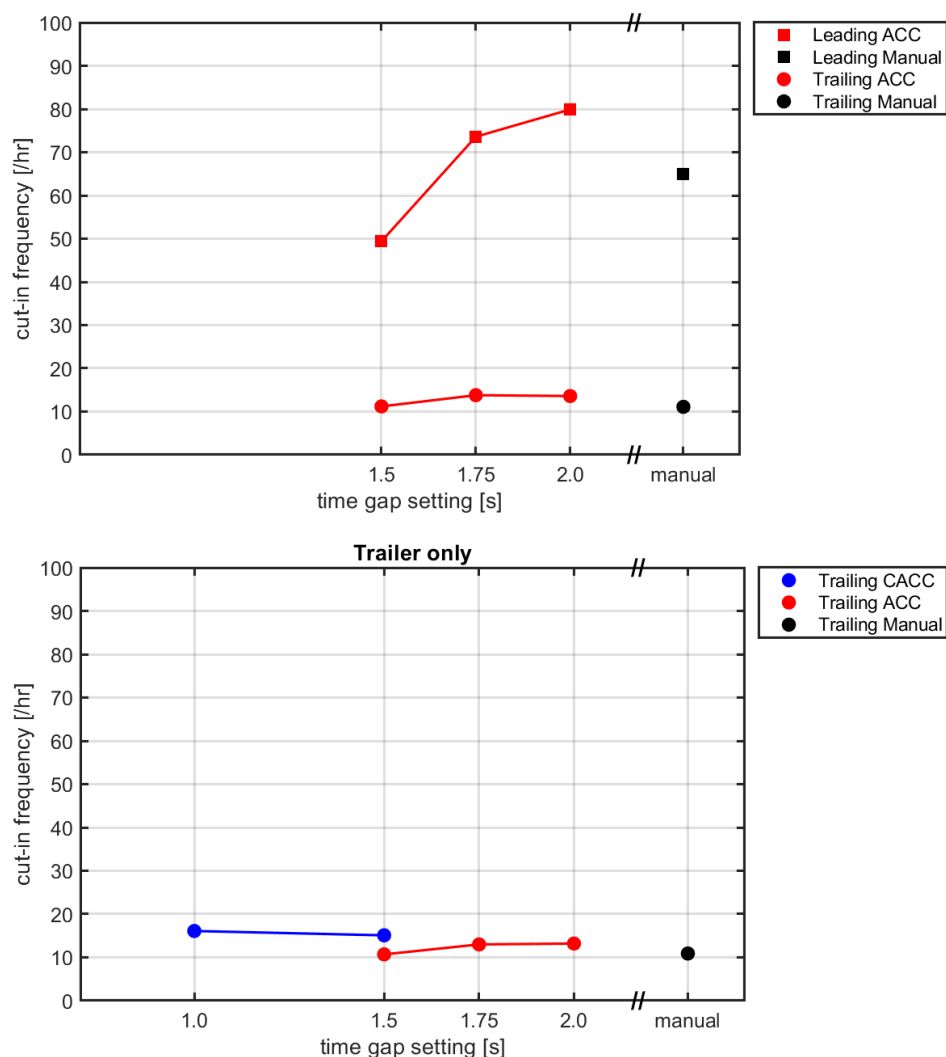


Figure 2-13 Frequency of cut-in manoeuvres as a function of experimental conditions (top: Design A; bottom; Design B).

2.3 Zone based results

From the total route, several zones were selected to explore how parts with different road complexity might influence the results. These were introduced in Section 2.1.1: Zone 1 and Zone 2 WB were relatively simple whereas Zone 2 EB and Zone 3 were more complex, with many tunnels, weaving sections and on/off-ramps. The analysis was restricted to the percentage of time that the ACC/CACC systems were active and to the frequencies of cut-ins.

Table 2-7 and Table 2-8 show the percentage of time respectively ACC or CACC was active per zone and per truck role. In the ACC condition, the zone did not have an effect on the time the system was active. On the other hand, in CACC condition the system activation was dependent on the zone. In Zone 2 EB and Zone 3, the percentage of time CACC was active was lower compared to the other zones.

Table 2-7 Percentage of time ACC was active as a function of truck role and zone.

Role	Intended platooning condition	Zone 1	Zone 2 WB	Zone 2 EB	Zone 3
Leader	ACC	91.5	95.2	95.8	92.9
Trailer	ACC	92.6	93.3	94.9	92.4

Table 2-8 Percentage of time CACC was active as a function of zone.

Role	Intended platooning condition	Zone 1	Zone 2 WB	Zone 2 EB	Zone 3
Trailer	CACC	81.8	88.9	73.4	60.5

Table 2-9 shows the average frequencies of cut-ins as a function of the zone and the platoon role. These numbers are pooled over all control modes (manual, ACC and CACC). The most pronounced effect of zone is found for the trailing truck, where Zone 3 showed a considerably higher cut-in frequency than the other zones. However, for the leader a reverse (but smaller) effect was found, i.e., a somewhat lower frequency of cut-ins in Zone 3.

Table 2-9 Frequency of cut-ins [/hr] as a function of platooning role and zone.

Role	Zone 1	Zone 2 WB	Zone 2 EB	Zone 3
Leading	44.4	50.0	45.5	35.4
Trailing	4.4	6.0	7.1	13.4

2.4 Scenario-based results: overview

As described in Section 1.4, traffic flow data were added in post-processing. These are shown in Figure 2-14. Based on these data, a threshold of 80 km/h for the traffic average speed (1-minute averages) was defined to separate free-flow from congested traffic. Unless mentioned otherwise, trip parts that were in congested traffic were excluded from the analysis. This was about 4% of the scenario instances.

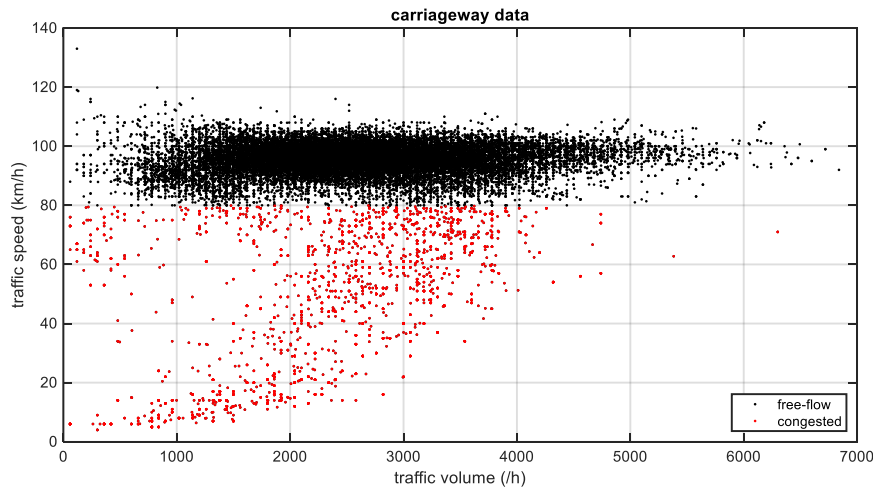


Figure 2-14 Traffic speed as a function of traffic volume: using an 80 km/h threshold to separate free-flow from congested traffic.

The following sections present the results per scenario, aggregated over all control modes (manual, ACC and CACC). The number of scenario instances that was used in the analysis is shown in Table 2-10. A Chi Square test showed that there was a dependency between the scenario occurrences and the truck role [$\chi^2 = 20E3$; $p < 0.001$]. Compared to the leading truck, the trailing truck was relatively frequently in car-following and in approaching scenarios. In contrast, the leader was relatively more frequently in free-driving and in cut-in scenarios. This can be seen as a direct effect of the experimental set-up, where the driver of the trailing truck was instructed to follow the leading truck. Since surrounding traffic often drives faster than our trucks, and is therefore moving away from the leader, the leader was relatively often in free-driving scenarios and cut-ins happen more often to the leader than to the follower.

Table 2-10 Number of scenario instances for leading and trailing truck (all control modes, after removal of congestion).

Scenario	Leading truck	Trailing truck	Total
Free driving	11539	513	12052
Car following	2505	17473	19978
Approaching	76	129	205
Cut-in	4275	541	4816
Total	18395	18656	37051

Table 2-11 Sum of scenario durations for leader and trailer (hours; truck level scenarios).

Scenario	Leading truck	Trailing truck	Total
Free driving	32.1	1.4	33.5
Car following	7.0	48.5	55.5
Approaching	0.1	0.2	0.3
Cut-in	5.0	0.7	5.7
Total	44.1	50.8	94.9

In Table 2-10 and Table 2-11, scenario data from the leading and trailing truck were shown independent from each other. In Table 2-14 it can be seen which combinations of leader and trailer scenarios were occurring simultaneously.

Table 2-12 Combined scenarios: total percentages of time (most prevalent combined scenarios marked; all intended platoon conditions).

Manual trips	Leader scenario				
Trailer scenario	Free driving	Car following	Approaching	Cut in	Total
Free driving	7.1	1.2	0.1	0.5	8.8
Car following	62.4	18.0	0.3	8.3	89.0
Approaching	0.5	0.2	0.0	0.0	0.7
Cut in	0.9	0.4	0.0	0.2	1.5
Total	70.9	19.7	0.4	9.1	100.0

In Table 2-13, Table 2-14, and Table 2-15 the same information is presented for the three intended control modes: manual, ACC, and CACC, respectively. As these tables show, the percentages are fairly similar when comparing the control modes. This shows that the relative frequencies of scenarios are not influenced by the control modes.

Table 2-13 Combined scenarios: total percentages of time (most prevalent combined scenarios marked; intended platoon condition: manual driving).

Manual trips	Leader scenario				
Trailer scenario	Free driving	Car following	Approaching	Cut in	Total
Free driving	4.6	1.0	0.1	0.4	6.1
Car following	62.0	22.2	0.3	7.0	91.5
Approaching	0.5	0.1	0.0	0.0	0.7
Cut in	0.9	0.5	0.1	0.2	1.7
Total	68.0	23.8	0.5	7.7	100.0

Table 2-14 Combined scenarios: total percentages of time (most prevalent combined scenarios marked; intended platoon condition: ACC).

ACC trips	Leader scenario				
Trailer scenario	Free driving	Car following	Approaching	Cut in	Total
Free driving	8.0	1.2	0.0	0.4	9.8
Car following	61.2	18.3	0.2	8.3	87.9
Approaching	0.6	0.2	0.0	0.0	0.8
Cut in	1.0	0.3	0.0	0.2	1.5
Total	70.7	20.1	0.3	8.9	100.0

Table 2-15 Combined scenarios: total percentages of time (most prevalent combined scenarios marked; intended platoon condition: CACC).

CACC trips	Leader scenario				
Trailer scenario	Free driving	Car following	Approaching	Cut in	Total
Free driving	7.2	1.1	0.1	0.6	9.0
Car following	63.9	15.9	0.3	8.9	89.0
Approaching	0.4	0.2	0.0	0.0	0.6
Cut in	0.8	0.3	0.0	0.2	1.4
Total	72.4	17.5	0.4	9.8	100.0

The scenario-based analysis on the platoon level will cover the three most frequent combinations. These were: the trailing truck in car following, and the leading truck in free driving, car following or cut-in.

2.5 Scenario-based results: Individual truck level

This section presents the results from the scenario-based analysis, where scenarios are observed at an individual truck level. See Section 2.1.2 for how each of these scenarios were defined.

2.5.1 Free driving

In free-driving scenarios, two PIs were analysed. These were the average driving speed and the standard deviation of speed. Results are presented in the following sub-sections.

2.5.1.1 Average speed

Average speed was analysed using the two designs explained in Section 2.1. The results of Design A and Design B are depicted in Figure 2-15. The results confirm that the drivers did what they were supposed to do in free-driving situations: maintain the speed limit of 80 km/h. The linear mixed-effects model showed significant effects of truck role and control mode and the interaction effect was significant as well [all $p < 0.01$]. Planned comparisons showed the following.

- In the manual condition, the trailer's mean speed was lower than the leader's mean speed (76.9 and 80.3 km/h, respectively) [$p < 0.001$].
- Within the ACC conditions, no significant differences were found [all $p > 0.3$].

In Design B (depicted in the lower part of Figure 2-15), the difference between manual and ACC at any time gap was significant [all $p < 0.01$]. Among the ACC and CACC, differences were not significant [all $p > 0.4$].

Referring back to 0, it was seen that free-driving scenarios were relatively rare for the trailing truck compared to the leading truck. This is no surprise in a study where the driver of the trailing truck is instructed to follow the lead truck. Therefore, having the trailing truck in a free driving scenario, the drivers would try to close the gap.

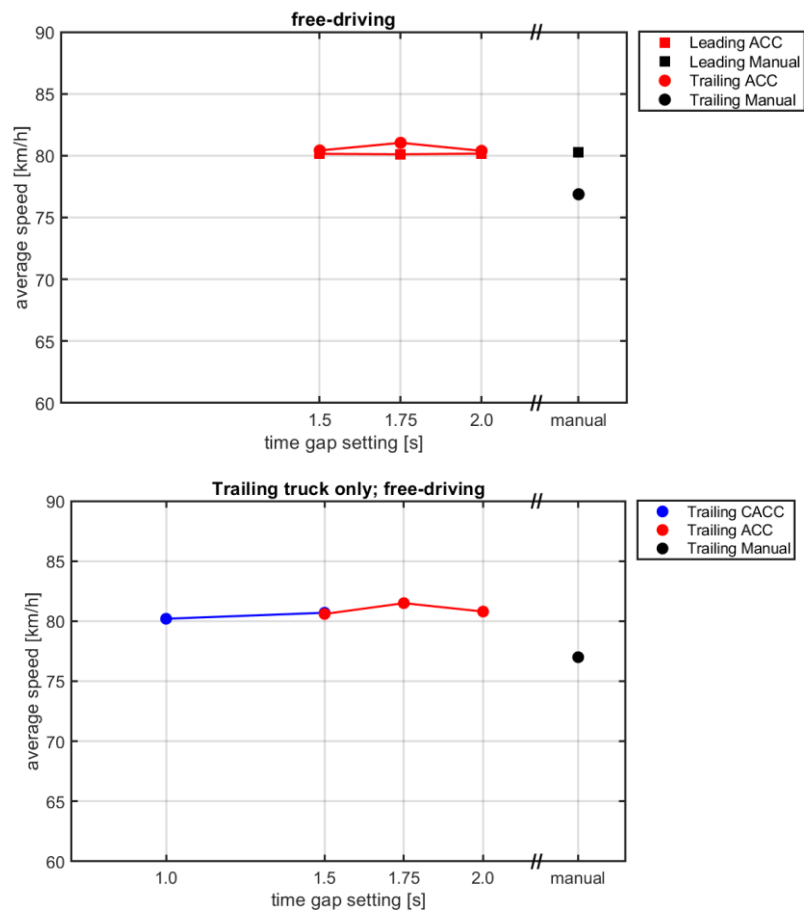


Figure 2-15 Average speed in free-driving scenarios as a function of experimental conditions (top: Design A; bottom; Design B).

2.5.1.2 Speed variation

Results from the linear mixed-effects model with respect to the standard deviation of speed are shown in Figure 2-16.

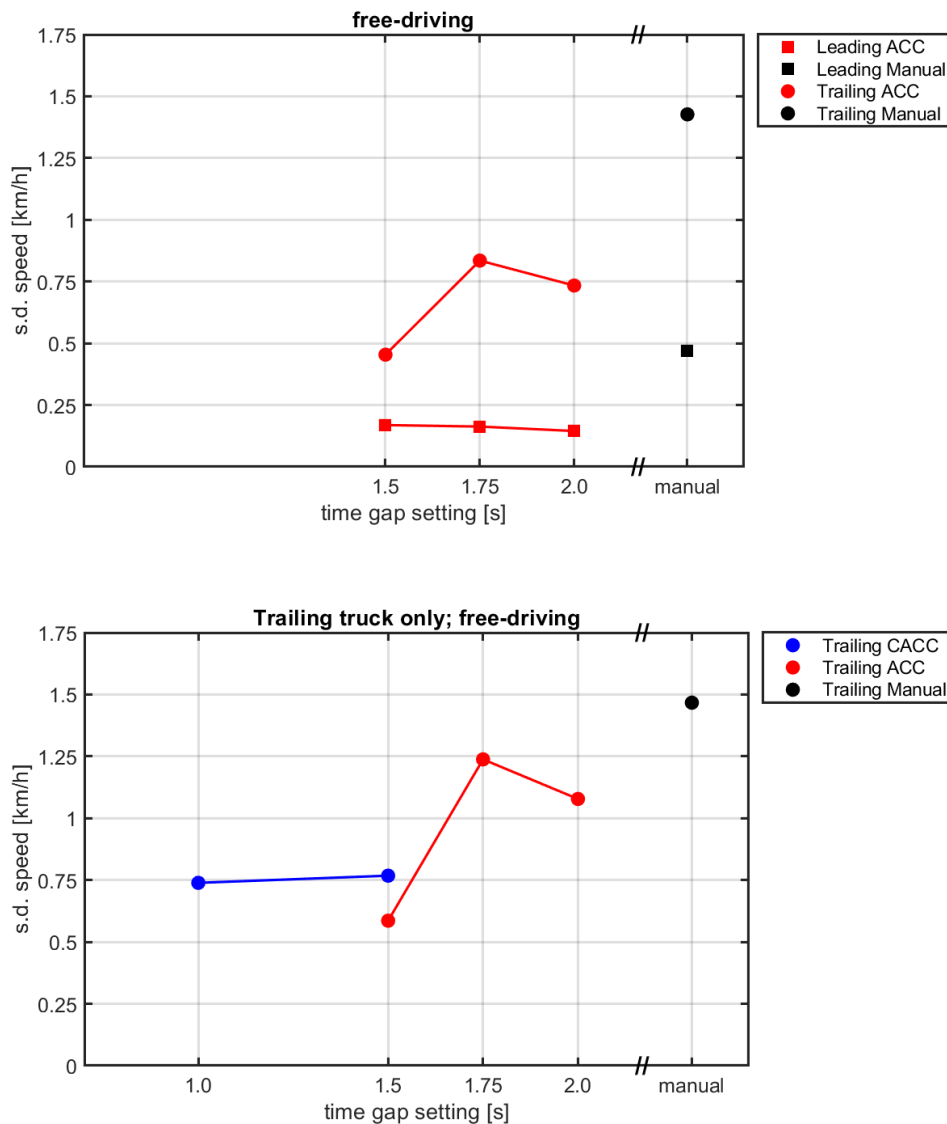


Figure 2-16 Standard deviation of speed in free-driving scenarios as a function of experimental conditions (top: Design A; bottom; Design B).

The statistical analysis showed the following:

- In Design A, there was a main effects of truck role [$p < 0.001$]: the standard deviation of speed was larger for the trailer than for the leader (0.85 and 0.26 km/h, respectively).
- The same analysis also revealed a main effect of truck condition and an interaction effect [both $p < 0.001$]. With respect to these, planned comparisons showed the following:
 - o In manual driving, the standard deviation of speed was higher than when driving with ACC; this effect was significant for both trucks [all $p < 0.001$].
 - o Within the leader, the ACC time gap had no influence on the standard deviation of speed [all $p > 0.8$]. Within the trailer, the difference between the 1.5 and 1.75 time gap settings reached significance [$p = 0.03$], showing a lower value at the 1.5 s time gap setting
- In Design B it was seen again that standard deviation of speed was lower for ACC/CACC conditions compared to manual driving [all $p < 0.001$; only 1.75 s time gap was not significant, $p = 0.8$]. Within CACC, there was no significant effect of time gap. Within ACC, the same

pattern of results was found as in Design A: only 1.5 and 2.0 s setting differed marginally [$p=0.05$], with slightly more variation in the 2.0 setting.

Overall, the results show that both ACC and ACC are realising more steady speeds than drivers do manually. The higher standard deviation of speed seen in the trailing truck is likely caused by the different nature of free driving in the different truck roles. When the leading truck was in free driving, the truck could simply continue on a steady speed. The trailing truck, however, needed to close the gap with the leading truck, which usually would require variations in speed.

2.5.2 Car-following

In car-following scenarios, three PIs were analysed, that express how the car-following task was executed. These were the average and standard deviation of the time gap and the standard deviation of speed. Results are presented in the following sub-sections.

2.5.2.1 Average time gap

The average time gap results are presented in Figure 2-17.

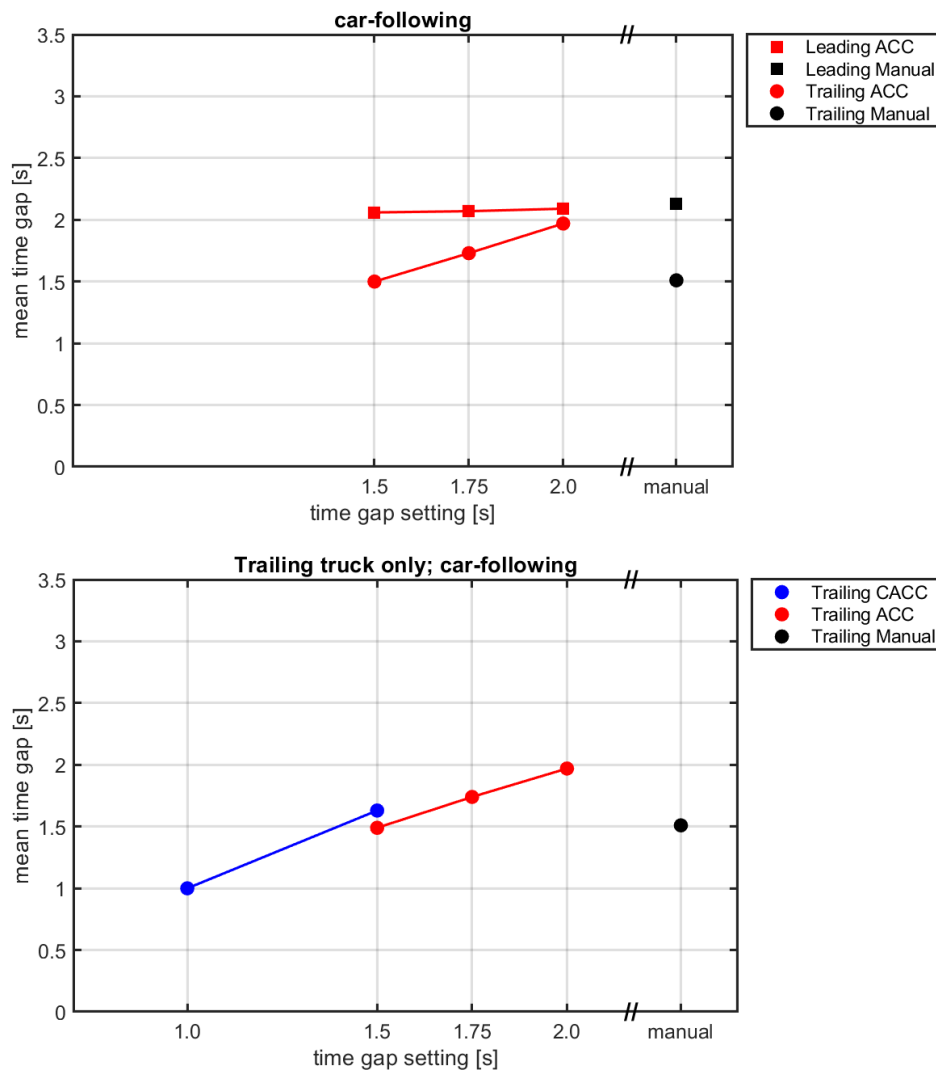


Figure 2-17 Average time gap in car-following scenarios as a function of experimental conditions (top: Design A; bottom: Design B).

Analysis A showed a significant main effect of role [$p < 0.001$], showing that overall, the leader maintained a larger time gap than the trailer. The overall averages were 2.1 s for the leader and 1.7 s for the trailer. The effect of truck condition (manual or any of the three ACC settings) was significant as well [$p < 0.001$], and so was the interaction [$p < 0.001$]. The largest difference between leader and trailer occurred in the manual condition, where the averages were 2.1 s for the leader and 1.5 s for the trailer [$p < 0.001$]. The interaction effect consisted of the trailing truck having an average time gap equal to the ACC's reference time gap, whereas for the leading truck, there was an average value of 2.1 s, irrespective of the time gap setting.

In Design B, it was confirmed that when driving in car-following scenarios with ACC or CACC, the average time gap that is realised matches the time gap setting of the controller (within 0.1 s).

Basically, these results confirm that CACC and ACC worked as intended: for the trailing truck, the realised time gaps matched the setpoints of the controller during car-following. Manually realised gaps by the truck drivers were on average in the same range as the controller settings: 2.1 s for the leader and 1.5 s for the trailing truck. Finally, for the leading truck, the average time gap was about

2 s, irrespective of the ACC time gap. This can be interpreted as an effect of driving not faster than 80 km/h, in traffic where most other vehicles (trucks included) driver faster than that. The leading truck would not increase its speed above 80 km/h to close the gap, with an average gap size larger than the controller's setpoint value as a result.

2.5.2.2 Time gap variations

Results in terms of standard deviation of the time gap are shown in Figure 2-18.

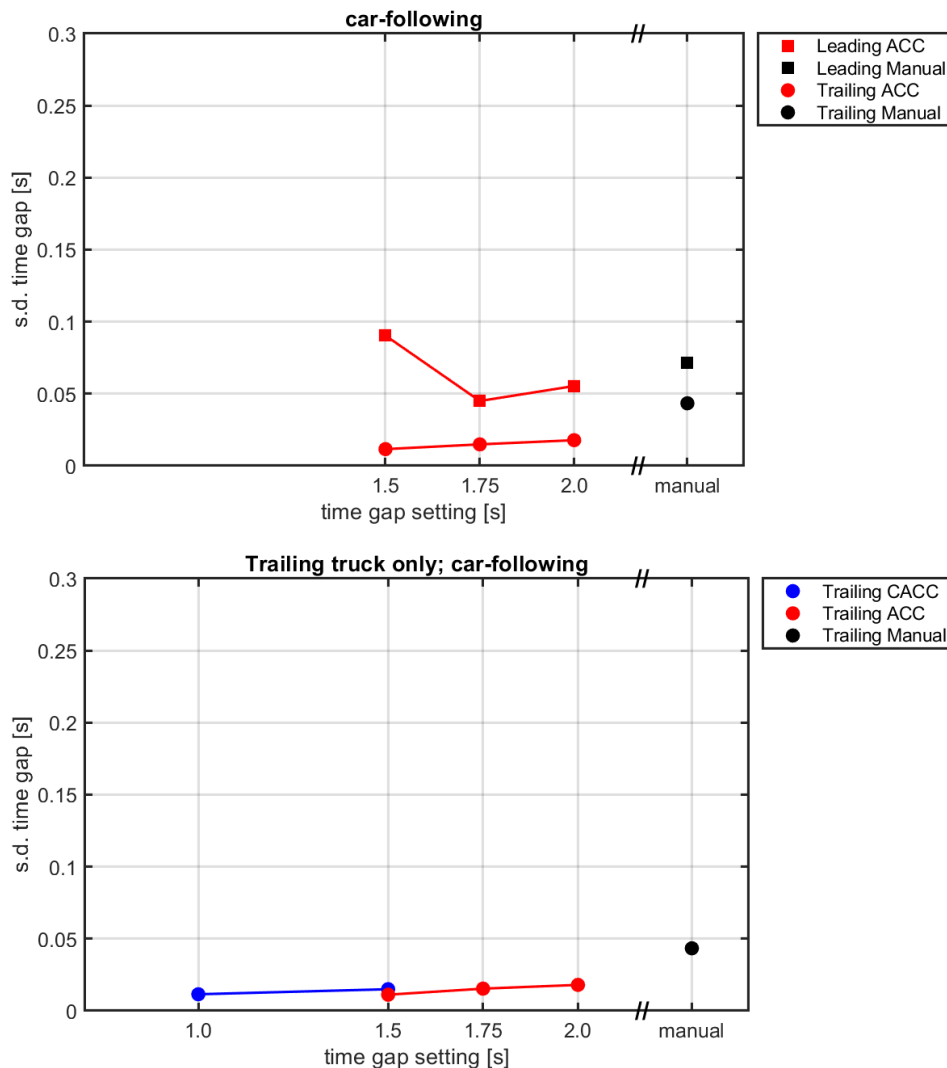


Figure 2-18 Standard deviation of the time gap in car-following scenarios as a function of experimental conditions (top: Design A; bottom; Design B).

A significant effect of Role [$p < 0.001$] was found, showing more gap variation for the leading truck than for the trailing truck. Overall averages were 0.06 and 0.03 s, respectively. The main effect of control condition and the interaction effect were significant as well [both $p < 0.001$]. Planned comparisons showed that within the trailer, all ACC conditions had significantly less gap variation than the manual condition [all $p < 0.001$]. In all four control conditions, the gap variations of the leader were larger than of the trailer [all $p < 0.001$].

Altogether this confirms that for the trailing truck, the ACC and CACC systems were successful in realising a relatively constant time gap. The larger values found for the leading truck are consistent with the explanation given in Section 2.5.2.1: if the leader is following another vehicle that is driving

faster than 80 km/h, the gap will increase over time, yielding a larger average in combination with a larger standard deviation.

2.5.2.3 Speed variations

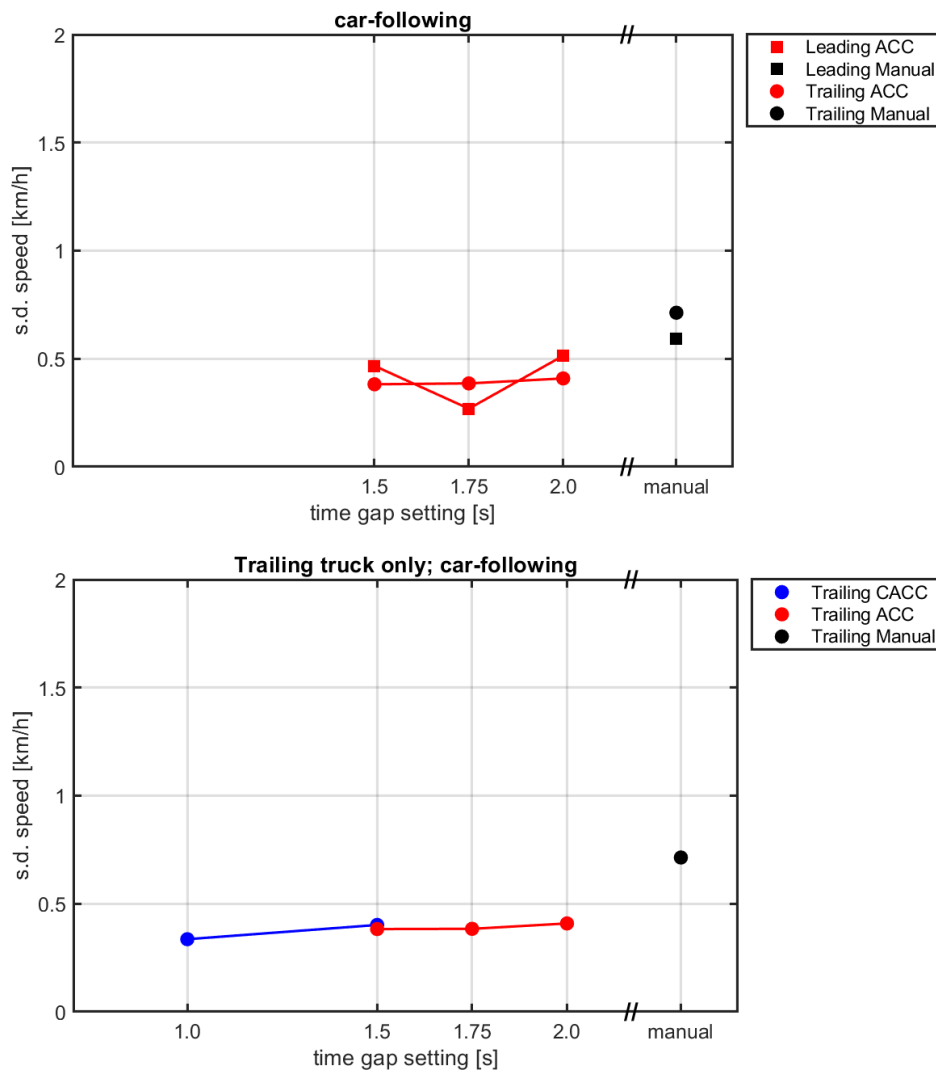


Figure 2-19 Standard deviation of speed in car-following scenarios as a function of experimental conditions (top: Design A; bottom; Design B).

Results in terms of standard deviation of speed during car-following are shown in Figure 2-19. In Design A, both main effects and the interaction effect were statistically significant [$p < 0.001$]. Planned comparisons showed the following pattern.

- There was a small but significant difference between leader and trailer in manual driving [$p < 0.001$]: averages were 0.6 and 0.7 km/h, respectively
- Within the trailer, there were no differences among the three ACC time gap settings [all $p > 0.8$]; the averages of the standard deviation of speed were significantly smaller with ACC than in manual driving [all $p < 0.001$].
- Within the leader, results varied: manual did not differ from ACC at 1.5 s time gap [$p > 0.3$] or 2.0 s time gap [$p = 0.2$], but ACC at 1.75 s had smaller averages than manual driving [$p < 0.001$].

Turning to the results of Design B: the variation in speed of the trailer was higher during manual driving (0.7 km/h) than during driving with one of the five platooning conditions (all rounding to 0.4 km/h) [all $p < 0.001$]. Within ACC, no significant differences in variation of speed were found [all $p > 0.15$] among the different time gap settings. Within CACC, the standard deviation of speed was significantly smaller at 1.0 s time gap setting than at the 1.5 time gap setting (although the difference was small: 0.33 vs 0.40 km/h).

Overall, these results mainly show that ACC and CACC perform the car-following task with less variation in speed than manual drivers do.

2.5.3 Cut-ins

Cut-in scenarios have already been analysed in terms of their frequency in Section 2.2.3. In the current section, several PIs of the cut-in scenarios themselves are analysed: given that cut-ins occur, how are they dealt with? This is analysed in terms of the minimum TTC and the maximum deceleration. These express the criticality of the scenario, and the magnitude of the avoidance reaction from the vehicle exposed to the cut-in.

A cut-in manoeuvre could happen in front of either of the two trucks, so *in front of* the platoon (leading truck is exposed to a cut-in) or *inside* the platoon (trailing truck is exposed to a cut-in). When the vehicle that is exposed to the cut-in vehicle was driving with ACC, the control system would decelerate as required in order to realise the ACC time gap setting. CACC would respond in a similar way, although at the same time the control function would automatically switch from CACC to ACC, for the trailing truck, as explained in Section 1.1.

2.5.3.1 Minimum TTC

Initial investigations showed that the average of the minimum TTC values were typically close to the upper limit of 60 s that was used as an arbitrary upper limit in the PI calculations, created to prevent meaningless high TTC values in the analysis (see Section 2.1). Since very high TTC values would not be of interest, it is more interesting to look at the distribution of minimum TTC in the lower range. Therefore, the (cumulative) distributions were analysed instead of applying the linear mixed-effects models.

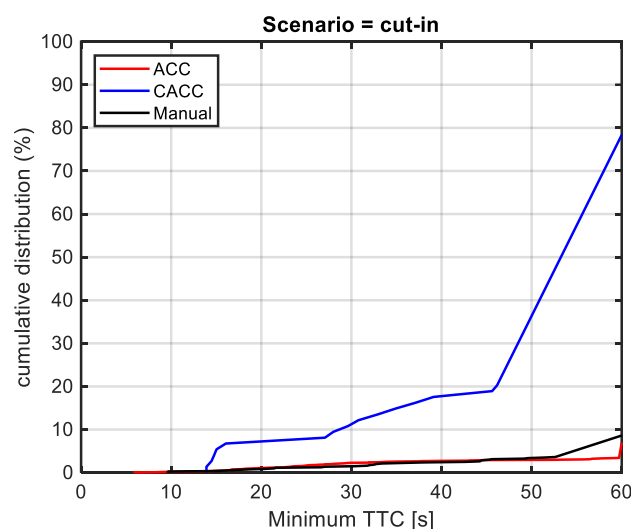


Figure 2-20 Cumulative distribution of minimum TTC in cut-in scenarios as a function of experimental conditions (pooled over both truck roles).

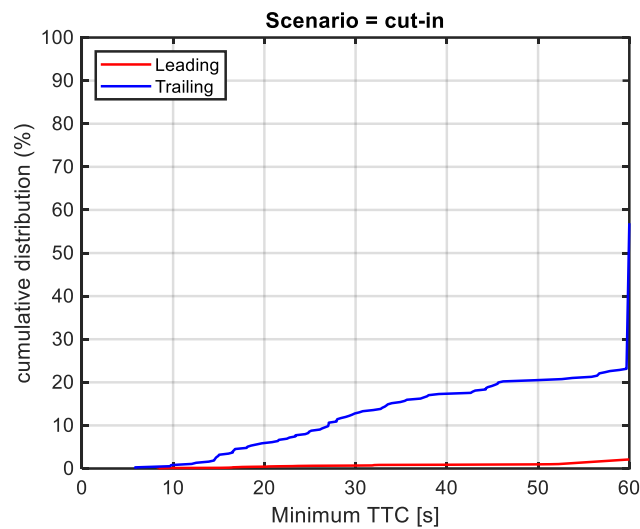


Figure 2-21 Cumulative distribution of minimum TTC in cut-in scenarios as a function of truck role (pooled over all control modes).

Results are shown in Figure 2-20 and in Figure 2-21. These cumulative distributions show that the overall minimum values of minimum TTC that occurred during cut-ins were in the order of magnitude of 9 to 13 s. The majority of minimum TTC values are considerably higher than that. Figure 2-21 shows that for the trailing truck, lower TTCmin values occurred than for the leading truck. However, this is a relative difference: in absolute terms, even the most critical cut-in scenario in the total data set was far above the 3.5 s threshold that is often used to identify conflicts.

2.5.3.2 Maximum deceleration

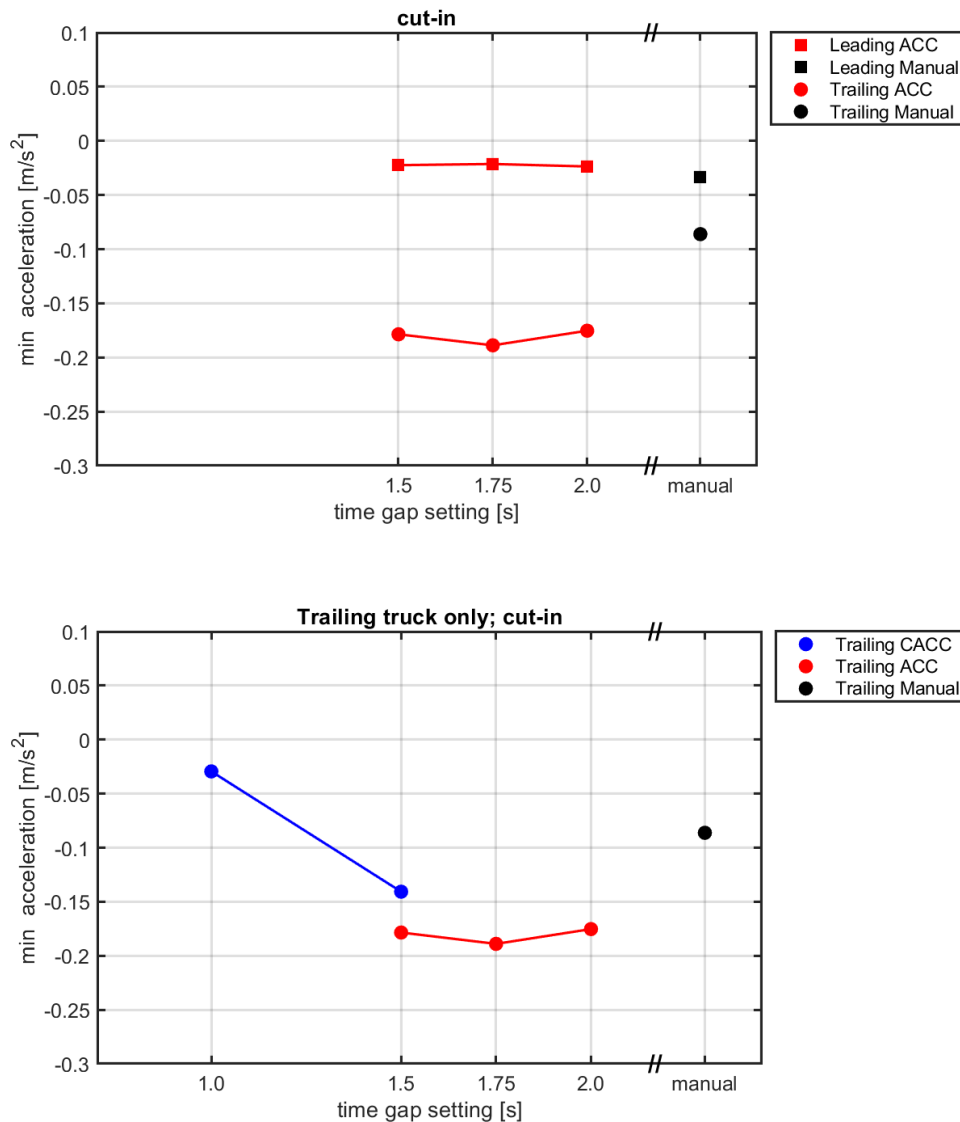


Figure 2-22 Maximum braking (=minimum acceleration) in cut-in scenarios as a function of experimental conditions (top: Design A; bottom; Design B).

Results for maximum decelerations in cut-in scenarios are shown in Figure 2-22, visualised as the minimum acceleration. Design A showed significant main effects and a significant interaction [all $p < 0.001$]. Overall, the trailer had a stronger deceleration than the leader (acceleration of -0.02 and -0.15 m/s^2 , respectively). Planned comparison showed that within the leader, no significant differences existed between any of the four conditions [all $p > 0.6$]. However, the difference in deceleration between leader and trailer was significant in all four conditions [all $p < 0.001$].

Design B showed that maximum deceleration during cut-ins did not differ among ACC time gap settings or with respect to CACC 1.5. time gap setting]. Only CACC at 1.0 s differed from ACC (1.75 and 2.0 s time gap; [$p = 0.04$ and $p = 0.01$]).

Deceleration levels obtained by only releasing the throttle pedal are typically in the order of magnitude of -0.5 to at most -1 m/s^2 . With this in mind, the levels that were found here are moderate, more in line with speed fluctuations than with pronounced deceleration.

2.5.4 Approaching slower lead vehicle

The last scenario that was analysed, was approaching a slower lead vehicle. When this happened, the ego vehicle must adjust its speed to that of the lead vehicle. How this was done is expressed in the maximum deceleration that occurs throughout the entire scenario. The criticality of the scenario is expressed in the minimum Time To Collision (TTC) that occurred in the scenario.

2.5.4.1 Minimum TTC

With the same reasoning as in the cut-in scenario, the cumulative distributions of TTC_{min} were compared. These are shown in Figure 2-23 and Figure 2-24. In contrast to the cut-in results, here the TTC_{min} values were not experiencing the ceiling effect at the 60 s upper limit. Therefore, the standard statistical analyses were conducted. The results are shown in Figure 2-25.

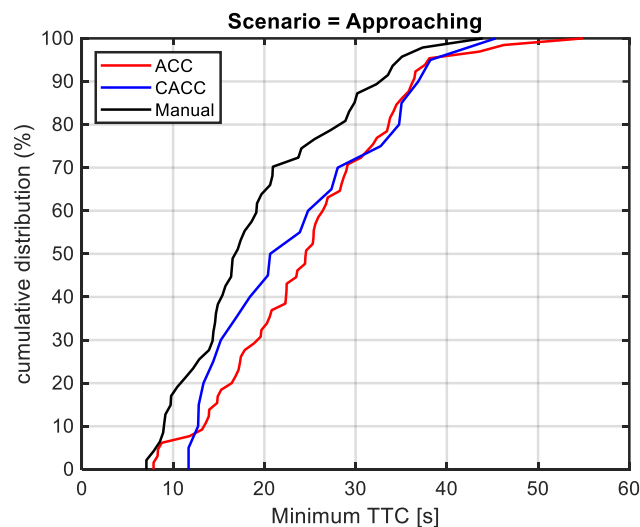


Figure 2-23. Cumulative distribution of minimum TTC in approaching scenarios as a function of experimental conditions).

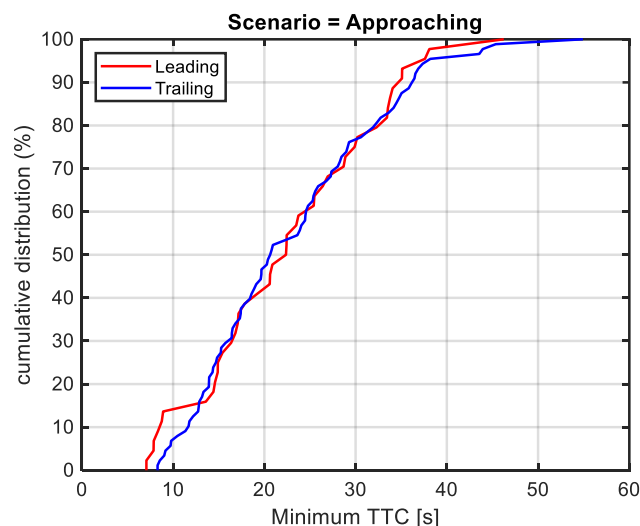


Figure 2-24 Cumulative distribution of minimum TTC in approaching scenarios as a function of truck role.

Analysis A only revealed a marginally significant effect of control mode [$p=0.06$]. The averages were 20.3 s for manual driving, and 20.3, 21.3 and 24.5 s for the ACC conditions (in increasing order of

time gap setting). Planned comparisons showed that only two conditions differed significantly: these were manual and ACC at 2.0 s time gap, in the trailing truck.

In Analysis B, the effect of control mode was significant [$p < 0.001$]. The planned comparisons showed that only two conditions differed significantly: ACC at the 2.0 s time gap differed from CACC at 1.0 s and from manual [both $p < 0.01$].

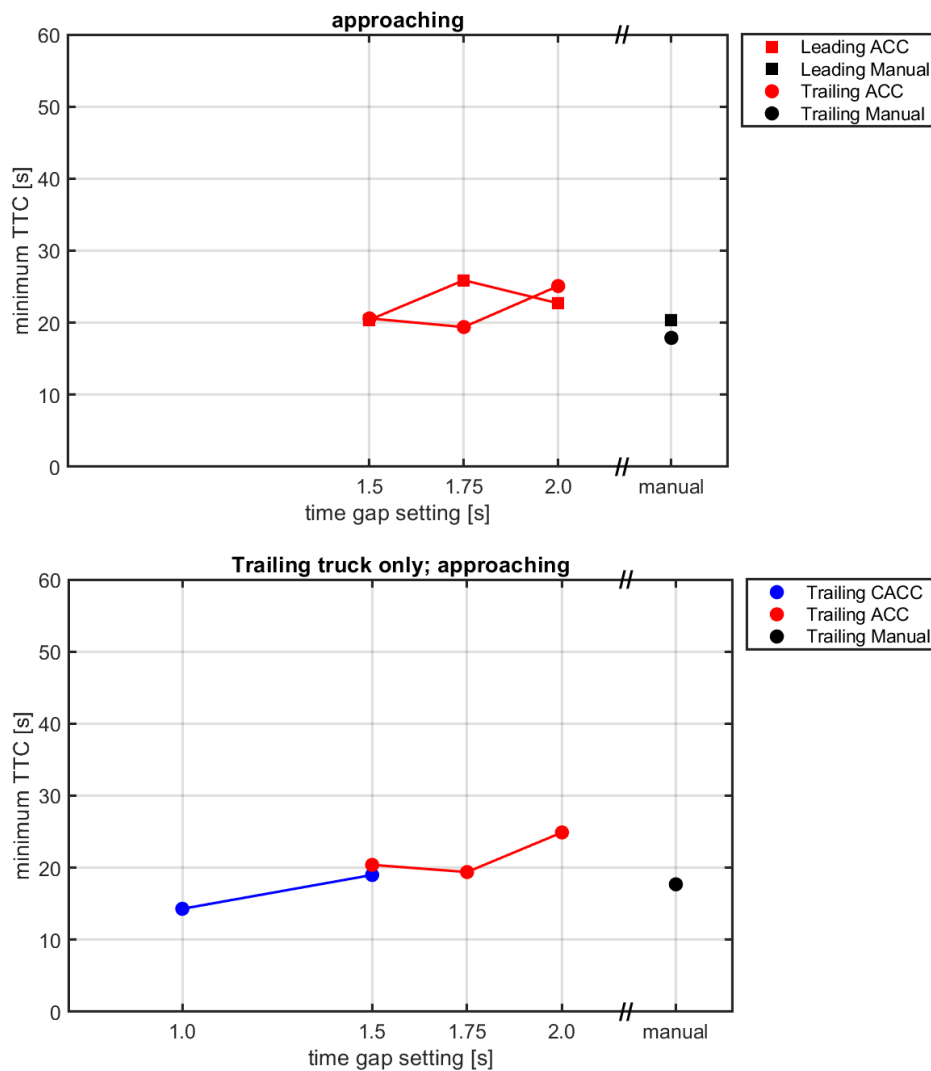


Figure 2-25 Minimum TTC during approaching scenarios as a function of experimental conditions (top: Design A; bottom; Design B).

The averages of the minimum TTC values were in the order of magnitude of 15 to 25 s. As Figure 2-23 already showed, TTC_{min} values were never smaller than 8 or 9 s. Thus, even the most critical approach manoeuvres as experienced during the trials were still far away from the $TTC = 3.5$ s threshold that is widely accepted as a conflict criterion.

2.5.4.2 Maximum deceleration

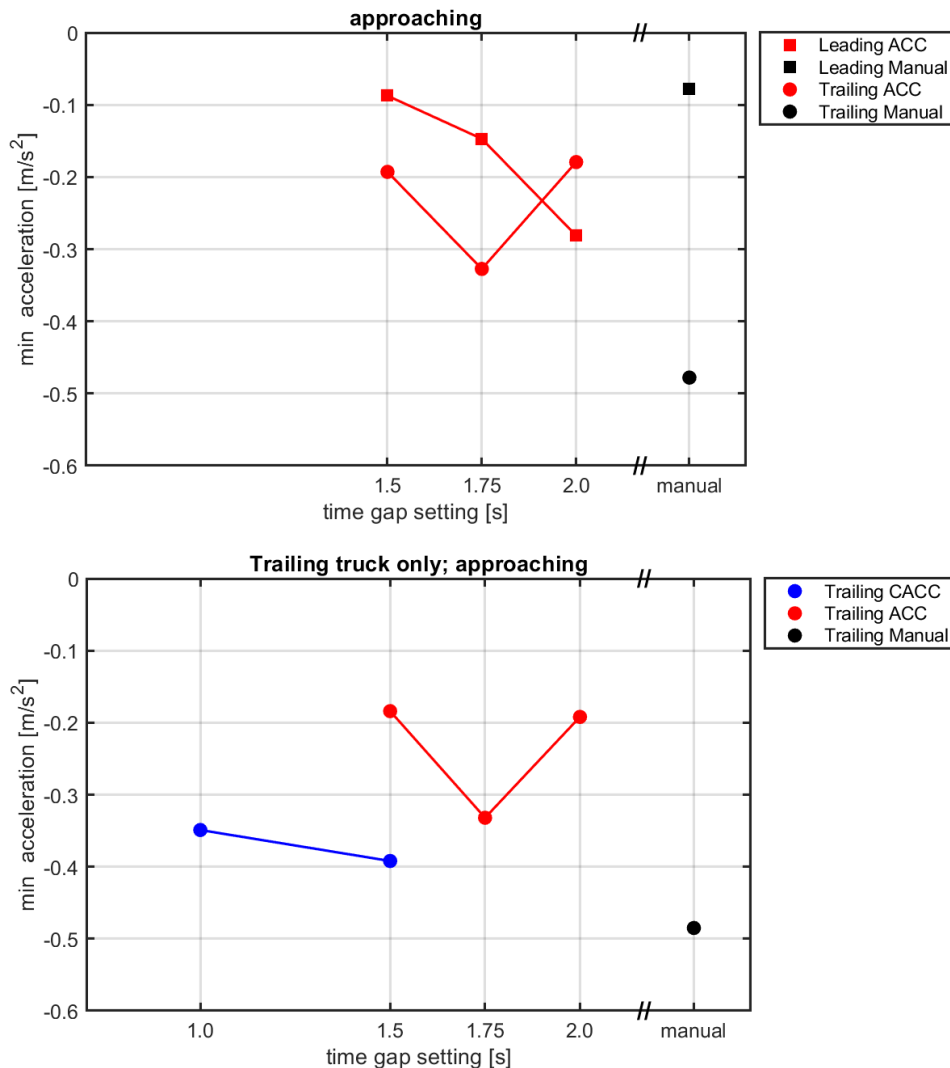


Figure 2-26 Maximum braking (=minimum acceleration) in approaching scenarios as a function of experimental conditions (top: Design A; bottom: Design B).

Figure 2-26 shows the results for maximum deceleration during the approach of a slower vehicle.

Design A showed no significant effect of control mode [$p=0.6$], but there was a main effect of truck role [$p=0.04$] and an interaction effect [$p=0.01$]. Planned comparisons showed that in manual driving, the trailing truck driver realised stronger deceleration levels than the leading truck driver (-0.48 and -0.08 m/s^2 , respectively) [$p<0.001$]. Among the six ACC conditions (2 roles X 3 time gap settings), no significant differences were found [all $p>0.5$]. Furthermore, within the leader, the manual condition did not differ from any of the ACC conditions [all $p>0.7$]. Within the trailer, the manual condition differed only from the ACC with 2.0 s time gap setting [$p=0.02$].

The maximum deceleration levels (expressed as minimum acceleration) were mild, in the order of magnitude of -0.1 to -0.5 m/s^2 . This is the same range as observed in cut-in scenarios (Section 2.5.3) and it is achieved by releasing the throttle pedal only; active braking is not required.

2.6 Scenario-based results: platoon level

In this section, the car-following behaviour of the trailing truck is analysed as function of the control mode and of the scenario the leading truck was experiencing at the same time. Three combinations are covered, as explained in Section 0. These were: the trailing truck in a car following scenario, while the leading truck was free driving, car following, or in a cut-in.

Since the focus was on the behaviour of the trailing truck, only Design B was relevant here. One factor was added: the lead car scenario, with three different levels (free driving, car following, and a cut-in). In terms of the average time gap of the trailing truck, Figure 2-27 shows results that are in line with Section 2.5.2 and that confirm again that the CACC and ACC controllers worked correctly in realising average time gaps of the trailing truck, realising averaged that matched their controller setpoints. The scenario the leading truck was dealing with had no additional effect. The bottom graph does not contain data for all time gap settings because these specific combinations were not present in the data.

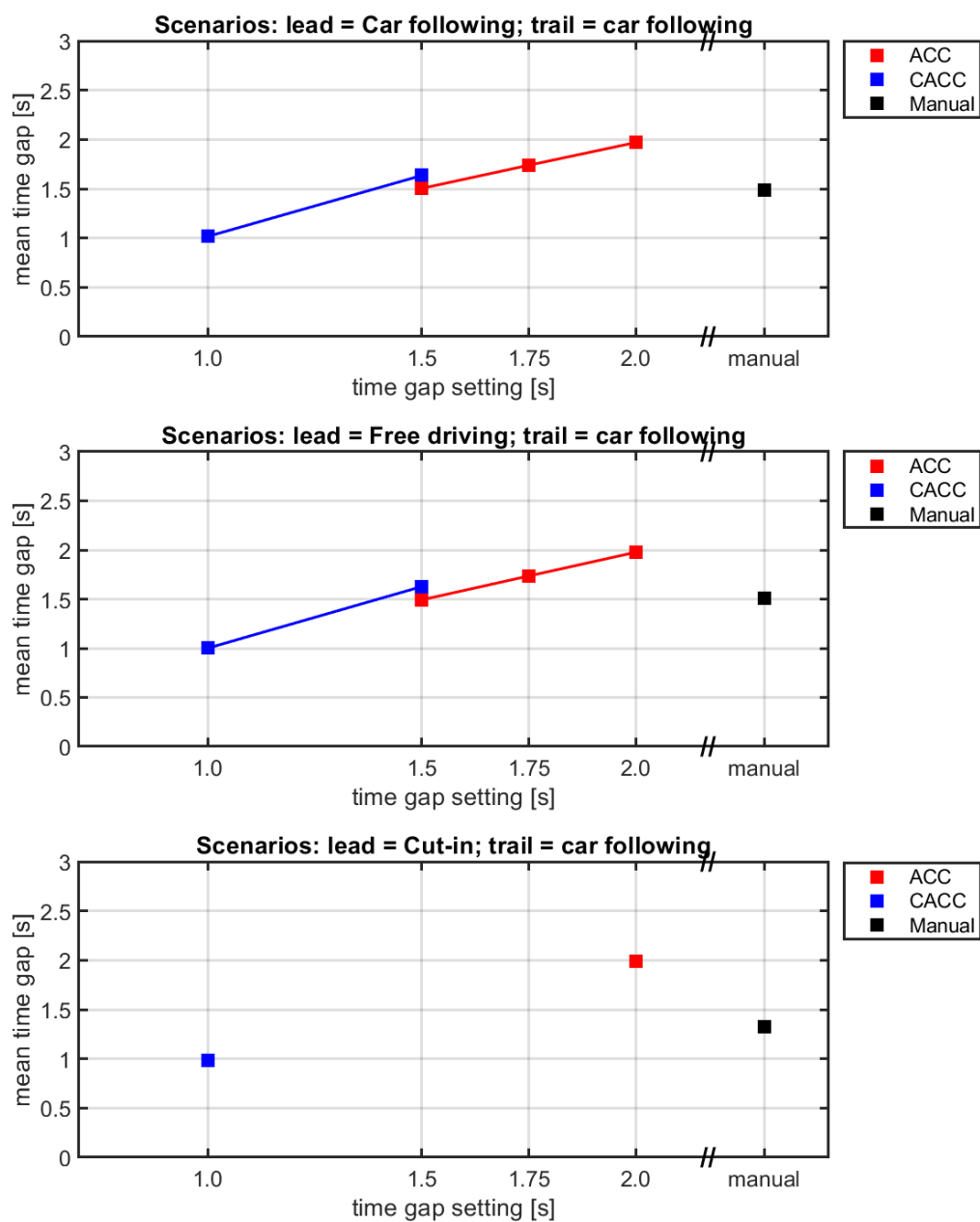


Figure 2-27. Average time gap of the trailing truck as function of the longitudinal control condition and the lead truck's scenario.

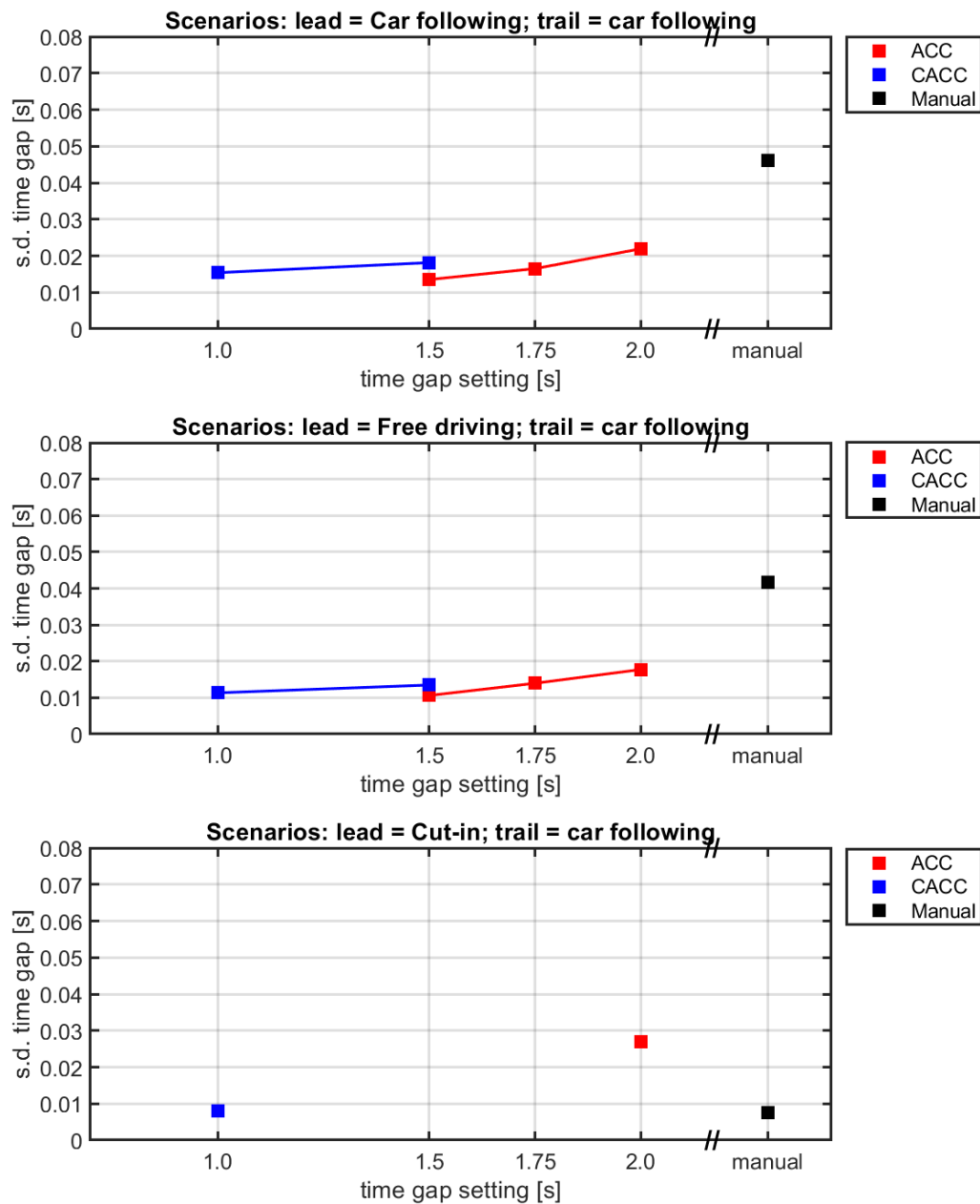


Figure 2-28 Standard deviation (s.d.) of the time gap of the trailing truck, as function of the longitudinal control condition and the lead truck's scenario.

In the analysis of the standard deviation of the trailing truck's time gap, it appeared that there was a significant effect of the lead truck's scenario [$p < 0.001$]. The overall averages are presented in Table 2-16.

Table 2-16 Standard deviation of the trailer's time gap in car-following, as a function of the lead truck scenario.

Leading truck scenario	Average of the standard deviation of the trailing truck's time gap [s]
Car following	0.0268
Free driving	0.0204
Cut-in	0.0118

A planned comparison showed that the free-driving condition had a significantly lower average than the car-following condition [$p < 0.001$].

Finally, the standard deviation of speed of the trailing truck (in car-following) was analysed as a function of the control mode and of the lead truck's scenario. Results are shown in Figure 2-29.

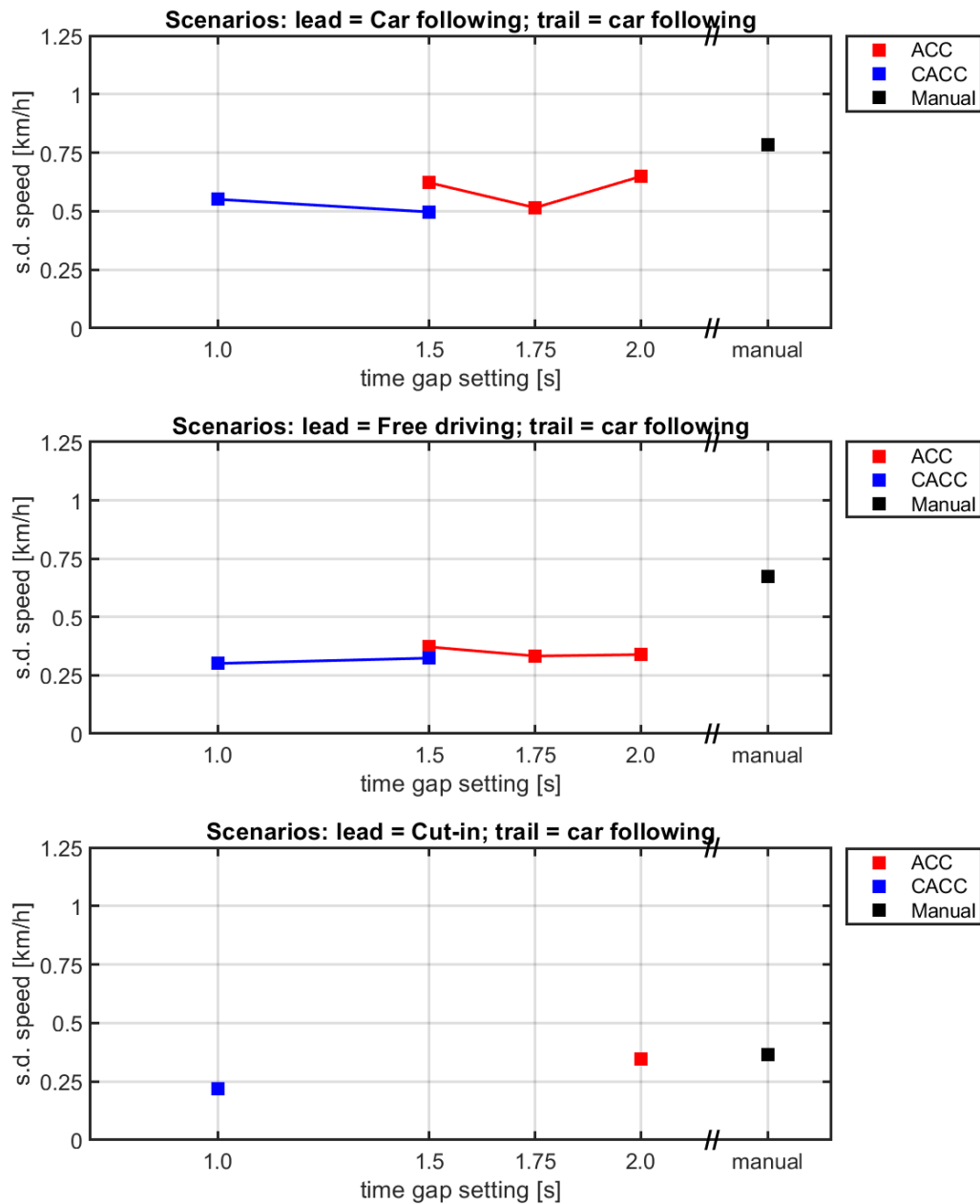


Figure 2-29. Standard deviation (s.d.) of speed of the trailing truck, as function of the longitudinal control condition and the lead truck's scenario.

There was a significant effect of lead truck scenario [$p < 0.001$]; see Table 2-17 for the averages over all control modes. Again, a planned comparison showed that the free-driving condition had a significantly lower average than the car-following condition [$p < 0.001$].

Table 2-17 Standard deviation of the trailer's speed in car-following, as a function of the lead truck scenario.

Leading truck scenario	Average standard deviation of the trailing truck's speed [km/h]
Car following	0.643
Free driving	0.415
Cut-in	0.307

In summary, there were two performance indicators where a significant effect of the *leader's* scenario was found in the *trailing* trucks' car-following behaviour. These were the standard deviation of speed and the standard deviation of time gap; both PIs were larger when the leading truck was car following compared to free driving. This can be seen as variations of speed propagating from one platoon member to the next. Comparing results from Section 2.5.1.2 and Section 2.5.2.3, it can be seen that the leader had a higher standard deviation of speed when in car-following compared to free driving. For the trailing truck this means that the speed variation of its leader is influenced by the scenario the leader is experiencing. A larger standard deviation of the leader's speed manifests itself as larger standard deviations of speed and time gap of the trailing truck.

2.7 Logbooks and debriefings

During each day of testing, log books were kept by the Operator as well as the drivers. As a final part of the information covered in MT1, these were scanned for elements that were mentioned frequently or that may point to critical situations.

Only two events were reported as rather critical situations:

- Manual hard braking because of traffic in front (2022-06-29 15:01, Both trucks)
- Critical cut-in from the right (2022-07-06 11:07, ET3).

Situations that happened often were the following:

- 10 times or more
 - Driver overrules the systems to make space for merging traffic on highway exit/entry/weaving section
 - Driver overrules system to brake for slow traffic ahead
 - CACC driving terminated due to errors (V2V, GPS errors)
 - Frontal Collision Warnings
- 5-10 times
 - Platoon deactivated without apparent reason.
 - Driver switches off ACC/CACC due to roadworks
- Less than 5 times
 - Lost target in CACC/ACC and driver had to take over (not critical)
 - Ghost vehicle causing mild braking

The following comments can be made with respect to these observations:

- Overruling the system to make space for other traffic and disengaging ACC/CACC due to roadworks: this was in line with the instructions in the operational protocol.

- Braking for ghost vehicles (n=2) occurred with maximum deceleration levels of 0.5 to 1 m/s²: this is mild braking only. It was easily detected by the drivers and simply pressing the throttle pedal was enough to overrule the system. An example is shown in Figure 2-30.
- Deactivations for no apparent reason or due to an error: these points were addressed in Section 2.2.2.

An example of braking for a 'ghost' is shown in Figure 2-30. The lowest sub-plot shows the pedal positions the vehicle received as input (as realised by the driver or by the ACC). Initially the throttle position is controlled by the ACC, such that a speed of 80 km/h is realised. At 11:45:25.7, ACC releases the throttle in response to a 'ghost'. As a result, the truck starts to decelerate, briefly reaching a minimum of -0.66 m/s². The minimum speed that is reached was 75.4 km/h. At t=11:45:27.6, the driver presses the throttle pedal, quickly reaching full throttle. In response to this, acceleration turns positive and speed is increased to the original level of 80 km/h.

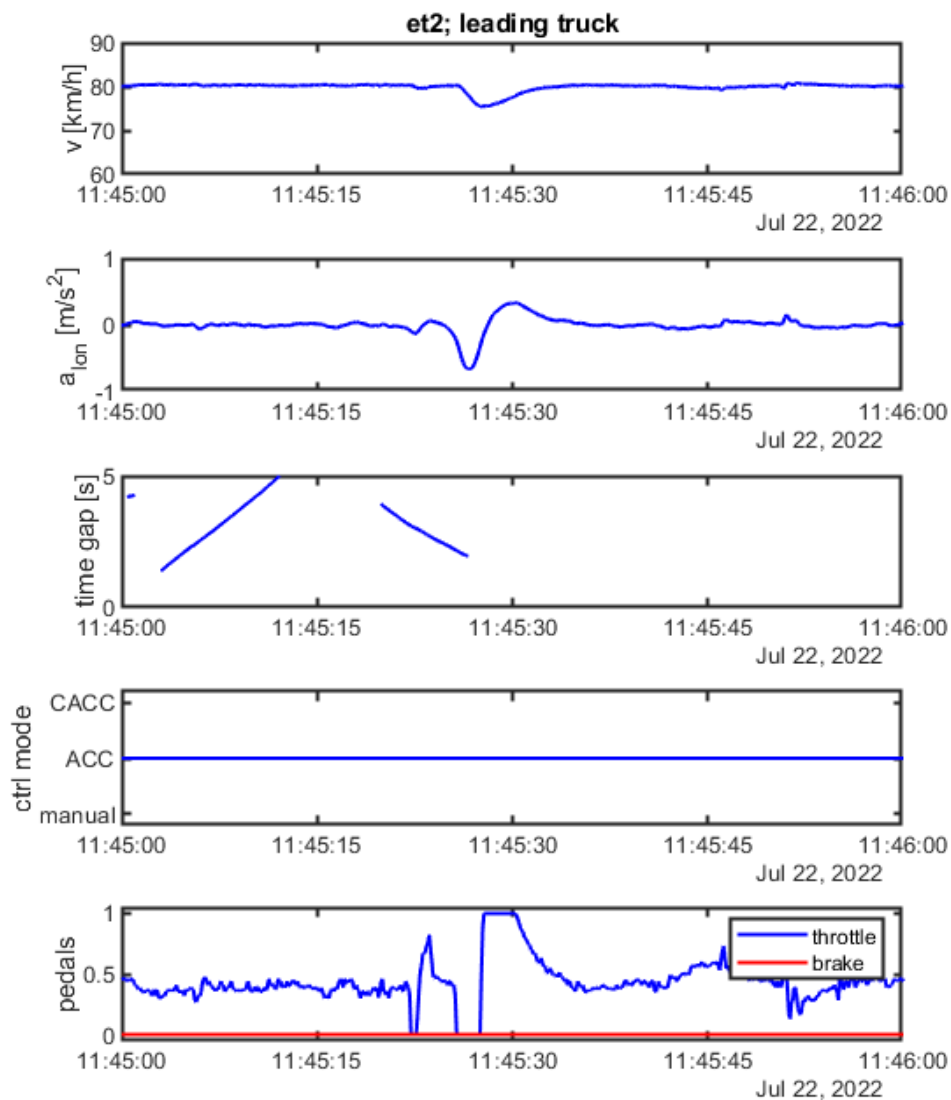


Figure 2-30 Example of ghost braking.

In informal debriefings with the test drivers, they reported no major issues either. They found the ACC/CACC application easy to use with an HMI that clearly showed the important information.

According to the test drivers the CACC function was most likely to get spontaneously terminated when the time gap setting was at the largest value (1.5 s). Another observation from operator and drivers was that the CACC function appeared more likely to be terminated when the trucks drove past the large barriers along the A16, shown in Figure 2-31. This might be explained by difficulties in the data association between the three sensor types (camera, radar and V2V). More specifically, barriers could trigger multi-path radar reflections that can disturb the radar object preselection, and subsequently the sensor fusion process (see also Kraus, Scheiner, Ritter, & Dietmayer, 2021). However, the drivers had the impression that the V2V tended to frequently fail on this stretch of road.



Figure 2-31. Frequent CACC dropout zone according to test drivers (potentially due to large barrier; image from Google Streetview).

2.8 Discussion

In terms of relative frequencies of scenarios, the results are qualitatively as expected for a setting with two trucks driving in a platoon. That is, the trailing truck was more in car-following and in approaching scenarios, whereas the leading truck was more in free-driving and cut-in scenarios. This is a direct effect of the experimental set-up. The same holds for the results in terms of average speed during free driving: the averages are close to 80 km/h, which is in line with the instructions of the test drivers. An effect of truck condition was found within the manual condition: the trailing truck's average speed was lower than the leading truck's average speed.

For both trucks, the free-driving speed variation with ACC/CACC systems was reduced compared to manual driving. This shows that the ACC/CACC systems were more capable of maintaining a specific speed than the test drivers. Maintaining a specific setpoint speed is obviously the objective of an ACC/CACC system without predecessor, so these results confirm correct functioning of the platooning systems.

In car-following scenarios, the results confirm that ACC and CACC work as intended: the average gap size was equivalent to the selected desired gap settings. The time gap variation was larger for the leader than for the trailer. This was probably caused by the preceding vehicle in front of the leading truck having a higher variation in speed than the preceding vehicle of the trailing truck what would typically be the lead truck. Overall, the variation in time gap was reduced by the platooning systems (ACC/CACC), which confirms that the ACC and CACC systems were aiming to keep a constant time gap, as intended. During approaching scenarios, no effects of platooning were found.

Cut-ins occurred more often in front of the leader than in front of the trailer. This can be interpreted as other traffic using the space that was available: most of the time, gaps ahead of the leader were larger than gaps ahead of the trailer. During cut-ins, the trailer decelerated stronger than the leader. Moreover, ACC or CACC yielded stronger deceleration than manual driving. Since time gaps were not significantly shorter during all ACC/CACC conditions, the most probable cause is that the driver in the manual conditions was anticipating on vehicles cutting in and started braking earlier (and

therefore gentler). The platooning systems started decelerating the moment the cut-in vehicle was detected in the ego lane and therefore had to decelerate stronger.

The most frequent scenarios per truck role were the leader in free driving and the trailing truck in car-following. The speed variations of the trucks in these conditions are summarised in Table 2-18, based on the results presented in Section 2.5. This shows that in the most common scenarios, when driving with ACC or CACC, the trailing truck had considerably more speed variation than the leading truck.

Table 2-18 Summary of speed variations of leading and trailing truck in their most frequent scenarios.

Ego Truck	Ego Scenario	Ego Control mode	Average standard deviation of speed [km/h]	Source
Leading	Free driving	ACC (any time gap)	0.15	Figure 2-16
Trailing	Car following	ACC or CACC (any time gap)	0.38	Figure 2-19

When looking at scenarios on a platoon level, it was shown that the most frequent combination was: the lead truck in free driving while the trailing truck was car following. Still looking at standard deviation of speed, the behaviour of the trailing truck was influenced by the scenario type of the lead truck, as shown in Table 2-19: having the leader in car following yielded larger speed fluctuations than having the leader in free driving.

Table 2-19 Trailing truck in car-following scenario: effect of lead truck's scenario on standard deviation of speed.

Leader Scenario	Control mode trailing truck	Trailing truck average standard deviation of speed [km/h]	Source
Free driving	ACC or CACC (any time gap)	0.33	Figure 2-29 middle
Car following	ACC or CACC (any time gap)	0.57	Figure 2-29 top

The analysis of scenario Performance Indicators was restricted to non-congested traffic. The reason for this was that congestion, while relatively rare, has an influence on most (if not all) performance indicators. Leaving congestion in would have confounded the analysis; at the same time, congestion was too rare to fully use it as a factor in the statistical analysis.

In Appendix B, effects of the traffic state on platooning performance are explored further. There, it is concluded that there was no performance difference between ACC and CACC during congested traffic. Appendix B also investigated driving behaviour as a function of infrastructure, differentiating between normal motorway, tunnels/bridges and weaving sections. Results showed that in tunnels or on the bridges, the ability to maintain the desired time gap was diminished for the ACC driving mode compared to the CACC driving mode.

Platooning performance was analysed by looking at parts of the trips where both platoon members had longitudinal control functions active. Results showed that, once activated, ACC tended to remain

active longer than CACC. Also, in trips where the platoon used ACC, the percentage of trip time with platooning active (as defined in Section 2.1.4) was higher than in trips where the platoon was using CACC.

The Truck Platooning Trial was designed using the FESTA methodology. Following the right branch of the FESTA-V (Figure 1-1), data were analysed and hypothesis were tested. The next steps would be to take results from MT1 as input for scaling up, using traffic flow simulations to estimate the traffic safety impacts of truck platooning on a larger scale. This was beyond the scope of the current project. Therefore, safety effects have to be estimated qualitatively based on an interpretation of the safety related Performance Indicators.

Cut-in scenarios are potentially critical. In terms of their safety effect, both the frequency of their occurrence and the severity should be judged. In terms of *frequency*, Figure 2-13 showed that the leading truck was exposed to considerably more cut-ins than the trailing truck. In terms of *severity*, Section 2.5.3 has shown that throughout the entire trial, no critical cut-in scenarios occurred at all. Even the most severe cases observed had minimum TTC values that were far above the 3.5 s threshold that is commonly used to identify conflicts. In relative terms the cut-ins were more severe for the trailing truck than for the leading truck, but in absolute terms, they were never critical at all. This should be interpreted in the context of how the tests were conducted, which was with safety drivers in the trucks, who had the task of continuously monitoring the ACC/CACC system as well as the traffic around the platoon, and to intervene when necessary to avoid critical situations.

In terms of speed choice, the results have shown that the drivers complied with their instruction, which was to respect the speed limit of 80 km/h. It should be noted that trucks on Dutch motorways typically drive a bit faster than this. Dicke-Ogenia et al. (2020) reported average truck speeds of typically around 90 km/h on various locations in the Dutch motorway network. Thus, the platoon tended to drive a bit slower than most of the other traffic. This automatically created 'drivable space' ahead of the leading truck, which was used by other traffic merging to lane of the platoon manifesting itself as the non-critical cut-in manoeuvres discussed above.

2.9 Conclusions

In MT1, the behaviour of ACC and CACC in traffic has been analysed in terms of system performance and behavioural Performance Indicators.

In general, ACC and CACC are longitudinal control systems that aim to maintain a certain time gap. Results confirm correct functioning of the systems. For the trailing truck (which is often driving in car following), ACC and CACC maintain an average time gap close to the setpoint, and they do so with less gap variation than drivers do when driving manually. The leading truck, driving at 80 km/h, was slower than most other vehicles (including trucks) on the route. Therefore, this truck was less frequent in car-following scenarios and with other traffic usually driving away from the truck, the average time gaps that were observed were typically around 2 s, irrespective of the ACC time gap setting.

Looking at the scenarios that cover stationary driving (free driving and car following):

- In free driving, ACC and CACC both reduced the speed variation, compared to manual driving. The variation was larger for the trailer than for the leader.
- In car following, ACC and CACC both reduced the time gap variation, compared to manual driving. Also speed variation was lower with ACC or CACC compared to manual driving.

Less variation in driving behaviour can qualitatively be interpreted as contribution to smoother traffic flow and improving traffic safety. Potentially critical scenarios (approaching slower vehicles ahead, cut-ins) were analysed. Throughout the entire test programme, no critical situations were observed at all: neither in manual driving, nor in ACC/CACC driving. In terms of the trailing truck's braking in response to cut-ins, the ACC and CACC yielded stronger decelerations, compared to manual driving. However, the levels of deceleration remained limited to mild decelerations (only releasing the throttle pedal, no active braking).

The platooning system used in the Truck Platooning Trial must be considered a prototype rather than a production-type system, ready for an end user. This required them to be driven by so-called safety drivers, rather than by any licenced (truck) driver. Altogether the results show that (within all technical and procedural measures taken), platooning tests can safely be conducted on the public road without causing risk to traffic safety or traffic flow.

A potential safety concern when dealing with ACC or CACC may be braking due to ghost objects (or false positives in other terminology). Throughout the entire test programme, only two of these were observed, and they resulted in mild decelerations only. Thus, ghost objects did not manifest themselves as a safety issue, neither in terms of probability nor in terms of severity.

In terms of platooning performance, results have shown that drivers who are aiming to use ACC/CACC are able to do so during large proportions of the total trip time (when driving on the motorway). The duration of phases with system active was typically larger for ACC than for CACC. This difference can be attributed to the dependency of CACC on more components (V2V, GPS): if any of these temporarily drops out, CACC is automatically terminated.

3 Emission measurements (MT3)

3.1 Methodology

3.1.1 Introduction

Macro Topic 1, as discussed in Chapter 2, focused on vehicle and safety impact on performance indicators for which a global and scenario analysis was performed. Macro topic 3, as discussed in this chapter, focuses on emissions measurements which are related to vehicle mass, velocity and accelerations, and the effect of slipstream in a platoon configuration. The two macro topics differ significantly and as such the analysis of emissions will be more aligned to that found in literature e.g. (Veldhuizen et. al., 2019). As stated in D1.2 (Hogema et al., 2022A) the main research questions for the macro topic on emissions are:

1. What is the quantitative effect of platooning on the fuel consumption, CO₂ emissions and NO_x emissions of the leading, and trailing truck?
2. What is the quantitative effect of platooning on the aerodynamic drag of the leading, and trailing truck?

The methodology section provides more information on the emission data measurements, vehicles, and loading conditions used. The results section will provide an answer to these questions.

3.1.2 Emission measurement data

Deliverable D3.2A (Hogema et al., 2022B) provides a full description of the emission measurement data. Three datasets have been used for emission analysis: SEMS data, OBU data, Logbook data.

Smart Emissions Measurement System (SEMS).

The data relevant for the measurement of emissions were acquired by means of the Smart Emissions Measurement System (SEMS). This system involved physical sensors that were installed on the tailpipe to measure instant levels of CO₂ and NO_x, among others; see Kadijk et al. (2015) or D1.2 (Hogema et al., 2022A) for further details. The SEMS system records the vehicle wheel speed from the CAN-bus, and the acceleration is derived from it, via numeric differentiation. In this chapter, unless indicated otherwise, all the data from the SEMS system were used when available, this is, the speed, position, acceleration. Furthermore, the CO₂, fuel consumption, NO_x were calculated combining sensor signals with CAN-bus signals and then stored into the SEMS database. Specifically, the NO_x mass flow and CO₂ mass flow were calculated as follows; first, the exhaust mass flow was calculated by summing air mass flow and fuel mass flow. Inlet air mass flow and fuel volume flow were available on the CAN-bus of each of the vehicles. The fuel density was an assumption: 835 g/l. The NO_x mass flow was calculated by multiplying the exhaust mass flow with the NO_x concentration (calibrated, corrected for NH₃). The CO₂ mass flow was calculated by multiplying the fuel mass flow by a fuel specific CO₂ emission factor, in this case, 3.15 CO₂/diesel mass ratio.

On-Board Unit (OBU)

The On-Board Unit (OBU) recorded control variables such as the active controller state (CACC/ACC/Manual) and the gap distance. This chapter uses the OBU data regarding the platoon information, such as the experimental condition, and the distance gap. The OBU data were carefully time-synchronized with the SEMS data and cleaned before the study as described in deliverable D3.2A (Hogema et al., 2022B).

Log book data

The log book data provided information on the experimental condition like the active target time gap and the role of the two trucks. The role of the vehicles in the platoon changed for the different experimental conditions, i.e., both vehicles drove both as a leading and trailing vehicle in the platoons, depending on the trip.

3.1.3 Vehicle and loading conditions

In order to compare the emissions of the trailing vehicle to the leading vehicle, it is important to compare the relevant vehicle characteristics and loading conditions. Table 1-2 and Table 1-4 provide details on loading conditions and maximum power of both vehicles. It can be seen that the loaded weight of ET2 is about 9% more than that of ET3, which results in a difference in power consumption for accelerations as well as a difference in roll resistance.

Even though both vehicles have similar properties as engine size and power, they are not fully identical. The engine speeds differ at 80 km/h: the engine of the vehicle ET3 operates at lower speed (about 40-50 RPM) than that of the ET2. This difference has an impact on the vehicle emissions and fuel consumption. As a result, it was not possible to compare the efficiency between the vehicles, in the same ambient conditions, slopes, and roads, but only within the vehicle for the different experimental conditions. In this case, since a vehicle naturally needs to execute different conditions at different times, all the surrounding conditions may differ from test to test and the vehicle speed is influenced. For this reason, the analysis needed to first consider potential differences due to external agents and second, focus on specific vehicle velocity ranges. Matching the vehicle speed between the two different operation conditions will capture the major aspects of fuel consumption. Although the gap distance of the trailing vehicle can also have an impact on the fuel usage of the leading vehicle due to changes in air resistance, this has been reported to be much less significant than the impact on the trailing vehicle (Vegendla et al., 2015). Therefore, this potential effect was ignored in the current analysis. Thus, a more reliable baseline could be established using all the data of each vehicle playing the role as leader. The data of each condition were compared to this baseline.

Another aspect to consider is that the CACC controller used on the trucks was a prototype and not a commercially available controller. The TNO controller is optimised for maintaining a specific time gap between leader and trailer, without taking energy consumption into account. Section 3.2.3 provides more information.

3.1.4 Factors of influence

For heavy trucks, air-drag is a limited aspect in the total fuel consumption, and only so at higher velocities. With a frontal area of 6 m², a drag coefficient (C_d) of 0.55 and a velocity of 80 km/h, the drag force at 20°C and sea level is 980 Newton. This is 190 g/km of total CO₂ emissions, and 7.4 litres/100 km of the fuel consumption. Removing the air drag completely will save 7.4 litres per 100/km on the motorway, but only 2.9 litres per 100 km at 50 km/h, as air drag is proportional to the square of the velocity.

In the analysis of the test data, it is important to understand the key factors of influence that may affect the data. This understanding will help to adequately present and interpret the test data.

Platooning is an approach to reduce aerodynamic drag of the trailing vehicle (Veldhuizen et al., 2019) which in turn should reduce the power consumption and associated fuel consumption and emissions.

The reduction of aerodynamic drag is caused by positioning the trailing vehicle in the wake of the leading vehicle. However, the wake of the leading vehicle reduces with increasing distance from the

rear of the leading vehicle. As such, the gap distance as used as a parameter for various testing configurations is an important parameter to compare emissions and aerodynamic drag. The most direct measurement of air drag is the pressure difference from the centre of the front of the vehicle to the centre of the back. The drag forces apply to the front. Given the C_d drag coefficient, it is clear that not the full frontal surface has the same pressure applied, but the pressure peaks at the centre. Placing the pressure sensor at the right location, where there is no flow (i.e., homoclinic point), avoids reduced pressure readings due to the dynamic pressure from flow at the sensor location, which can be substantial. Still pressure measurements from other locations provide good relative results, showing the effects of different conditions, in particular at the same velocity, and the same flow effects. The results should be scaled to the appropriate total effect, such as the estimate of about 980 Newton drag force at 80 km/h with large headways.

As explained in the previous section, the two vehicles used during the trials are not identical. It is therefore not possible to conduct a straightforward comparison between leading and trailing vehicle to assess fuel consumption and emissions. The specific difference in vehicles does not affect the dynamic pressure measurements and therefore this parameter can still be assessed.

For each test configuration as indicated in Table 1-2, the vehicles alternated as leading and trailing vehicle thereby providing fuel consumption and emission data for both positions. As indicated above, the velocity has a strong relation to aerodynamic drag. The velocity domain for which data can be compared needs to be relatively narrow in order to provide a valid comparison.

3.2 Results

3.2.1 Velocity sensitivity analysis

As indicated in Section 3.1.4, velocity has a quadratic relation to aerodynamic drag which in turn affects fuel consumption and emissions. It is desirable to include as much data as possible whilst considering the velocity influence. Therefore this subsection presents a sensitivity analysis. The target velocity is 80 km/h, i.e. the velocity during CACC operation, and the tables presented show the averages for the aforementioned parameters for the following velocity ranges:

- 80 km/h +/- 5 km/h
- 80 km/h +/- 3 km/h
- 80 km/h +/- 1 km/h

The averages of the parameters were calculated using the following equation:

$$Average = \frac{1}{n} \sum_i^n parameter_i$$

For the condition that:

Velocity is within a set domain e.g. (80km/h +/- 1km/h, etc)

In the cases of CO₂, NO_x and fuel consumption, the tables present the averaged measures over the specified subsets of the data. $P = \frac{P_{measured} - P_{\infty}}{P_{\infty}}$

In addition, due to the different loading conditions and engine configuration as discussed in section 3.1, a distinction is made between the specific vehicle and its position in the platoon i.e. leader or trailer.

In the following tables certain data fields are empty. The CACC condition only applies to the trailer vehicle hence no data is reported in the tables. This is indicated with N/A (Not Applicable). Some data fields are also empty for other settings. In those instances, the vehicle did not operate at the specified velocity and/or mode to provide adequate data for analysis. This is indicated with N/M (Not Measured)

Table 3-1 Average fuel consumption for various velocity ranges, trucks & positions and platoon conditions (N/A is Not Applicable; N/M is Not Measured).

Vehicle	Position	Control Mode + Setting Speed range	Fuel [l/100 km]					
			CACC (1.0)	CACC (1.5)	ACC (1.5)	ACC (1.75)	ACC (2.0)	Manual
ET2	Leader	+/- 1 km/h	N/A	N/A	20.32	21.06	20.37	19.36
		+/- 3 km/h	N/A	N/A	21.43	22.18	21.79	21.53
		+/- 5 km/h	N/A	N/A	21.58	22.43	22.00	21.93
	Trailer	+/- 1 km/h	19.75	N/M	19.83	N/M	22.04	23.04
		+/- 3 km/h	23.47	N/M	23.55	N/M	23.63	24.13
		+/- 5 km/h	24.46	N/M	24.21	N/M	24.12	24.64
ET3	Leader	+/- 1 km/h	N/A	N/A	20.33	N/A	20.69	21.21
		+/- 3 km/h	N/A	N/A	22.42	N/A	21.34	22.39
		+/- 5 km/h	N/A	N/A	22.69	N/A	21.48	23.11
	Trailer	+/- 1 km/h	19.72	20.55	19.83	20.53	20.78	20.6
		+/- 3 km/h	21.23	22.55	21.58	22.33	22.58	21.88
		+/- 5 km/h	22.15	23.49	22.06	22.89	23.46	22.77

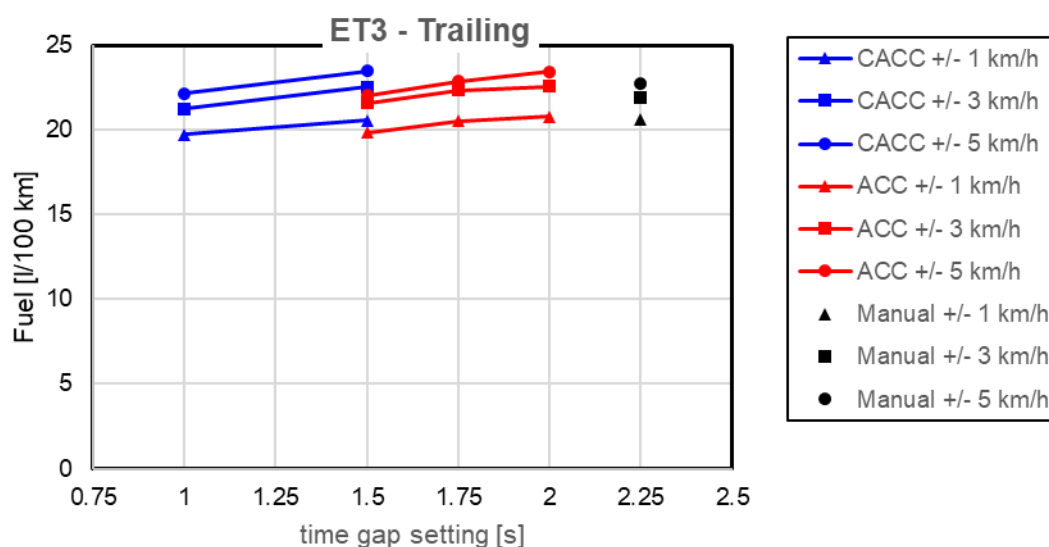


Figure 3-1 Average fuel consumption for truck ET3 in Trailing position for different control modes and settings at different speed ranges.

Table 3-1 provides an overview of the average fuel consumption for various velocity ranges, vehicles and positions, and platoon conditions. It can be observed that when applying a larger velocity range, the average fuel consumption tends to increase. The trend between various gap settings however, remains similar as can also be observed in Figure 3-1, which shows vehicle ET3 in trailing mode for various conditions.

Table 3-2 Average CO₂ emissions for various velocity ranges, trucks & positions and platoon conditions (N/A is Not Applicable; N/M is Not Measured).

Vehicle	Position	Control Mode + Setting Speed range	CO ₂ [g/km]					
			CACC (1.0)	CACC (1.5)	ACC (1.5)	ACC (1.75)	ACC (2.0)	Manual
ET2	Leader	+/- 1 km/h	N/A	N/A	538	558	540	513
		+/- 3 km/h	N/A	N/A	568	588	577	571
		+/- 5 km/h	N/A	N/A	572	594	583	581
	Trailer	+/- 1 km/h	523	N/M	526	N/M	584	611
		+/- 3 km/h	622	N/M	624	N/M	626	639
		+/- 5 km/h	648	N/M	642	N/M	639	653
ET3	Leader	+/- 1 km/h	N/A	N/A	539	N/M	548	562
		+/- 3 km/h	N/A	N/A	594	N/M	566	593
		+/- 5 km/h	N/A	N/A	601	N/M	569	612
	Trailer	+/- 1 km/h	522	545	525	544	551	546
		+/- 3 km/h	563	598	572	592	598	580
		+/- 5 km/h	587	623	585	607	622	603

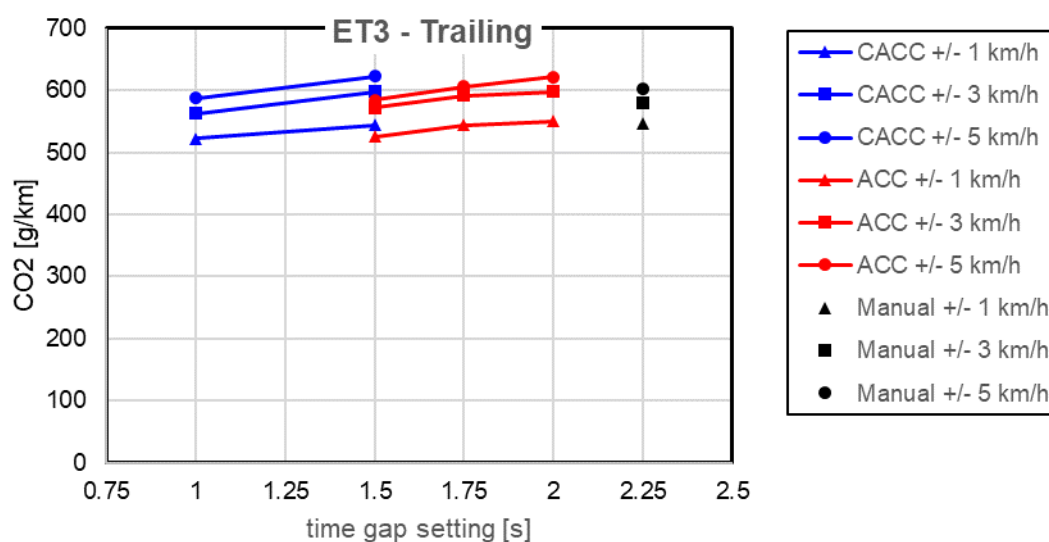


Figure 3-2 Average CO₂ emissions for truck ET3 in Trailing position for different control modes and settings at different speed ranges.

Table 3-2 and Figure 3-2 provide information of the CO₂ emissions similar to fuel consumption and show a similar trend.

Table 3-3 Average NO_x emissions for various velocity ranges, trucks & positions and platoon conditions (N/A is Not Applicable; N/M is Not Measured).

Vehicle	Position	Control Mode + Setting Speed range	NO _x [mg/km]					
			CACC (1.0)	CACC (1.5)	ACC (1.5)	ACC (1.75)	ACC (2.0)	Manual
ET2	Leader	+/- 1 km/h	N/A	N/A	362	299	314	95
		+/- 3 km/h	N/A	N/A	369	360	439	151
		+/- 5 km/h	N/A	N/A	397	361	457	170
	Trailer	+/- 1 km/h	46	N/M	173	N/M	385	450
		+/- 3 km/h	73	N/M	250	N/M	459	533
		+/- 5 km/h	104	N/M	282	N/M	492	584
ET3	Leader	+/- 1 km/h	N/A	N/A	132	N/M	161	246
		+/- 3 km/h	N/A	N/A	227	N/M	229	285
		+/- 5 km/h	N/A	N/A	279	N/M	266	308
	Trailer	+/- 1 km/h	164	231	241	245	246	225
		+/- 3 km/h	236	363	274	361	369	288
		+/- 5 km/h	288	454	334	413	453	322

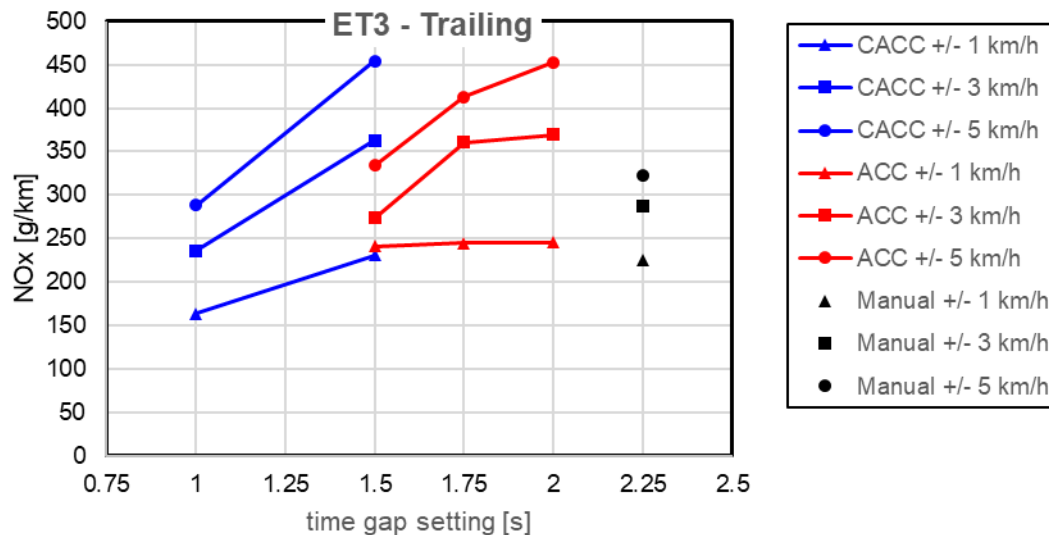


Figure 3-3 Average NO_x emissions for truck ET3 in Trailing position for different control modes and settings at different speed ranges.

Instead of showing values for dynamic pressure, the relative values are used. This is necessary due to the specific location of the sensors on the vehicle which have a big influence in the pressure measurement as mentioned in Section 3.1.4 i.e. if the sensor is not located in a homoclinic point, the air flow translates in a lower pressure reading in the sensor. The dynamic pressure shown in this section in table 3.4 and in Figure 3.4 is the pressure reduction experienced at the front of the vehicle with respect to a vehicle without a leader, this is given by:

$$P = \frac{P_{measured} - P_{\infty}}{P_{\infty}}$$

where $P_{measured}$ is the instantaneous pressure measured with the sensor and P_{∞} is the average value of the pressure when the vehicle has no leader.

Table 3-4 Average relative dynamic pressure for various velocity ranges, trucks & positions and platoon conditions (N/A is Not Applicable; N/M is Not Measured).

Vehicle	Position	Control Mode + Setting Speed range	Average relative dynamic pressure					
			CACC (1.0)	CACC (1.5)	ACC (1.5)	ACC (1.75)	ACC (2.0)	Manual
ET2	Leader	+/- 1 km/h	N/A	N/A	-10%	-10%	-1%	-21%
		+/- 3 km/h	N/A	N/A	-4%	-13%	-1%	-11%
		+/- 5 km/h	N/A	N/A	-4%	-11%	0%	-11%
	Trailer	+/- 1 km/h	12%	N/M	0%	N/M	-9%	-33%
		+/- 3 km/h	12%	N/M	5%	N/M	-6%	-36%
		+/- 5 km/h	12%	N/M	6%	N/M	-6%	-37%
ET3	Leader	+/- 1 km/h	N/A	N/A	-29%	N/M	0%	-22%
		+/- 3 km/h	N/A	N/A	-28%	N/M	0%	-7%
		+/- 5 km/h	N/A	N/A	-28%	N/M	0%	-5%
	Trailer	+/- 1 km/h	-14%	-10%	-7%	-15%	-7%	-23%
		+/- 3 km/h	-14%	-10%	-5%	-18%	-6%	-17%
		+/- 5 km/h	-13%	-11%	-5%	-19%	-6%	-16%

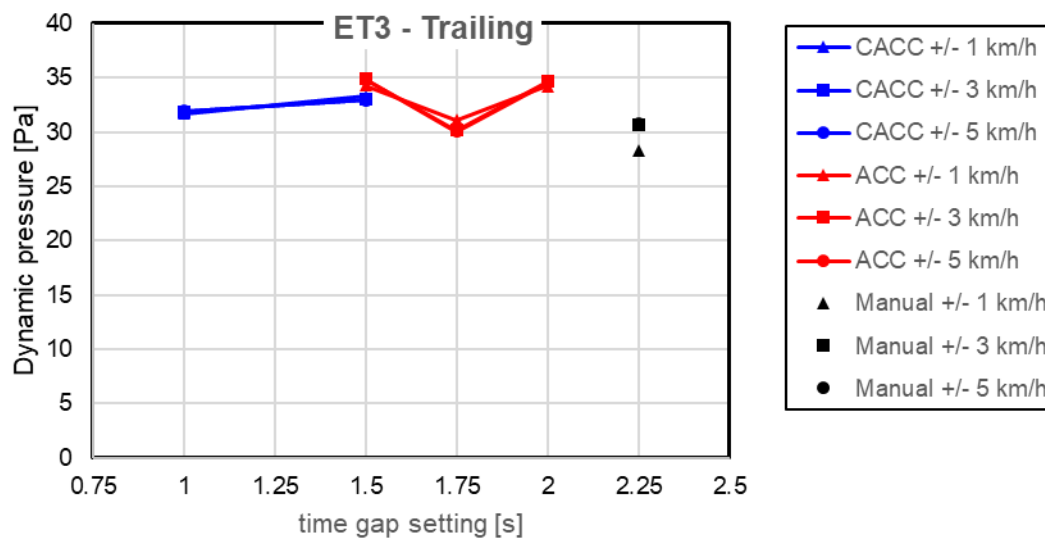


Figure 3-4 Average dynamic pressure for truck ET3 in trailing position for different control modes and settings at different speed ranges.

A velocity range of 80 km/h $\pm$ 5 km/h will be used for further analysis as the trend is similar compared to the most narrow velocity range. Using a wider velocity range allows for more data to be taken into account which is preferable.

3.2.2 Measurement results of fuel consumption, CO₂ emissions and NO_x emissions and dynamic pressure

This subsection presents the measurement results of fuel consumption, CO₂ emissions and NO_x emissions and dynamic pressure for a velocity range of 80 km/h $\pm$ 5 km/h. To assess the statistical significance of differences, t-tests were performed to compare the *control mode + setting* conditions. Bonferroni correction was applied to reduce an increased Type I error probability due to multiple comparisons. This analysis was done for each vehicle-position combination separately.

Figure 3-5 shows the average fuel consumption for different configurations for vehicle ET2 and ET3 respectively. These figures, together with for the CO₂, show that there was no fuel or CO₂ benefit for a trailing vehicle for the specific conditions of this experiment. Figures 3.11 and 3.12 show that the dynamic pressure in front of the vehicles was reduced, with reducing distance gap, as expected. On ACC, the leading vehicle also showed a reduction of dynamic pressure due to the presence of vehicles in front of the platoon. The condition of ACC 1.75 seemed to have an additional air pressure reduction and this can indicate that 1.75 s of time gap at 80 km/h is a particular good configuration that requires further investigation.

Fuel and CO₂ reductions for smaller time gaps are also observed for the same controller. The fuel consumption of the trailing vehicle decreased with the distance gap, varying on the range of 1.5 l/100 km (see Figure 3-5). Figure 3-7 shows the same type of behaviour for the NO_x emissions: for the same controller, the shorter time gaps reduce emissions, but the CACC controller is outperformed by the ACC and the manual driver.

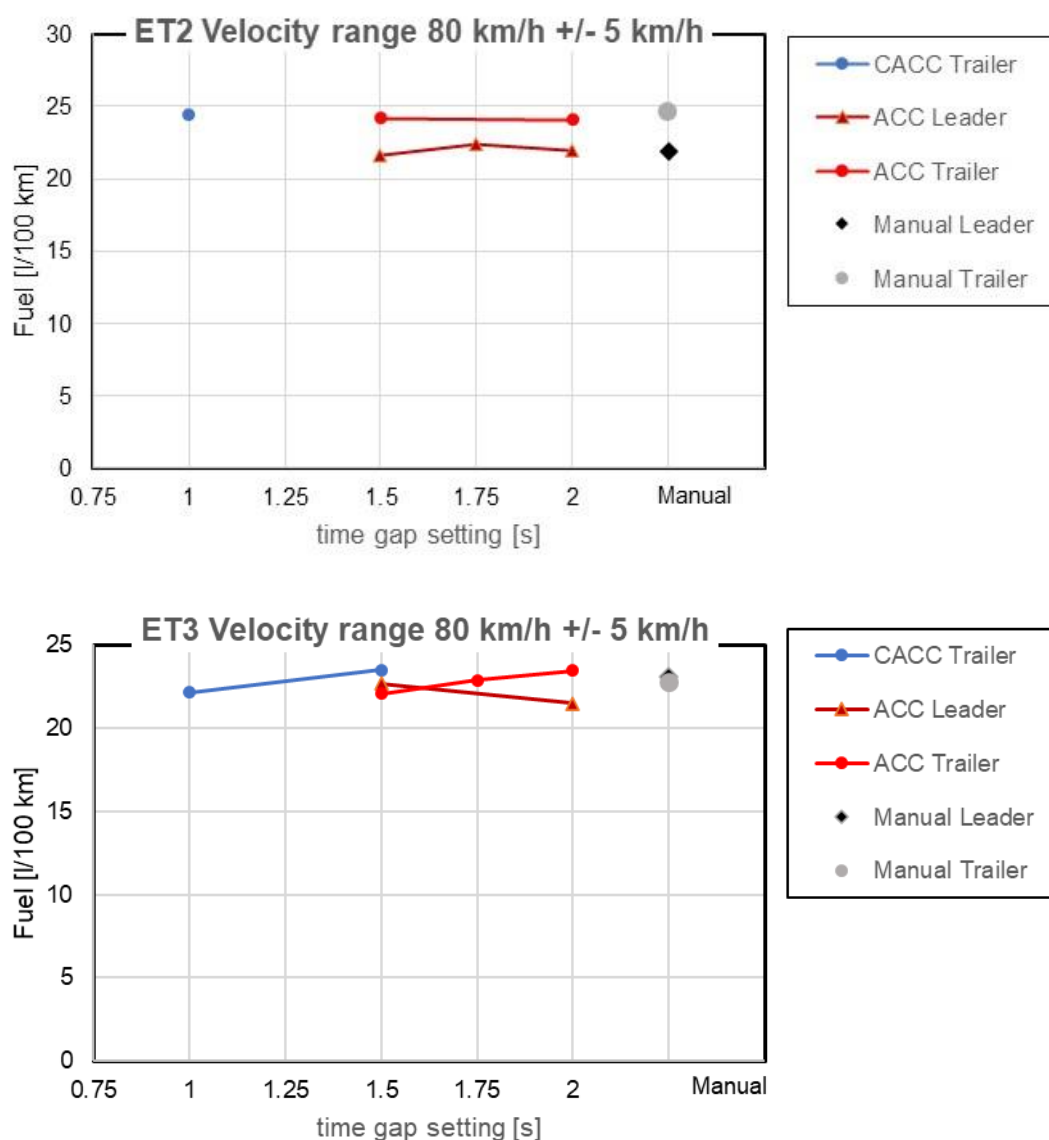


Figure 3-5 Average fuel consumption for trucks ET2, ET3 for different positions, control modes and settings.

Table 3-5 Average fuel consumption for a velocity range of 80 km/h +/- 5 km/h, ET2 & ET3 vehicles, various positions, platoon conditions and settings (N/A is Not Applicable; N/M is Not Measured).

		Fuel [l/100 km]					
Vehicle	Control Mode + Position	CACC (1.0)	CACC (1.5)	ACC (1.5)	ACC (1.75)	ACC (2.0)	Manual
ET2	Leader	N/A	N/A	21.58	22.43	22.00	21.93
	Trailer	24.46	N/M	24.21	N/M	24.12	24.64
ET3	Leader	N/A	N/A	22.69	N/M	21.48	23.11
	Trailer	22.15	23.49	22.06	22.89	23.46	22.77

The data for vehicle ET2 Trailer is limited and does not show an expected trend of increasing fuel consumption with increasing time gap like the data for vehicle ET3 Trailer shows.

The statistical tests showed the following results.

- For *ET2, Leader*, the differences among the ACC conditions were all significant [all $p < 0.05$]; the lowest fuel consumption was obtained at the shortest time gap setting (ACC 1.5 s). The manual condition differed only from ACC (1.75 s), showing lower fuel consumption in manual driving than in this ACC condition [$p < 0.05$].
- For *ET2, Trailer*, no significant differences were found [all $p > 0.6$]
- For *ET3, Leader*, ACC (2.0 s) showed significantly lower fuel consumption than both other conditions [both $p < 0.01$]. Manual driving and ACC (1.5 s) did not differ [$p > 0.9$].
- For *ET3, Trailer*:
 - CACC (1.0) showed lower fuel consumption than CACC (1.5) [$p < 0.01$];
 - ACC (1.5) had lower fuel consumption than ACC at higher time gaps [both $p < 0.05$]; ACC (1.75) and ACC (2.0) did not differ significantly [$p = 0.09$].

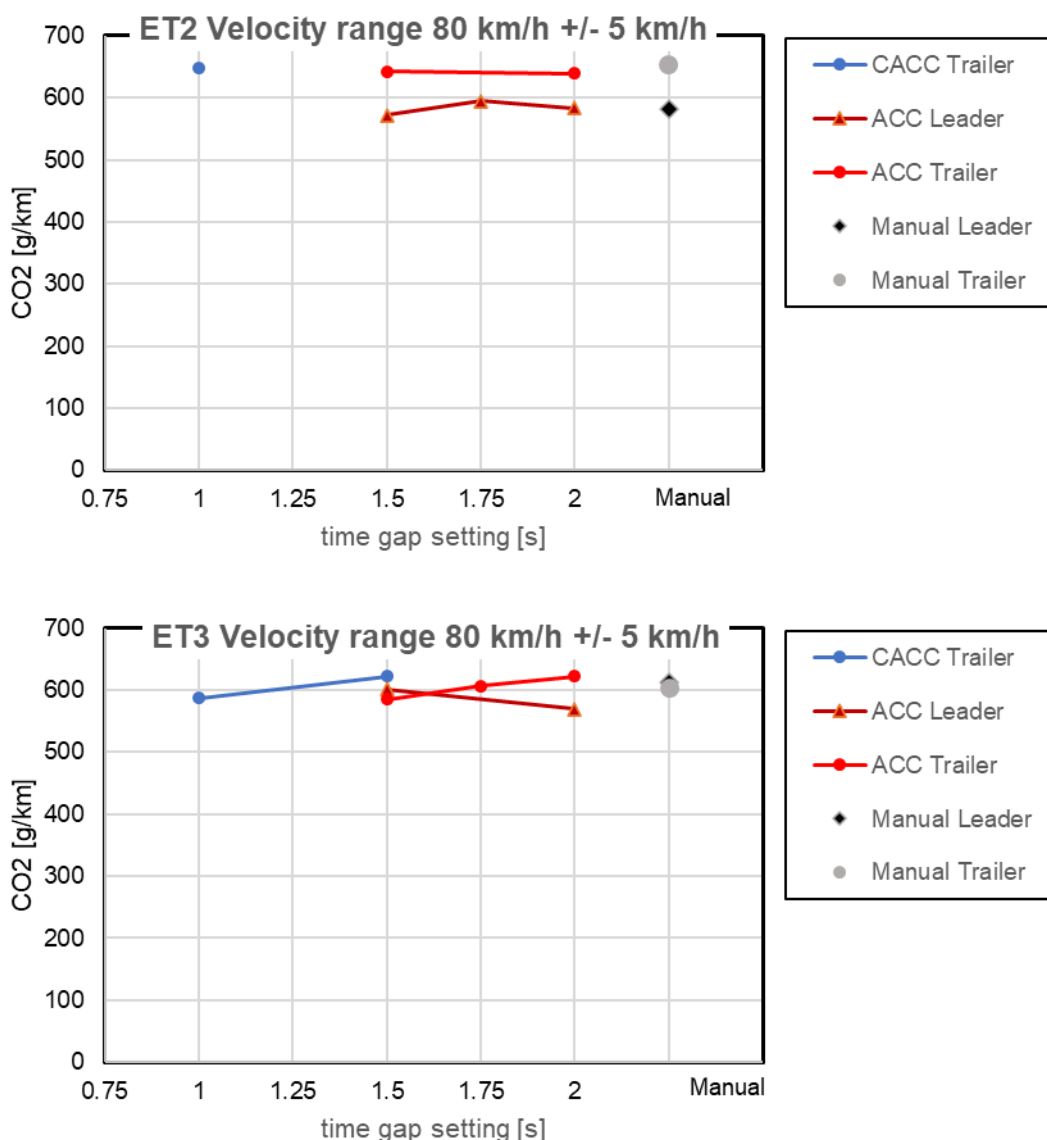


Figure 3-6 Average CO₂ emissions for trucks ET3, ET3 for different positions, control modes and settings.

Table 3-6 Average CO₂ for a velocity range of 80 km/h +/- 5 km/h, ET2 & ET3 vehicles, various positions, platoon conditions and settings (N/A is Not Applicable; N/M is Not Measured).

		CO ₂ [g/km]					
Vehicle	Control Mode + Setting Position	CACC (1.0)	CACC (1.5)	ACC (1.5)	ACC (1.75)	ACC (2.0)	Manual
ET2	Leader	N/A	N/A	572	594	583	581
	Trailer	648	N/M	642	N/M	639	653
ET3	Leader	N/A	N/A	601	N/M	569	612
	Trailer	587	623	585	607	622	603

The statistical tests showed the same pattern of results as presented above for fuel consumption.

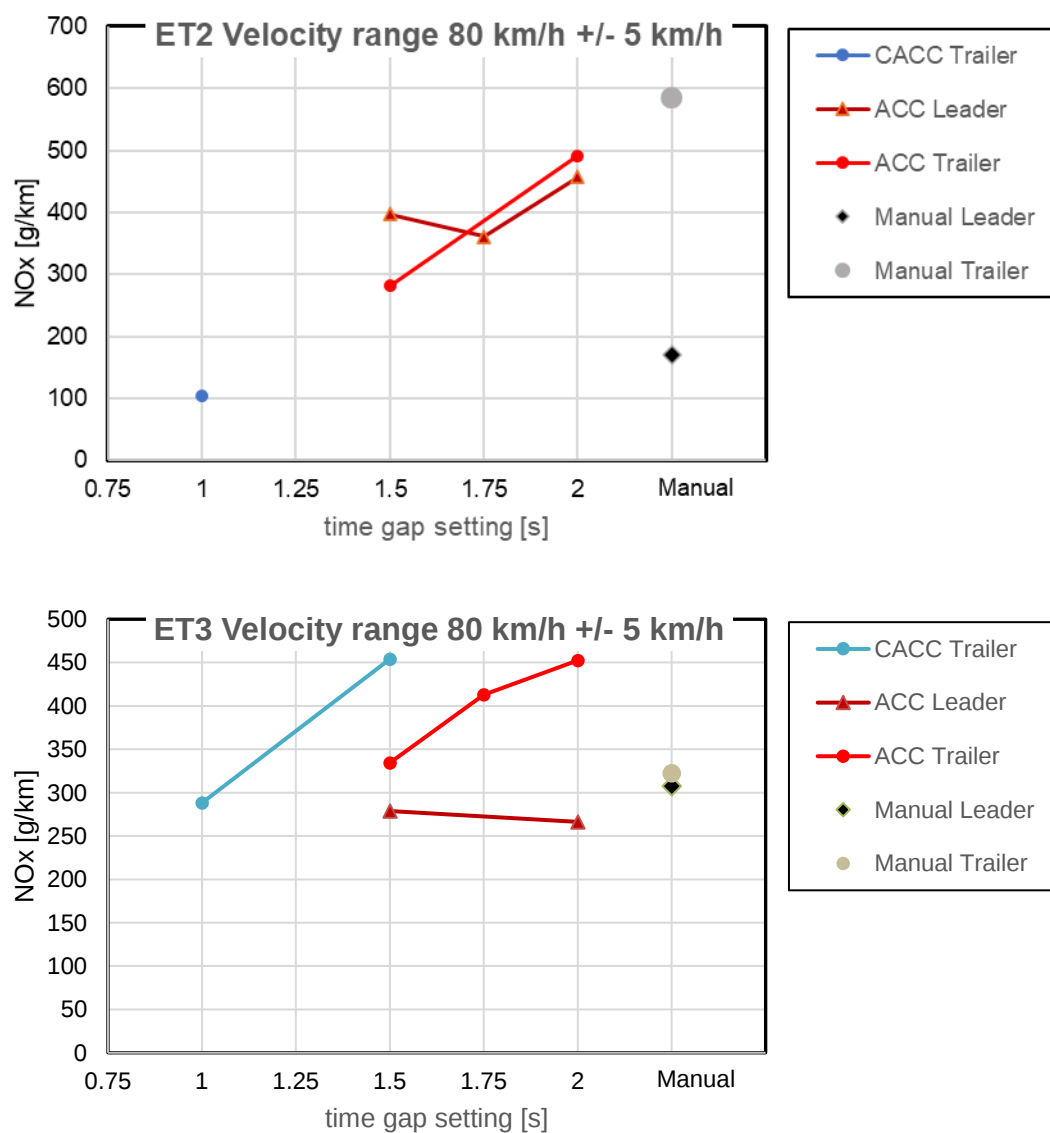


Figure 3-7 Average NO_x emissions for trucks ET2, ET3 for different positions, control modes and settings.

Table 3-7 Average NO_x for a velocity range of 80 km/h +/- 5 km/h, ET2 & ET3 vehicles, various positions, platoon conditions and settings (N/A is Not Applicable; N/M is Not Measured).

		NO _x [g/km]					
Vehicle	Control Mode + Setting	CACC (1.0)	CACC (1.5)	ACC (1.5)	ACC (1.75)	ACC (2.0)	Manual
	Position						
ET2	Leader	N/A	N/A	397	361	457	170
	Trailer	104	N/M	282	N/M	492	584
ET3	Leader	N/A	N/A	279	N/M	266	308
	Trailer	288	454	334	413	453	322

The statistical tests showed the following results.

- For *ET2 Leader*, all control mode / setting conditions differed significantly [all $p < 0.01$], with one exception: ACC (1.5) versus ACC (1.75), a level of $p = 0.07$ was found. Thus, in ACC driving, the largest time gap setting had more NO_x emissions than the lowest or middle time gap setting.
- For *ET2 Trailer*, all control mode / setting conditions differed significantly [all $p < 0.01$]. Lower time gap settings yielded lower NO_x emissions.
- For *ET3 Leader*, no significant differences were found [all $p > 0.22$].
- For *ET3 Trailer*:
 - The difference between the CACC conditions 1.0 and 1.5 s was significant [$p < 0.001$], showing lower NO_x emissions at the lower time gap setting.
 - ACC had lower NO_x emissions at 1.5 s compared to 1.75 or 2.0 s [both $p < 0.02$], whereas the difference between 1.75 and 2.0 s was not significant. Thus, the lowest time gap setting yielded the lowest NO_x emission.

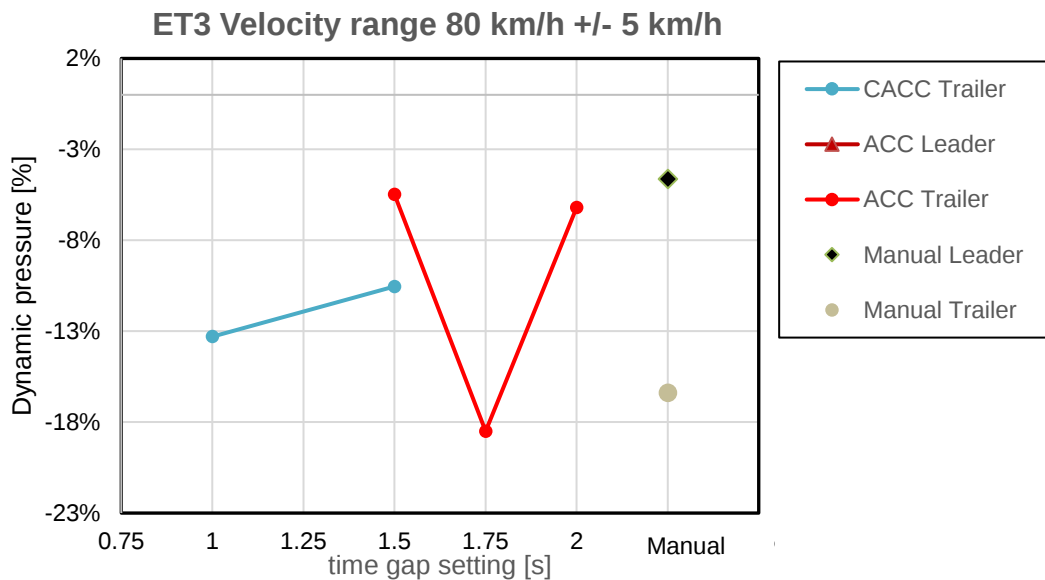
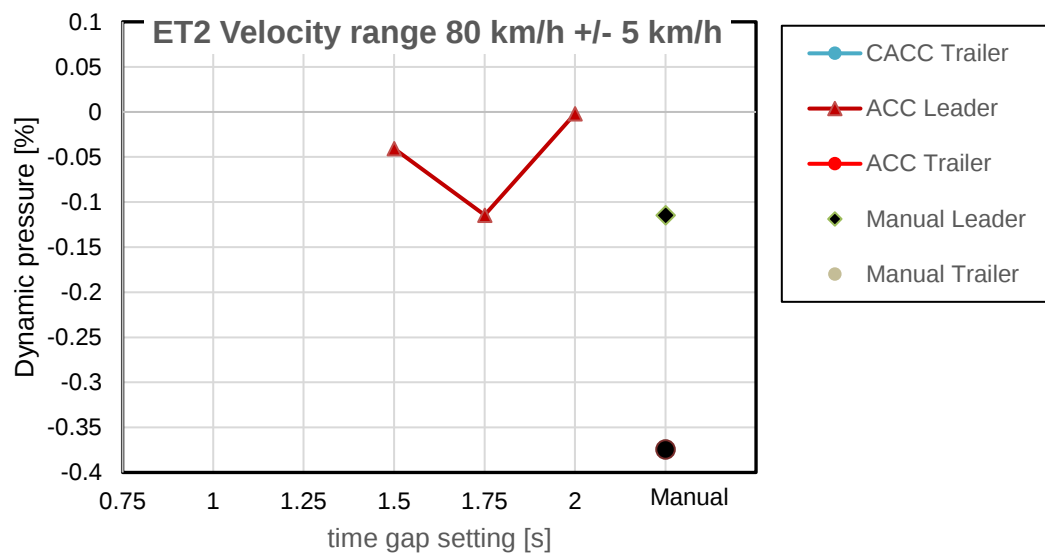


Figure 3-8 Dynamic pressure reduction on the front of the vehicle for ET2 and ET3.

Table 3-8 Average relative dynamic pressure for a velocity range of 80 km/h +/- 5 km/h, ET2 & ET3 vehicles, various positions, platoon conditions and settings (N/A is Not Applicable; N/M is Not Measured).

		Average relative dynamic pressure [%]					
Vehicle	Control Mode + Setting	CACC (1.0)	CACC (1.5)	ACC (1.5)	ACC (1.75)	ACC (2.0)	Manual
	Position						
ET2	Leader	N/A	N/A	-4%	-11%	0%	-11%
	Trailer	12%	N/M	6%	N/M	-6%	-37%
ET3	Leader	N/A	N/A	-28%	N/M	0%	-5%
	Trailer	-13%	-11%	-5%	-19%	-6%	-16%

3.2.3 Influence of the controller behaviour

As indicated in Section 1.1 the ACC/CACC controller used on the trucks has been developed by TNO and is not a commercially available controller. As established in Sections 2.5 and 2.8, the velocity fluctuation of the trailer vehicle driving in ACC or CACC mode was larger than that of the leader vehicle. Results also showed that the ACC/CACC controller did succeed in minimising the time gap variation. This subsection shows the difference in velocity profiles between leader and trailer to understand potential effects on fuel consumption.

Figure 3-9 show two velocity profiles of leader and trailer vehicles with the latter in CACC mode. It can be observed that the velocity of the trailing vehicle has a larger standard deviation than the leading vehicle as reported in Section 2.8. It can be observed that the amplitude of the velocity fluctuations of the trailing vehicle is in the order of magnitude of 0.37 km/h, with a period of 8 s. The power needed to accelerate the trailing truck in this manner will be more than for the leader truck which will have a negative effect on fuel consumption, CO₂, and NO_x emissions for the trailing truck.

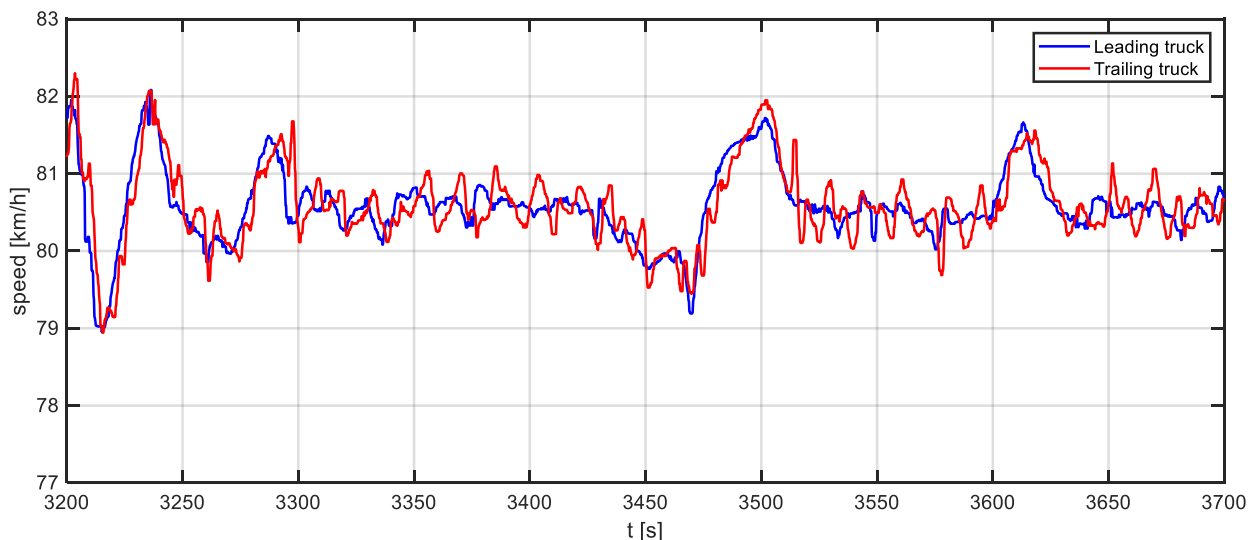


Figure 3-9. Example timeseries of two vehicles where the trailing vehicle is controlled by the CACC controller with a target time gap of 1 s.

Figure 3-10 shows the pressure reduction on the front of the vehicle as a function of the distance gap, using all data in the speed range of 80 +/- 5 km/h. It can be seen that, as mentioned in Section 3.2.2, the reduction of pressure with distance gap is observed. This reduction in pressure represents a lower power demand by the trailing vehicle, which in this case cannot be observed because the increased power demand due to the velocity fluctuations in the CACC counteracts this effect. The ACC also produces speed fluctuations whose amplitude is in between those observed in the CACC controller and the manual driving, as the piece-wise standard deviation of the speed indicated in Section 2.8.

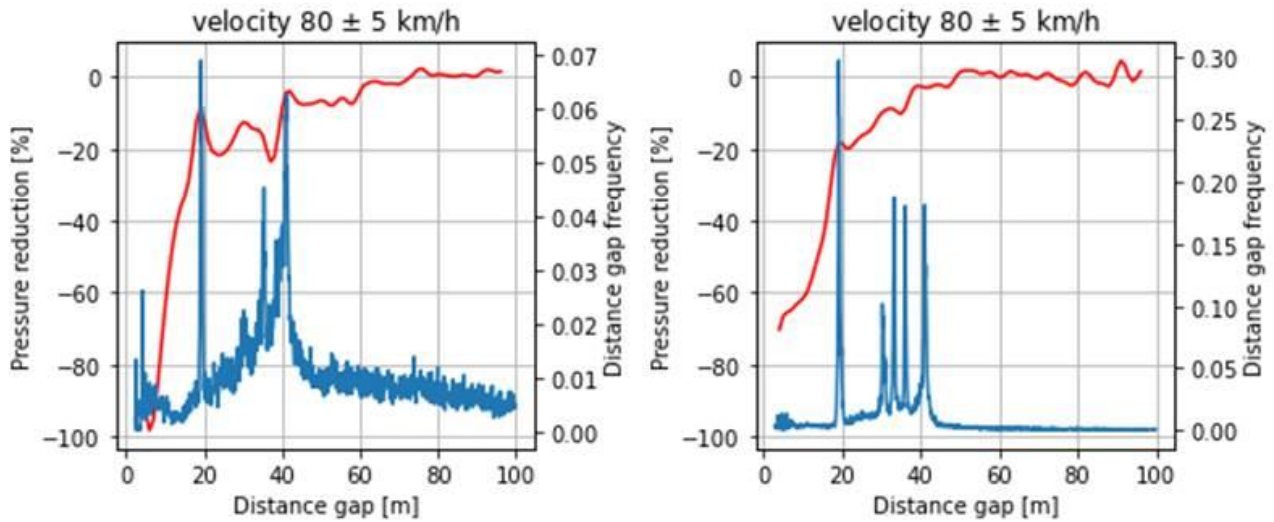


Figure 3-10 In red pressure reduction as a function of the distance gap. In blue, the frequency of the distance gap. All the data of for the speed range 80 ± 5 km/h. On the left, ET2 and on the right ET3.

To further verify this hypothesis, in Figure 3-11 the fuel consumption of the trailing vehicle as a function of relative acceleration between both vehicles (defined as $\Delta a = a_{\text{trailer}} - a_{\text{leader}}$) is shown. Together with what was shown in Figure 3-9 and this relation allows to determine the increase in fuel usage by the trailing vehicle. There is a factor 98.46 (l/100 km)/(m/s²) for vehicle ET2 and 108.39 (l/100 km)/(m/s²) for vehicle ET3, which means an increase of 9.8 (ET2) and 10.8 (ET3) l/100 km of every 0.1 m/s² of acceleration. Provided that the observed speed fluctuations have an amplitude of 0.1 m/s with a period of 10 s, it would be expected that the controller is responsible for an increase of fuel consumption of in the order of magnitude of 3 l/100 km when the trailing vehicle has a larger acceleration than the leading one. This is only partially compensated by the deceleration intervals and overall by the pressure reduction.

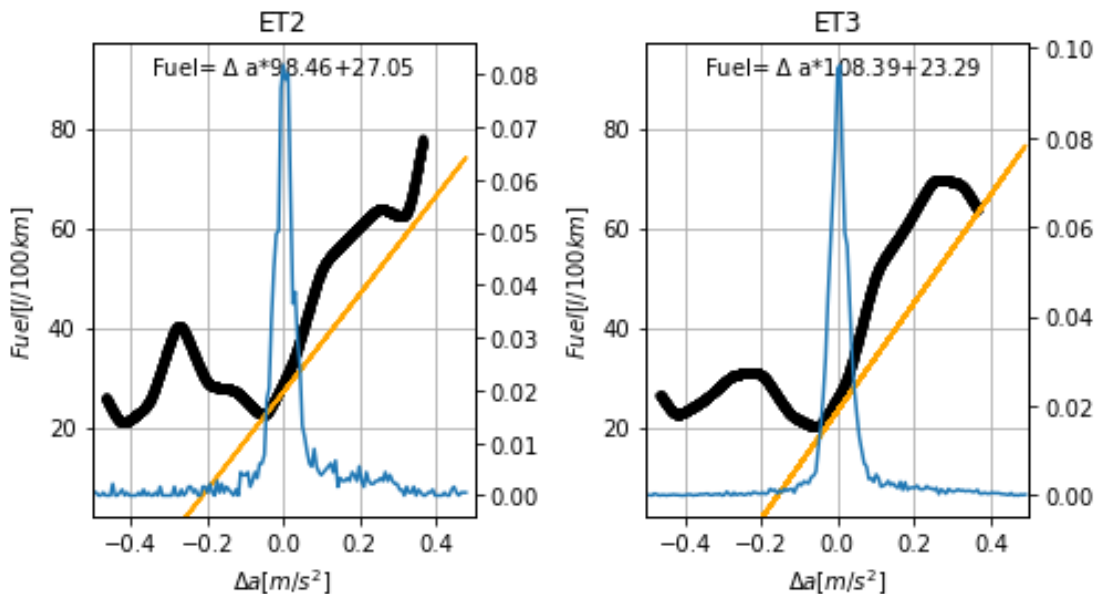


Figure 3-11 Fuel consumption of the trailing vehicle as a function of the relative acceleration between the vehicles. In black, the binned-averaged fuel consumption and in orange, a linear fit indicating the trend. Left and right panels show vehicles ET2 and ET3, respectively.

3.3 Discussion

Two DAF euro VI (EcoTwin3) vehicles have been equipped with sensors to measure data while driving on the corridor Rotterdam-Venlo. The vehicles interchanged position in the platoon along the study (vehicle ET2 was sometimes the leading vehicle while vehicle ET3 took that role other times). All measurements took place between 09:00 and 18:00 hours Central European Time (CET) during weekdays. Since the vehicles operated at different engine speed (for the same vehicle velocity) and their load differed, it is not possible to compare the fuel consumption and emissions between vehicles but the comparison is only done using the same vehicle.

Although the reduction on air drag in the trailing vehicle is observed and it decreased with the distance gap, there is no noticeable benefit in fuel consumption nor emissions. The tight behaviour of the ACC and CACC controllers in this case counteracts the effect of the air drag reduction, and thus limiting the potential energy efficiency of platooning. This is attributed to the fact that the controllers are designed to keep a stable distance gap but not to optimize energy usage. Further investigation determined that the effect of speed variability on fuel consumption is effectively larger than that attributed to the air drag reduction benefit explaining the poor energy performance of platooning with this controller. Either case, with a controller design that takes these effects into consideration, the energy benefits of the air drag reduction could be observed. The NO_x emissions follow the same behaviour of that of the fuel consumption. This is expected since an increase in power demand is expected to impact both NO_x emissions as well.

In the development of this platooning system, emphasis was on controller performance and especially on fail-safety (Bijlsma et al., 2016; Bijlsma & Hendriks, 2017). In tuning the controllers, fuel consumption and emissions were not among the criteria. Therefore, findings with respect to this Macro Topic should be interpreted in this context and not be generalised to assumed effects of platooning in general. These results do not contradict previous studies that show platooning benefits on fuel consumption due to reductions in air drag, but highlights the importance of an appropriate controller design for such purpose. This is in line with previous research that indicates the importance of design an algorithm that reduces the acceleration is necessary to obtain a fuel consumption benefit from truck platooning (Nie et al., 2020). At the same time, different previous studies already found that optimizing other than the fuel consumption can lead to increased fuel usage levels (Huand et al., 2018, Zhao et al., 2017).

Finally, the results can be compared with current literature (Veldhuizen, Van Raemdonck, & van der Krieke, 2019). This comparison is shown in Figure 3-12. Overall, truck platooning has shown different levels of benefits in fuel consumption for trailing vehicles. The current results do not contradict those findings but they do turn the focus to the controller design.

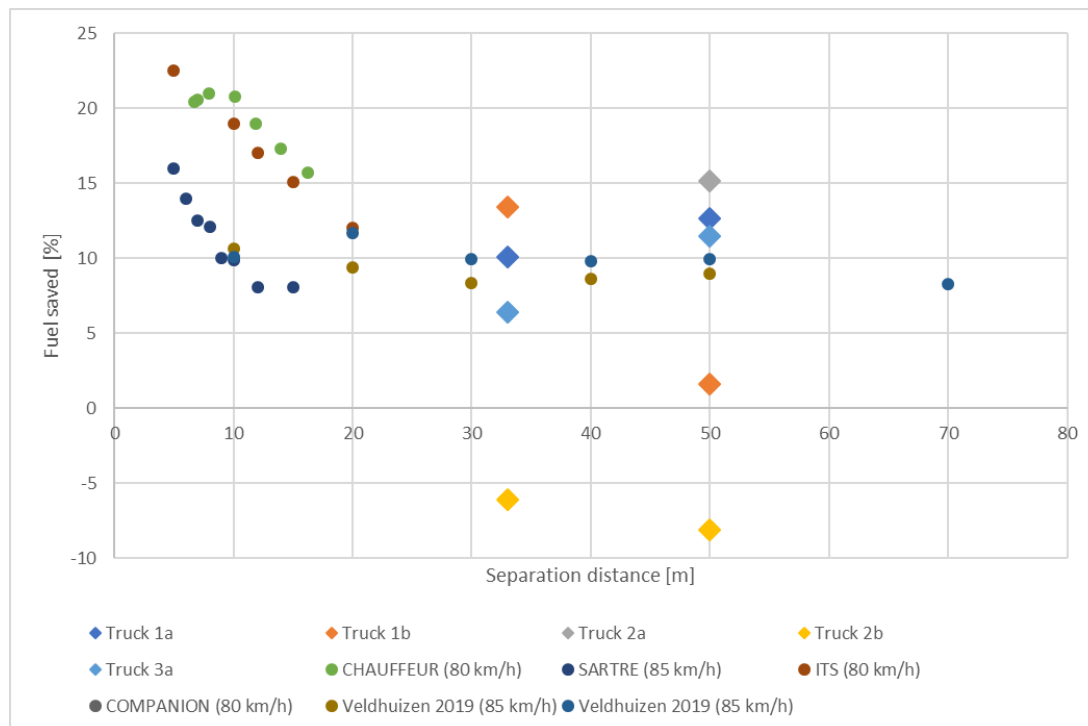


Figure 3-12. Fuel consumption benefits of platooning (see Veldhuizen et al., 2019).

The results show that for this particular CACC controller design there are no benefits on the fuel consumption and on the contrary, the trailer vehicle in CACC mode consumes more energy. This is not in conflict with previous studies done on platooning, on the contrary, it highlights the importance of including the optimization on the design of the algorithm. Most of the previous studies were done on ACC or looking at the following distance of vehicles driving manually. The benefits of truck platooning gained from reducing the air friction hold, as they are established based on several works and are also shown here (Veldhuizen, et al., 2019, McAuliffe et al., 2017). In the current project, the vehicles use ACC or CACC and manage to keep the time gap very precisely, but at the expense of energy consumption. When the goal is to design a platooning algorithm to improve sustainability, the platooning algorithms must have energy as one of their optimization objectives.

This study shows that the technology is ready and capable of keeping vehicles driving at a small time gap in a cooperative fashion. The communication and the response of the vehicles was developed enough to guarantee such behaviour. With such positive results, it can be stated that the vehicles will be able to handle the dynamics required by an algorithm that optimizes other quantities other than time gap.

3.4 Conclusions

This chapter discussed the results of the truck platooning trials on Macro Topic 3: emissions. The experimental results show that the relative dynamic pressure reduces with reducing gap distance between leader and trailer vehicle which is in line with results found in literature (Veldhuizen et al., 2019; McAuliffe et al., 2017). Though the reduction of relative dynamic pressure with reducing gap distance would reduce the demand for energy and thereby show a similar trend for emissions and fuel consumption, a consistent similar trend was not observed. A comparison in velocity profiles between leader and trailer vehicle showed an increased amplitude of velocity fluctuations of the trailer compared to that of the leading vehicle resulting in an increase in energy demand of the trailing

vehicle. This effect is believed to be caused by the time gap optimisation criterion of the CACC controller used, ignoring fuel consumption as a criterion. Despite the relative pressure reduction, this controller criterion results in an increased energy demand of the trailing vehicles which counteracts the reduction due to slipstreaming effect.

4 Driver acceptance (MT4)

As explained in Section 1.4, the truck drivers completed a set of questionnaires after completion of a driving session with one pre-defined platooning condition. This served to answer the research questions concerning impact on drivers in terms of workload, acceptance and trust.

As stated in the Evaluation Plan D1.2 (Hogema et al., 2022A), there is one remark to make with respect to MT4, driver acceptance. In general, many research questions can be formulated regarding the impact of platooning on drivers. These can cover impacts on: when and how drivers use the platooning system; behaviour during and after specific scenarios (cut-ins, transition of control situations, etc); learning effects; effects on workload, acceptance, trust, situational awareness, vigilance; and so on. However, as stated in the Truck Platooning Trial, the platooning system was operated by safety drivers, rather than by regular end users. This will pose limitations on the generalisability of the results, which is inherent to this type of field trial. See for instance L3Pilot, a large-scale EU project that involved testing of Level 3 systems on public roads (Pettinen et al., 2019). In the scoping of the UMneo TPT, it was decided to restrict research regarding the driver to two main components:

- The operational behaviour of the driver in relation to the platooning system, which was covered in Chapter 2
- Other driver impacts will be evaluated using various questionnaires, covering user aspects of workload, acceptance, and trust. This is the topic of this chapter.

4.1 Methodology

The set of Performance Indicators (PIs) used in this Macro Topic are listed in Table 4-1. The questionnaires that were used are listed in Appendix A.

- Workload was assessed in all conditions, including the manual condition. This was done with the Rating Scale Mental Effort (RSME) (Zijlstra, 1993).
- Acceptance and trust are related to ACC or CACC and are therefore not applicable in manual driving. Acceptance was assessed with the rating scales defined by Van der Laan, Heino and De Waard (1997). The technique consists of nine 5-point rating-scale items. The raw scores are transformed into two scales ranging from -2 to +2: one a scale denoting the usefulness of the system, and one scale designating satisfaction.
- Trust was assessed using a set of questions that were scored on a 5-point Likert scale. The scores were shifted and inverted, yielding a range of -2 = “fully inapplicable” to +2 = “fully applicable”.

In D3.2A (Hogema et al., 2022B), it was explained how the questionnaire data were checked for completeness and consistency in terms of the experimental conditions. It turned out that one out of 91 questionnaires was missing and could not be retrieved. Furthermore, two of the questionnaires were not completely filled (missing five and nine out of 21 questions, respectively). Otherwise, the questionnaire data were complete and consistent in terms of the coded conditions.

Table 4-1 Driver acceptance: performance indicators.

	Performance Indicator	Scale
Acceptance	Usefulness, satisfaction	5-point Likert scale
Workload	Self-rated effort	0 to 150
Trust	Trust	5-point Likert scale

In terms of the statistical design, the same approach as in MT2 was used (see Figure 2-9). This means that two statistical designs were used for each performance indicator:

- Design A explicitly compared data from the leading and the trailing truck drivers, including ACC and manual driving.
- Design B looked at questionnaire data from CACC, ACC and manual driving, all obtained from drivers of the trailing truck.

4.2 Results

In this section, the subjective results with respect to workload (4.2.1), acceptance (4.2.2) and trust (4.2.3) are presented.

4.2.1 Workload

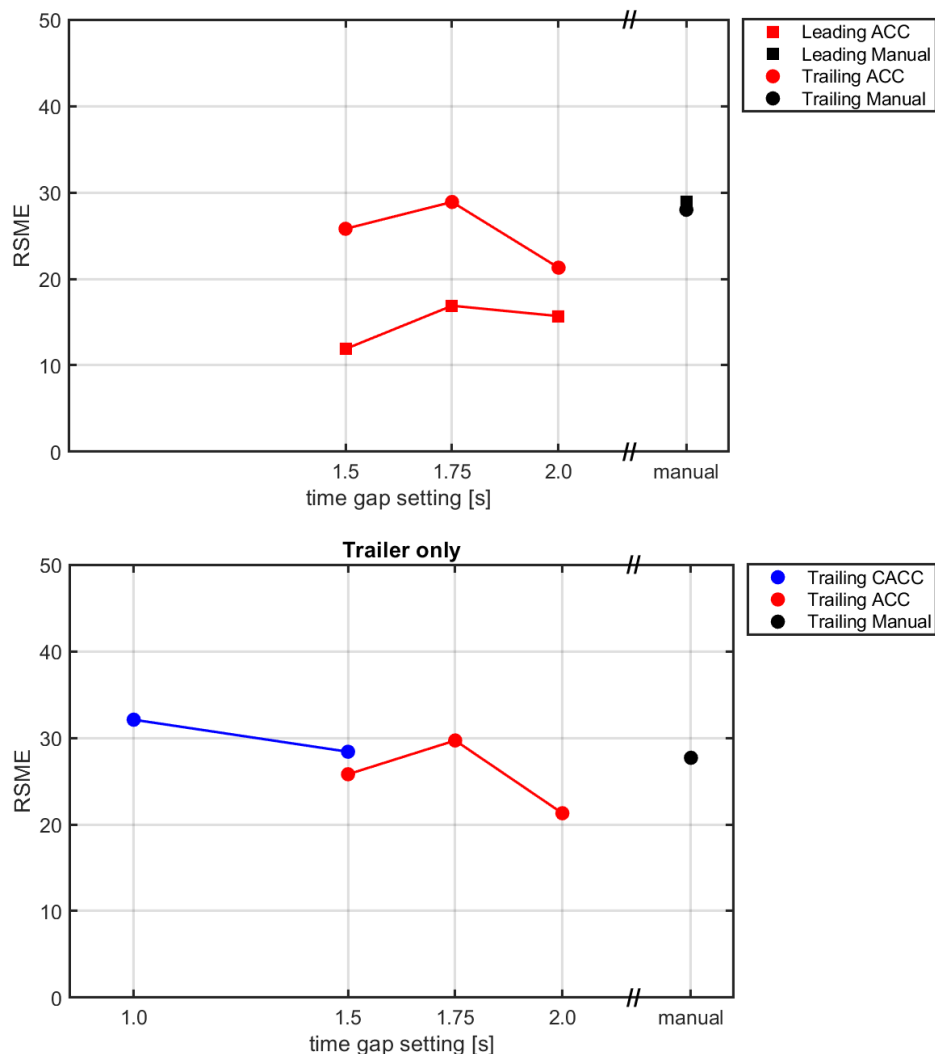


Figure 4-1 Workload as a function of experimental conditions (top: Design A; bottom: Design B).

The effect of conditions and truck role on workload is shown in Figure 4-1. Design A revealed a significant effect of Role [$p < 0.01$], showing that workload was higher for the trailer than for the leader (means 25.4 and 17.8, respectively). Also a significant effect of truck condition [$p < 0.05$] was found, showing within the leader condition, the workload was significantly higher for manual driving than for driving with ACC (at 1.5 s and 2.0 s time gap setting). No significant difference was found in workload among trailer conditions [Design B: all $p > 0.18$].

Within the trailer and within the leader, planned comparisons showed no significant differences among the CACC/ACC settings. This pattern was found in both statistical designs.

4.2.2 Acceptance

Following the procedure from Van der Laan, Heino and De Waard (1997), *usefulness* was determined by averaging the ratings on 5 items (useful-useless, good-bad, effective-superfluous, assisting-worthless and raising alertness-sleep inducing). *Satisfaction* was determined by averaging

the ratings with respect to the remaining four items (pleasant-unpleasant, nice-annoying, likeable-irritating and desirable-undesirable)

Usefulness

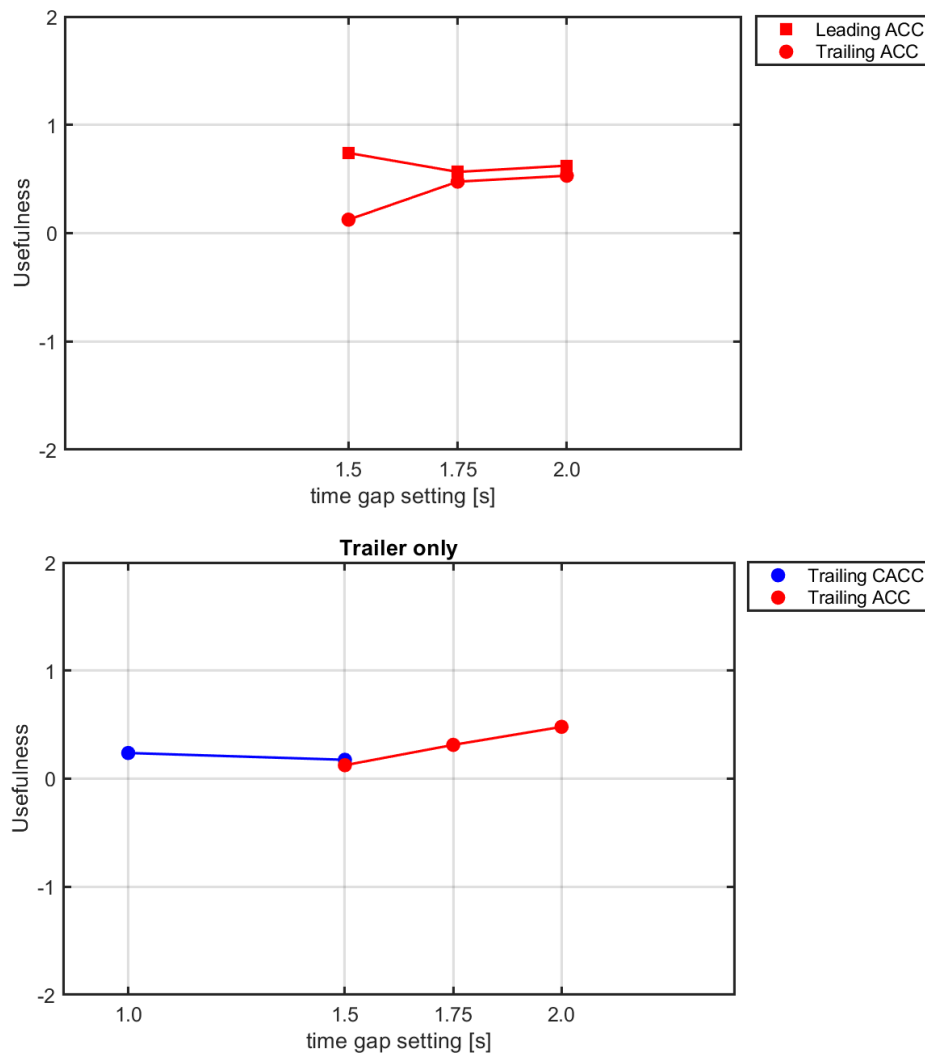


Figure 4-2 Usefulness as a function of experimental conditions (top: Design A; bottom: Design B).

Results in terms of usefulness as experienced by the driver are shown in Figure 4-2. The planned comparison showed a main effect of Role [$p < 0.05$], showing higher scores for the leader than for the trailer (0.64 and 0.44, respectively). The interaction was not significant [$p = 0.13$]. Within the trailer and within the leader, planned comparisons showed no significant differences among the CACC/ACC settings.

Satisfaction

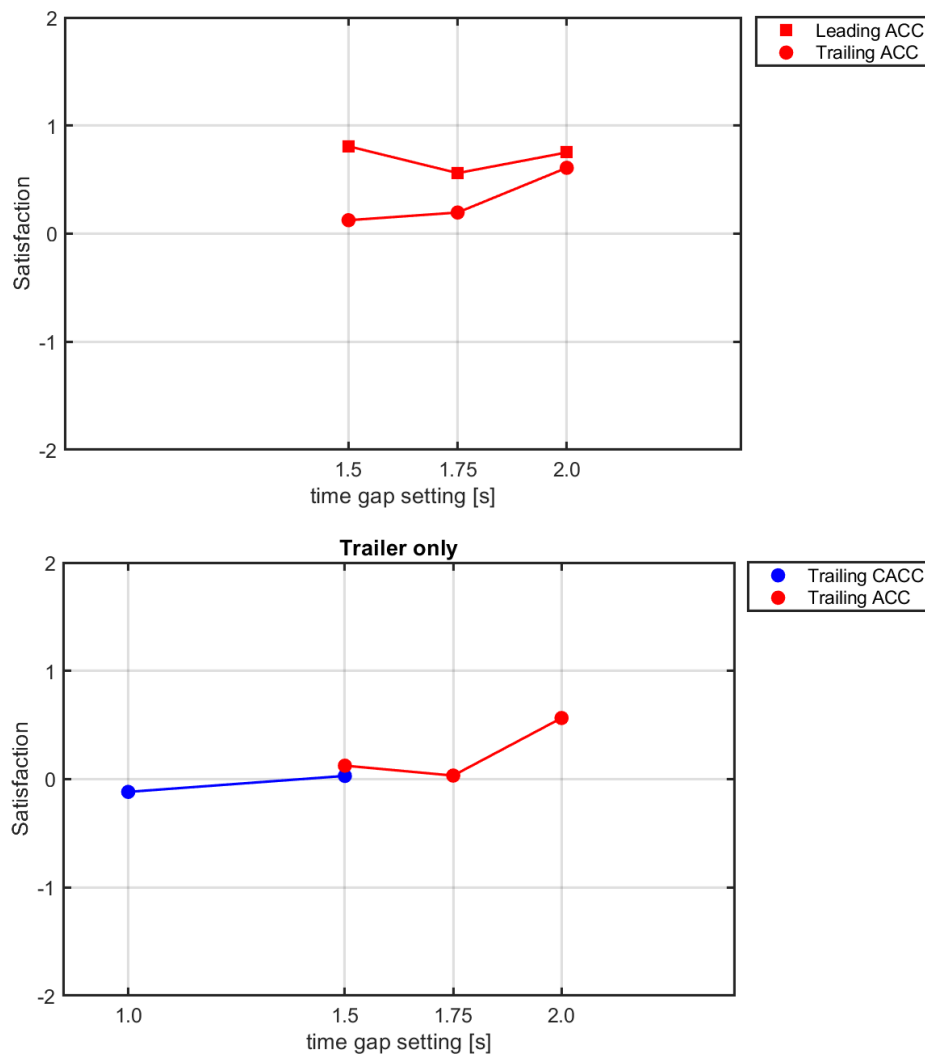


Figure 4-3. Satisfaction as a function of experimental conditions (top: Design A; bottom; Design B).

Figure 4-3. shows the results of satisfaction as perceived by the drivers. The planned comparison showed a significant effect of Role [$p < 0.01$], showing higher scores for leader than trailer (0.72 and 0.40, respectively).

Within the trailer and within the leader, planned comparisons showed no significant differences among the CACC/ACC settings.

4.2.3 Trust

In Design A, a significant effect of truck role was found in only one of the questions (see Table 4-2). The average scores showed that the drivers of the lead truck agreed more with the “system is reliable” statement than the drivers of the trailing truck (the latter having an average of 0.01, i.e. neutral) [$p = 0.02$]. The table also shows that:

- the *adverse* statements typically get an overall *negative* score, expressing disagreement with the statement (in the range between -1.11 and -0.11).
- The *positive* statements get an overall *positive* score (in the range between 0 and 0.3), expressing agreement with the statement.

Overall, this shows a reasonable degree of trust in the systems. The same analysis showed no significant differences in trust among the three ACC time gap settings.

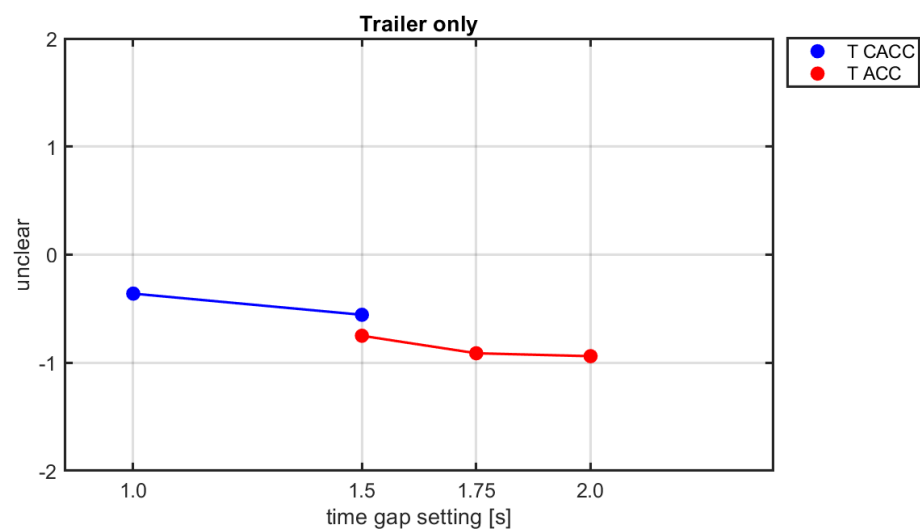
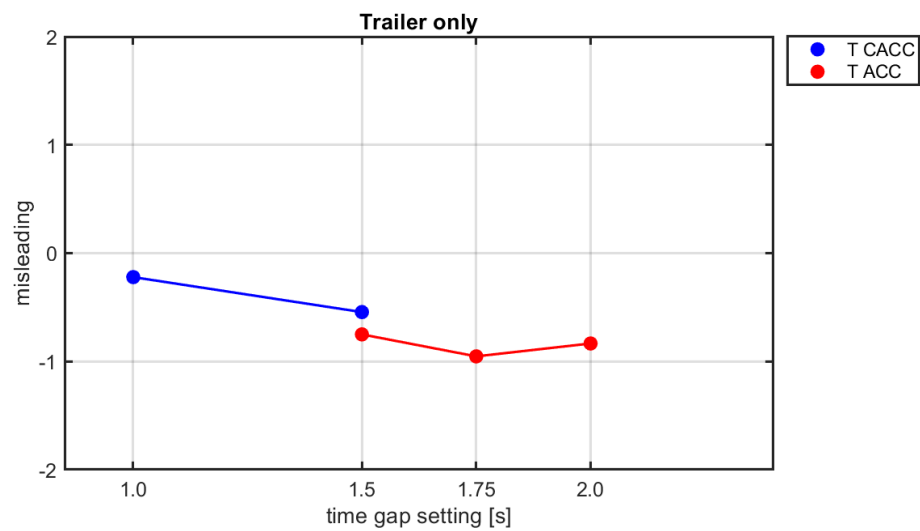
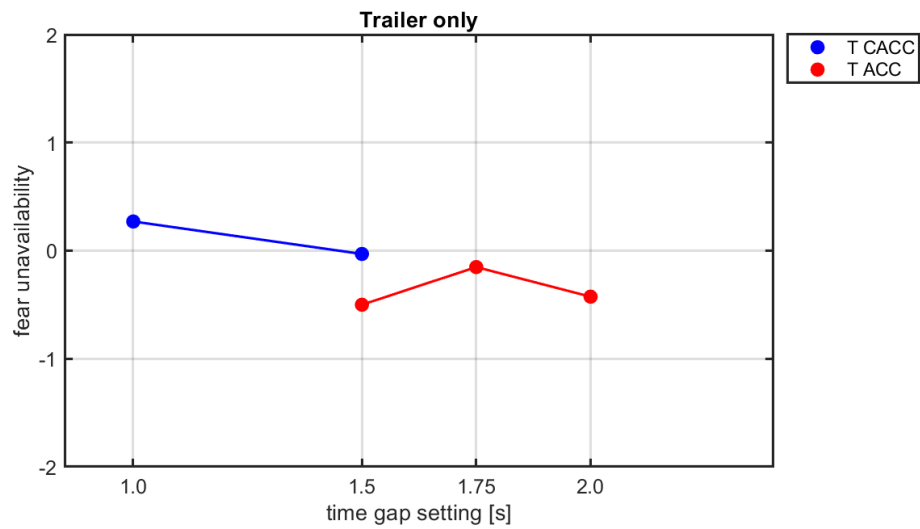
Table 4-2 Summary of trust questionnaires: effect of role (scores from -2=fully inapplicable to +2=fully applicable; the p column shows p-value of the difference between leading and trailing truck).

	Leader	Trailer	p
I do not trust the technology	-0.27	-0.54	0.13
I fear that the technology will cease to function or become unavailable	-0.67	-0.62	0.59
The system is misleading	-0.66	-0.83	0.34
It is unclear how the system works	-1.11	-0.92	0.19
I do not trust the goal, method or performance of the system	-0.60	-0.58	0.78
I do not trust the system	-0.11	-0.27	0.57
The functioning of the system has many disadvantages	-0.68	-0.74	0.82
I am convinced about the system	0.31	0.01	0.14
The system offers safety	0.23	0.18	0.46
The system is a partner that can be trusted	0.20	0.19	0.79
The system is reliable	0.46	0.01	0.02

Results from Analysis B where (marginally) significant differences were found are summarised in Table 4-3. In each question, five conditions (2x CACC and 3x ACC) were compared, yielding 10 pairwise comparisons. Each of these was made over ten separate questions that dealt with trust, yielding 100 comparisons in total. In only six of these, (marginally) significant effects were found. Thus, large differences among the ACC/CACC conditions did not occur. The effects reported in Table 4-3 point towards slightly lower trust in some CACC conditions than in some ACC conditions.

Table 4-3 Summary of trust results where (marginally) significant differences were found in Design B (the p column shows p-value of the difference between Condition 1 and Condition 2).

Statement	Condition 1	Condition 2	p
I fear that the technology will cease to function or become unavailable	CACC (1.0 s)	ACC (2.0 s)	0.041
The system is misleading	CACC (1.0 s)	ACC (1.75 s)	0.055
	CACC (1.0 s)	ACC (2.0 s)	0.062
It is unclear how the system works	CACC (1.0 s)	ACC (2.0 s)	0.054
The functioning of the system has many disadvantages	CACC (1.0 s)	ACC (2.0 s)	0.002
	CACC (1.5 s)	ACC (2.0 s)	0.050



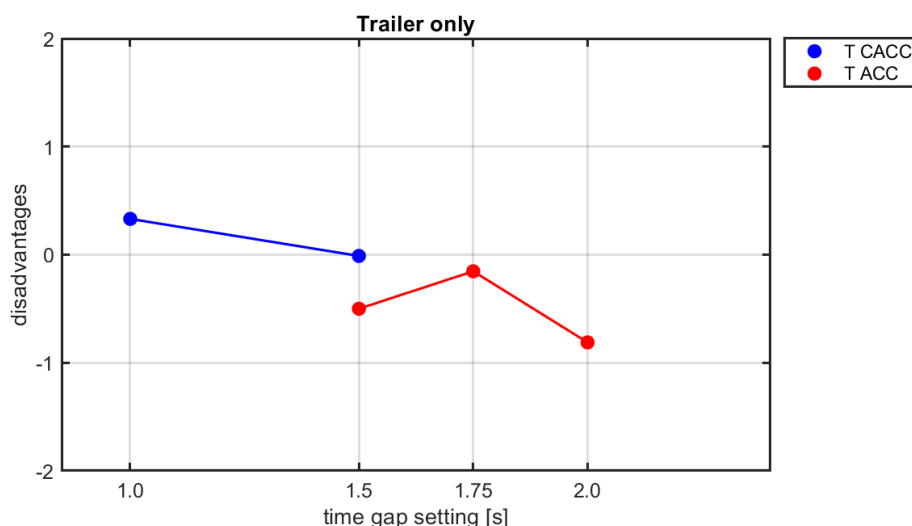


Figure 4-4. Trust results for questions where (marginally) significant differences were found (Design B); see Table 4-3 for significance. All scales from -2 = “fully inapplicable” to +2 = “fully applicable”.

4.3 Discussion

Results regarding how drivers experience the platooning systems must be seen in the context of the trials in which these results were obtained. This was a setting where drivers were in the role of safety drivers, specifically instructed to monitor the platooning system and be ready to intervene when needed. Furthermore, during the runs, drivers and operator shared a joint voice communication channel. Via speech, they continuously exchanged what was happening around the platoon, to ensure a common situational awareness. This set-up can be expected to yield a higher workload than platooning in an operational setting.

Driving with ACC, drivers experienced a higher **workload** in the trailing truck than in the leading truck. The latter condition did not differ from manual driving (in either role). Altogether, results suggest that ACC reduced the workload, for the leader, whereas for the trailer, no effect of ACC or CACC on workload was found. The average workload levels were in the range of the rating scale between ‘a little’ and ‘somewhat’ loading.

A reduction of workload due to ACC, measured with the same rating scale, has been reported by other authors as well, ranging from Hoedemaeker and Brookhuis (1998) to Van Kempen et al. (2021). This fits in the results from a meta-analysis by De Winter, Happee, Martens and Stanton (2014), showing that ACC resulted in lower self-reported workload than manual driving in 22 out of 24 studies.

Acceptance of ACC, measured as usefulness and satisfaction, was slightly higher for leader than for trailer. Within the trailer, no effects of ACC versus CACC were found. Usefulness was on the positive part of the scale for both roles. Satisfaction scores were slightly positive for the leader and neutral for the trailer.

In terms of **trust**, the results show that there was a neutral to moderately positive level of trust in the system. The scores did typically not differ between the drivers of the leading versus the trailing truck, with one exception: the “system is reliable” statement received more agreement from lead truck drivers than from trailing truck drivers. Within the trailing truck, a few (marginally) significant differences were found that suggest slightly less trust in CACC than in ACC.

4.4 Conclusions

Overall self-reported workload levels remained moderate in all conditions, in spite of the additional tasks involved in fulfilling the safety driver role. In the *leading truck*, introducing ACC gave a workload reduction with respect to manual driving; in the *trailing truck*, ACC or CACC did not have an effect compared to manual driving.

In terms of *acceptance*, the leading truck driver had higher scores than the trailing truck driver. This pattern was also found in one of the ‘trust’ questions. Generally, both acceptance and trust results were on the positive side of the scale.

Comparing ACC and CACC (within the trailing truck only), no differences were found in terms of workload or acceptance. In terms of trust, there were some indications pointing to less trust in CACC than in ACC.

5 C-ITS infrastructure (MT5)

5.1 Methodology

In contrast to the other Macro Topics, MT5 has a Proof of Concept nature rather than a formal research nature. No statistical tests will be conducted, but logged data will be analysed to descriptive statistics from the infrastructure as well as the vehicle perspective regarding: The description of the experiments can be found in Section 1.3.

Two types of messages were involved:

- ★ ETSI Cooperative Awareness Messages (CAMs) were used by the On-Board Unit (OBU) of the trucks to communicate their platooning status to the roadside
- ★ When the roadside had received CAMs showing that trucks in platooning mode were passing the C-ITS test site, it used ETSI Infrastructure to Vehicle Information Messages (IVIMs) used to send instructions to those trucks.

The messages are described in detail in Appendix C.

There were four C-ITS zones: Weaving Northbound, Tunnel Northbound, Weaving Southbound, and Tunnel Southbound. For each of these zones, a reference position was defined as a location along the road where the message was applicable. In the analysis, the “HMI distance” and “HMI time” were determined as the distance [m] and time [s] with respect to this reference point, where the message was presented on the HMI.

The Performance Indicators were defined in D1.2:

- Percentage of platoon passages that is correctly detected
- Amount of infrastructure advices received and displayed by the vehicles
- Distance at which these advices are received and displayed by the vehicles.

5.2 Results

A total of 20 test days were held between 1st June 2022 and 30th September 2022. However, on some days the truck did not use the testbed on the A16. In total the testbed on the A16 was crossed 19 times by the trucks.

The four zones (Weaving Northbound, Tunnel Northbound, Weaving Southbound, Tunnel Southbound) and two trucks triggered 8 events during each round, so a total of 152 events were triggered.

The logging from Swarco (roadside operator) was missing for all days, except 16th June 2022.

The logging on that day showed that the roadside only detected the truck with stationId `302174038`. The CAMs show that `platooning` was activated.

The log data from the vehicles is incomplete for many days. Sometimes no IVIs are logged, but it is unclear if this is because no IVIs were received or because no IVIs were sent. Because of the absence of log data from Swarco, no final statement can be made about this.

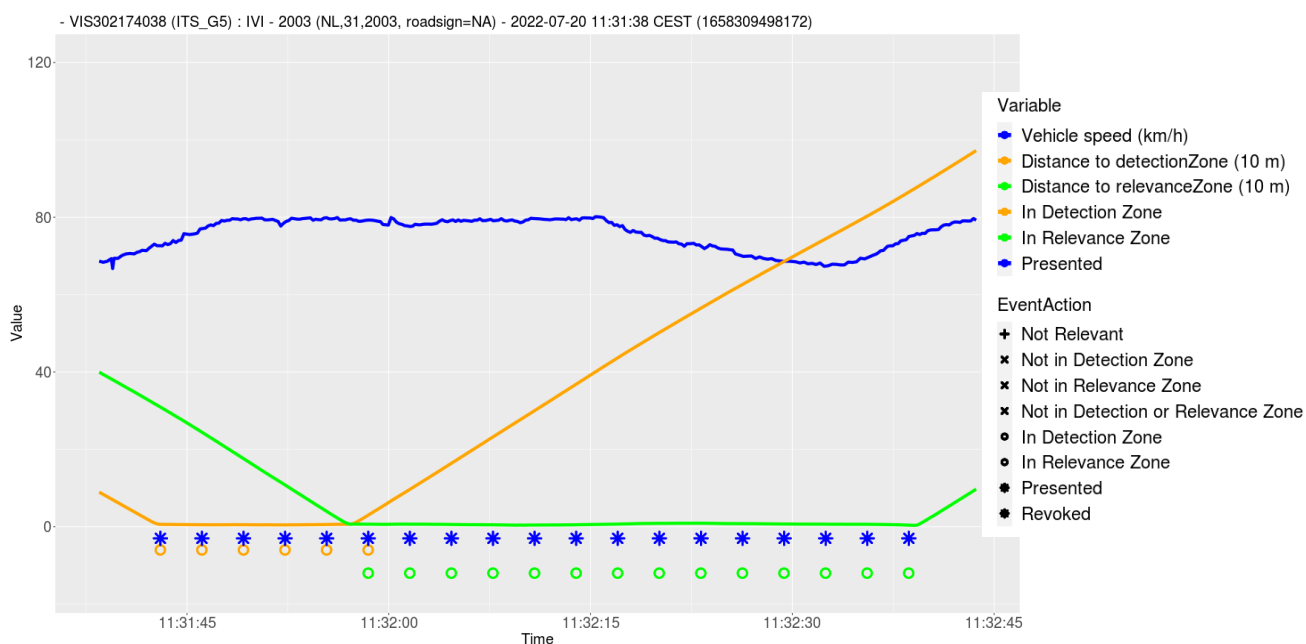


Figure 5-1 Speed and distance to the event position of stationId 302174038. The markers shown on the bottom of the graph indicate where the truck was driving w.r.t. to the zones, and if the advice message was displayed on the HMI.

Descriptive statistics on the number of received IVI advice messages and the HMI display distance and time before the reference position are presented in Table 5-1. These are further discussed in Section 5.3.

Table 5-1 Summary of the number of received IVI advice messages and the HMI display distance and time before the reference position.

Location	Station Id	Event count	IVI received	HMI display	HMI Distance [m]		HMI Time [sec]	
			count	count	Min	Max	Min	Max
Weaving Northbound	302174038	19	14	9	266	312	12.3	16.3
Weaving Northbound	302174031	19	11	8	233	388	10.8	17.8
Tunnel Northbound	302174038	19	14	9	191	314	8.9	15.8
Tunnel Northbound	302174031	19	10	7	153	387	7.7	18.6
Weaving Southbound	302174038	19	7	4	169	207	8.0	9.6
		Late	2	4	-529	-65	-22.5	-2.2
Weaving Southbound	302174031	19	5	4	145	217	6.8	10.1
		Late	5	5	-336	-52	-14.5	-1.3
Tunnel Southbound	302174038	19	8	7	241	280	11.3	13.2
Tunnel Southbound	302174031	19	8	7	248	294	11.5	13.7

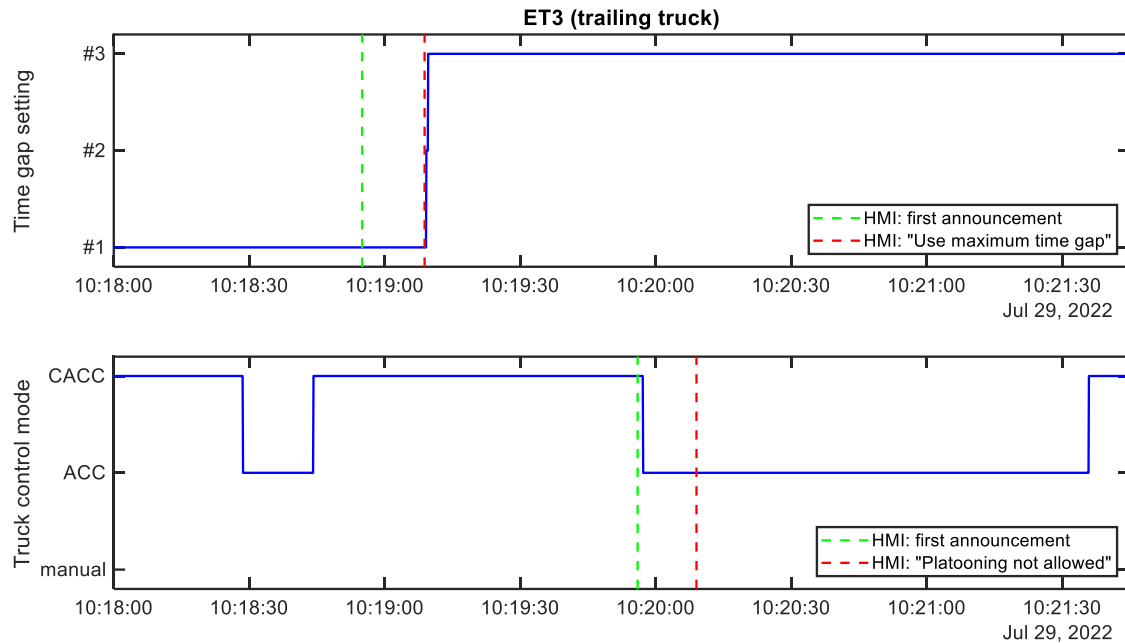


Figure 5-2 Example of time series of C-ITS on the HMI and the resulting actions from the driver.

An example of a truck passing the C-ITS test site in Northbound direction is shown in Figure 5-2, showing the trailing truck's time series of the control mode and the time gap setting. Initially, the truck was driving with CACC at the shortest time gap setting. At 10:18:18, the driver control mode was changed to ACC (reason unknown) and 16 s later, CACC was activated again. At 10:18:55, the first announcement appeared on the HMI that soon the largest time gap had to be used. At 10:19:09, within a second of the "Platooning: use maximum time gap" instruction becoming valid, the driver changed the time gap to the largest value. When approaching the tunnel, the first announcement of the upcoming "Platooning: not allowed" zone was displayed on the HMI at 10:19:56. The driver changed control mode from CACC to ACC one second later, so well before reaching the point where the instruction became valid ($t=10:20:09$). This demonstrates the correct functioning of the overall C-ITS use case, including the driver responding to the instructions on the HMI. Since this is only a single example, no conclusions are drawn about the timing of driver responses to the HMI messages.

5.3 Discussion

The research questions (which were defined in D1.2, Section 2.3.4):

1. What percentage of platooning events is correctly detected by the roadside?

This question cannot be answered, due to the unavailability of the Swarco roadside log data.

2. Amount of infrastructure advice messages received and displayed by the vehicles.

From a total of 152 events in total 84 IVI advice messages were received by the vehicles. This resulted in 64 IVI advice messages being displayed in the vehicles.

3. Distance at which these advice messages are received and displayed by the vehicles.

The distance at which the IVI advice messages were received was in most cases well before entering the detection zone, meaning that the reception was well before the moment it was needed for displaying. Only for the Weaving Southbound zone the message was sometimes received too late.

The distance and time at which the advice message was shown was adequate for most zones. Again, the Weaving Southbound is the exception.

The Weaving Southbound zone has this problem because the zone is located just after the merging of two roads (`A16` and `A16p`), and the detection zone for the advice is only covering one of the two roads. The IVI advice message is also in most of the cases not received while driving on the merging road.



Figure 5-3 Weaving Southbound zone, with the detection zone as a cyan-coloured line, the relevance zone as a yellow-coloured line, and the two trucks visualized with blue and red arrows. On the merging road no detection zone is given.

5.4 Conclusions

The log data that has been gathered indicates that messages are received well in time. Only for the Weaving Southbound zone the message is received too late when the trucks drive on the merging road. In this case the message is also displayed too late. To solve the late reception, an extra roadside unit should be located on a gantry on this merging road. To solve the late displaying of the message, the message should be extended with an extra detection zone on the merging road leading up to the event position.

In the current implementation, the moment of displaying the message depends on the detection zone defined inside the advice. Other implementations may choose other algorithms to decide when to display the message on the HMI.

6 Conclusions and recommendations

6.1 Conclusions

This report is the final report for the UMneo TPT activity by TNO. It reports the findings of 20 days of truck platooning on the public road in the Netherlands in 2022. In general, during the 20 days of driving on public roads no unexpected events occurred. Overall, the truck platooning system operated as planned.

The high level research questions that form the core of the work were reported in D1.2 (Hogema et al., 2022A):

Table 6-1 High-level research questions per Macro Topic. Ref (Hogema et al., 2022A).

ID	Title	Research Question
MT1	Vehicle and Traffic Impact on safety indicators	What can be inferred/extrapolated as the platoon's qualitative impact on traffic safety and throughput?
		How do we assess dynamic situations that may be safety critical?
		What typical behaviour do we see from other road users in presence of a platoon?
(MT2)*	(Bridges and Viaducts)	(Effects of platooning on the infrastructure: not part of this deliverable)
MT3	Emission measurements	What is the quantitative effect of platooning on the fuel consumption, CO ₂ emissions and NO _x emissions of the leading, and trailing truck?
		What is the quantitative effect of platooning on the aerodynamic drag of the leading, and trailing truck?
MT4	Driver acceptance	How do truck drivers react to, and accept automated driving?
		How do they accept it in safety critical situations?
MT5	C-ITS infrastructure	How can roadside infrastructure detect and guide (truck) platoons?
		How can truck platooning be enhanced by C-ITS for specific infrastructure (bridges and tunnels e.g.)?

*) Note: Macro Topic 2 is reported in a separate document

The conclusions form the answers to each of the high level research questions and are stated per high-level research question in a bulleted format. More detailed information can be found in the section conclusions per chapter.

6.1.1 Conclusions MT1: Vehicle and Traffic Impact on safety indicators

What can be inferred/extrapolated as the platoon's qualitative impact on traffic safety and throughput?

- ACC and CACC were seen to perform the driving task with less variation (in terms of gap variation and speed variation) compared to manual driving. Less variation in driving behaviour can qualitatively be interpreted as contribution to smoother traffic flow and improving traffic safety.

How do we assess dynamic situations that may be safety critical?

- The scenarios that potentially might be safety critical are cut-ins and approaching slower traffic ahead. However, the data analysis showed that the scenario manifestations during the trials were never safety critical (neither in manual driving nor in ACC/CACC driving).

What typical behaviour do we see from other road users in presence of a platoon?

- It was found that cut-in manoeuvres occur much more frequently in front of the leading truck than in front of the trailing truck. This is understandable in the context of this Truck Platooning Trial, where the safety drivers were instructed to comply with the speed limit (80 km/h). This was usually slower than most other traffic, including other trucks. Other vehicles that overtook the platoon would return to the slow lane after passing the leading truck.

In addition to these conclusions with respect to the research questions, the analysis of MT1 has provided insight in the functioning of the truck platooning concept in the context of the specific Dutch road and traffic situations.

Looking at the percentage of driving time that a truck had its systems active, the medians were 93.3% for ACC and 76.2% for CACC. The results suggested some effect of the road and traffic environment: Parts of the route with higher complexity (in terms of presence of tunnels, weaving sections and on/off ramps) showed a lower percentage of time with CACC active than the other parts of the route. In terms of speed choice, the test drivers complied with their instruction, which was to respect the speed limit of 80 km/h. The speed of other traffic (including trucks) was typically higher than this. This automatically created 'drivable space' ahead of the leading truck. Thus, cut-in manoeuvres conducted by other traffic occurred much more frequently in this large drivable space ahead of the leading truck, than in front of the trailing truck, where typically a gap of 1 to 2 s was available. As stated above, no critical cut-in manoeuvres have been observed throughout the trial.

6.1.2 Conclusions MT3: Emission measurements

What is the quantitative effect of platooning on the fuel consumption, CO₂ emissions and NO_x emissions of the leading, and trailing truck?

- For vehicle ET3 in trailer position, the test results showed a decrease in fuel consumption, CO₂ emissions and NO_x emissions with decreasing gap distance with respect to the leading vehicle, depending on the type of controller i.e. CACC or ACC.
- For both ET2 and ET3 vehicle in leader position, there is no clear trend of fuel consumption, CO₂ emissions, NO_x emissions, and dynamic pressure with decreasing gap distance, which corresponds to findings of other trials (McAuliffe, B 2017, Van Kempen, E, 2022)
- For vehicle ET3 in trailer position at time gap setting 1.5 s, the test results showed for the vehicle driving in CACC compared to ACC increases of
 - fuel consumption 6% increase,
 - CO₂ emissions 6% increase,
 - and NO_x emissions 36% increase
- As discussed in Section 3.2.3, the aforementioned increases are related to the CACC controller used, which was optimized for maintaining a specific gap distance resulting in high frequency speed corrections. In turn, these speed corrections resulted in a higher energy demand which in turn increased rather than minimized energy consumption and thereby fuel consumption, CO₂ emissions and NO_x emissions.

What is the quantitative effect of platooning on the aerodynamic drag of the leading, and trailing truck?

- As depicted in Figure 3-10, the results show that the relative dynamic pressure reduces with reducing gap distance, which demonstrates the slip stream effect. Between gap distances of 20 m and 40 m, which are close to time gaps 1 s and 2 s, the relative dynamic pressure changes 1% with every 1 m distance change.

6.1.3 Conclusions MT4: Driver acceptance

How do truck drivers react to, and accept automated driving?

- Acceptance of ACC, measured as usefulness and satisfaction, was slightly higher for leader than for trailer. Within the trailer, no effects of ACC versus CACC were found. Usefulness was on the positive part of the scale for both roles. Satisfaction score were slightly positive for the leader and neutral for the trailer. In terms of trust, there were some indications that CACC received slightly lower scores in ACC.

How do they accept it in safety critical situations?

- As stated in Section 6.1.1, critical situations did not occur during the Truck Platooning Trial. Part of this may be attributed to the way the safety drivers fulfilled their task.

6.1.4 Conclusions MT5: C-ITS infrastructure

How can roadside infrastructure detect and guide (truck) platoons?

- In the C-ITS solution that was realised, the trucks communicated to the roadside when they were platooning. In response, the roadside system transmitted location-specific instructions for the platooning vehicles. These instructions covered time gap restrictions and “platooning prohibited” instructions.

How can truck platooning be enhanced by C-ITS for specific infrastructure (bridges and tunnels e.g.)?

- The C-ITS allows the roadside to put static or dynamic constraints on platooning in relation to specific infrastructure elements.
- The messages were generally received well in time.

6.2 Recommendations

This section provides an overview of recommendations for future platoon trials.

- It is recommended that platoon trials on a test track will be conducted in order to compare the fuel consumption, emissions and dynamic drag to road tests. Comparing this should provide insights into the potential effects of the wake of other traffic, on the lead truck.
- As discussed in Section 3.1.4, the CACC controller design should not only aim for minimising deviations in gap distance, but also use fuel consumption as a design criterion.
- In the current project, C-ITS information was only shown on an HMI as instructions for the drivers. A next step would be to have the platooning system automatically comply with the instructions received from the roadside.

- More detailed logging of how and why platooning is cancelled can increase the understanding of when and where platooning is possible or not. This can also help to identify locations or situations where it should be advised not to use platooning.
- Steps from the current (carefully controlled) trial towards platooning in practice should include at least the following steps.
 - Trials that still use safety drivers, but with fewer restrictions on where they can activate platooning. For example, in the current study, drivers were instructed to manually switch off platooning before entering a tunnel (even though the platooning system was designed to automatically disengage after entering a tunnel). In future controlled trials (still with safety drivers) will provide insight in how well platooning can cope with more challenging situations.
 - Naturalistic driving studies, to obtain insight in the effects of platooning systems when end users are using them in an operational setting.

7 Signature

This report is also stored at TNO under:

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Project name	Truck Platooning Trial – Ursa Major neo
Project number	060.37962

Helmond, 23-03-2023



Bastiaan Krosse
Head of department



Jeroen Hogema
Lead Author

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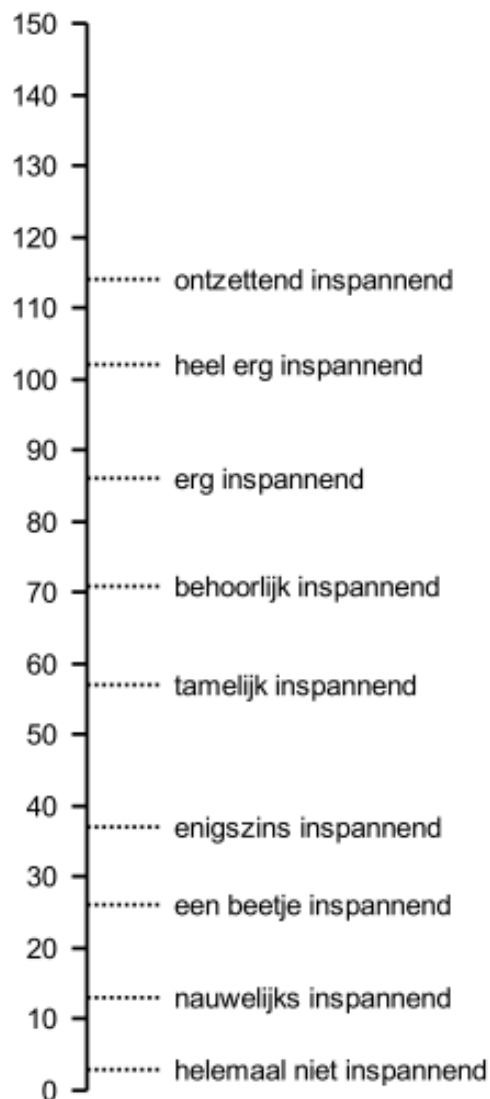
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Appendix A Questionnaires

A.1 Workload

INSPANNINGSCHAAL

Wilt u door het zetten van een streepin onderstaande lijn aangeven hoeveel inspanning het u gekost heeft om deze rit uit te voeren



A.2 Acceptance

Wat is uw beoordeling over rijden met (C)ACC?
Graag de kruisjes op de 5-punt schaal neerzetten!

Nuttig ☐ 1	☐ 2	☐ 3	☐ 4	Zinloos ☐ 5
Plezierig ☐ 1	☐ 2	☐ 3	☐ 4	Onplezierig ☐ 5
Slecht ☐ 1	☐ 2	☐ 3	☐ 4	Goed ☐ 5
Leuk ☐ 1	☐ 2	☐ 3	☐ 4	Vervelend ☐ 5
Effectief ☐ 1	☐ 2	☐ 3	☐ 4	Onnodig ☐ 5
Irritant ☐ 1	☐ 2	☐ 3	☐ 4	Aangenaam ☐ 5
Behulpzaam ☐ 1	☐ 2	☐ 3	☐ 4	Waardeloos ☐ 5
Ongewenst ☐ 1	☐ 2	☐ 3	☐ 4	Gewenst ☐ 5
Waakzaamheid- verhogend ☐ 1	☐ 2	☐ 3	☐ 4	Slaapverwekkend ☐ 5

In English, the items of this questionnaire were:

- useful-useless
- pleasant-unpleasant
- bad-good
- nice-annoying
- effective-superfluous
- irritating - likeable
- assisting-worthless
- undesirable - desirable-
- raising alertness-sleep inducing

A.3 Trust

	<i>Helemaal van toepassing</i>				<i>Helemaal niet van toepassing</i>
Ik vertrouw niet op de technologie.	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Ik ben bang, dat de techniek opeens uit valt of niet meer beschikbaar is.	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Het systeem is misleidend.	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Het is onduidelijk hoe het systeem werkt.	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Ik wantrouw het doel, de werkwijze of de prestatie van het systeem.	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Ik vertrouw niet op het systeem.	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
De werkwijze van het systeem heeft veel nadelen.	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Ik ben overtuigd van het systeem.	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Het systeem biedt veiligheid.	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Het systeem is een te vertrouwen partner.	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5
Het systeem is betrouwbaar.	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5

In English:

1. I do not trust the technology
2. I fear that the technology will cease to function or become unavailable
3. The system is misleading
4. It is unclear how the system works
5. I do not trust the goal, method or performance of the system
6. I do not trust the system
7. The functioning of the system has many disadvantages
8. I am convinced about the system
9. The system offers safety
10. The system is a partner that can be trusted
11. The system is reliable

The scale ends were labelled as “fully applicable” and “fully inapplicable”.

Appendix B Traffic impacts: in the context of traffic and road sections

The analysis in this appendix was conducted by the TU Delft (Simeon Calvert, Ali Nadi Najafabadi, and Zhengliang Duanmu) in addition to the other analyses found in this report, to give a greater degree of insights into the performance of the platooning in the context of different traffic states, road sections types and the platoons manoeuvring.

B.1 Context with state-of-the-art

Autonomous vehicles have been under development for decades. Many well-established and relevant technologies are available. However, the application of the actual application of self-driving cars is still in its infancy and the impact of fully automated vehicles needs to be further explored. Therefore, real-life data are vital for building a more solid basement for the operation of vehicle automation technologies.

Adaptive cruise control (ACC) is one of the technologies already being used in many consumer-grade vehicles. The ACC allows the vehicle to automate the longitudinal driving task during the car following behaviour and free driving behaviour. Cooperative Adaptive Cruise Control (CACC) is an extension of ACC which allows vehicles to communicate with other vehicles with short-range wireless communication (Ploeg et al., 2011). Communication between vehicles can provide a more comfortable and safe driving experience, as the vehicle brakes much more softly (Xu & Sengupta, 2003). To improve the efficiency of freight transport, the implementation of the CACC in trucks may be a suitable solution. With the ACC/CACC system, trucks can be operated as a platoon. The longitudinal behaviour (both longitudinal and latitudinal for some platooning projects) is controlled by the automation system. Many studies have already been divided into the traffic flow effect of the ACC and CACC. The enabling of CACC is believed to improve traffic flow stability (Delis, Nikolos, & Papageorgiou, 2016), safety, and infrastructure capacity (Liu, Kan, Shladover, Lu, & Ferlis, 2018) under certain conditions. Conclusions are drawn primarily by simulation and are mainly about passenger vehicles. As compared to passenger vehicles, there are fewer studies about truck platooning. However, Truck platooning is believed to affect safety, fuel consumption, traffic efficiency, and comfort (Bergenheim, Shladover, Coelingh, Englund, & Tsugawa, 2012).

From the literature, the expected impact of the truck platoon can be summarized in four categories: safety, fuel consumption, traffic efficiency, and comfort (Bergenheim, Shladover, Coelingh, Englund, & Tsugawa, 2012).

As for the safety impact, it is believed that truck platooning results in a lower accident rate due to the higher automation level and the fact that most traffic accidents are caused by human errors (Janssen, Zwijnenberg, Blankers, & de Kruijff, 2015). There are also quantitative analyses of the truck safety impact. Two indicators are used to evaluate the safety aspect of truck platooning: the number of brake threats and the time-to-collision. The simulation result of Faber et al. (2020), shows that truck platooning harms traffic efficiency and safety when the density of the road is high. Their study also shows that the implementation of the truck platoon on the main road will decrease the efficiency and safety of the road, no matter if the traffic is high or low.

The two main factors that can cause danger during platoon driving are the cut-ins of the surrounding traffic and the hazard of a vehicle running into the preceding vehicle in the platoon (Axelsson, 2017).

Truck platooning also improves fuel consumption. Since one-quarter of the fuel consumption is related to aerodynamic drag, platooning driving could decrease fuel consumption by reducing air drag (Zhang, Chen, Ma, & Pan, 2020). According to a field test done by Transport Canada's Motor Vehicle Test Centre (McAuliffe, Croken, Ahmadi-Baloutaki, & Raeesi, 2017), truck platooning has a fuel saving of 5.2% to 7.8% compared to three trucks traveling independently under certain conditions.

As for the traffic efficiency impact, there are different opinions. Many studies are already divided into the traffic flow effect of the ACC and CACC. The possible benefits of CACC could be the improvement in capacity, flow stability, and fuel consumption. Van Arem et al. (2006) conclude that the CACC can improve traffic flow stability and slightly increase traffic flow efficiency under certain simulation conditions. An essential factor in the ACC/CACC application is the penetration rate. According to Van Arem et al. (van Arem, van Driel, & Visser, 2006), the improvement in traffic flow is highly dependent on the penetration rate of CACC. A high penetration rate will result in an improvement in traffic throughput and a low penetration rate will even lead to performance degradation. VanderWerf et al. (Werf, Shladover, Miller, & Kourjanskaia, 2002) used Monte Carlo simulations based on detailed models. The result of the simulation indicates that the ACC has a limited impact on traffic. And with the increase in penetration rate, the return rate is decreasing; there will be no capacity increase after 40% ACC. Another significant result is that CACC can potentially double the capacity of a highway lane at a high penetration rate. Calvert et al. (Simeon C. Calvert & van Arem, 2020) conducted research based on data collected in real traffic. The string stability of CACC driving is much better than that of ACC driving, and three-vehicle platoons were able to platoon longer than a seven-vehicle platoon. The result shows that it is possible to operate CACC vehicles on the (sub)urban arterial while ACC vehicles are unsuitable for this area. And because the penetration rate is too small for a field operational test, traffic flow improvements are difficult to derive.

Studies on the CACC truck application show that the impact of truck platooning is different than passenger vehicle platooning. The influence of the truck platoon on traffic flow should be considered in two parts, the longitudinal traffic flow effects and the lateral effects. Calvert et al. (S. C. Calvert, Schakel, & van Arem, 2019) have conducted an experiment to evaluate the traffic flow effects of truck platooning. The simulation result shows that the negative influence on traffic flow performance is small when traffic demand is less than 80% of the capacity. However, a large negative effect was found in the congestion scenario. They suggested that truck platooning should be restricted to traffic states that are not nearly congested or congested.

This research is carried out to determine the effect of truck platooning on traffic flow using empirical data. The use of real-life truck platooning data allows us to explore the differences between ACC and CACC, and manual systems under different conditions. This research contains two parts: 1) data fusion and 2) statistical analysis. For data fusion, loop detector data, infrastructure information and weather data will be added to the original data set. For statistical analysis, the time gap distributions under different categories are analysed to determine the performance of the truck platoon. Additionally, analysis of the lane change behaviour and the reaction time of the platoon to congestion will also be analysed.

B.2 Methodology

B.2.1 Data Fusion

To study truck platooning in the contexts of traffic states and road sections, the first methodological step is to combine data from two other sources (i.e. loop detector data and road network characteristics) with the truck platoon data. Loop detector data can provide the speed and flow of a certain route over a certain period, and road network data can provide the type of road section. This can help us to analyse the interaction between the truck platoon and the traffic environment.

The trial truck platooning data contains the latitudes and longitudes of the trucks. With these coordinates, the speed and flow of the surrounding vehicles collected from NWD loop detectors can be attached to the trial data. Loop detector data contain speed and traffic flow information with an interval of 1 min. The structure of the NDW loop detector data is shown in Figure B.1.

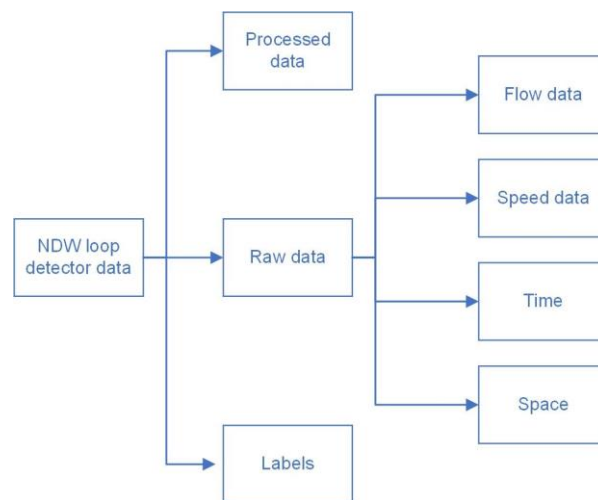


Figure B.1: Structure of the NDW loop detector data

To obtain the state of surrounding traffic and combine it with the truck platooning data, the space-time traffic information from loop detector data is matched to the space-time truck platooning trial data using the nearest interpolation method. The data matching steps is shown in Figure B.2.

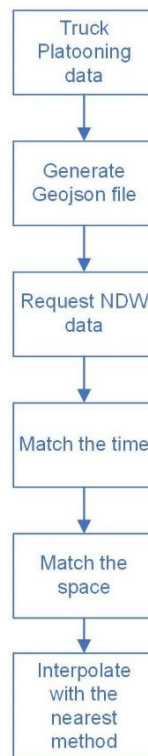


Figure B.2: Loop detector data attachment method

From the open street map data, there are three types of road segments on which the truck platoons drove during the experiments. These road types, i.e. waving sections, bridges, and regular motorways, are added to the fields of the truck platooning data.

The attachment method consists of two different parts: identification and attachment. The first part is to identify and obtain the coordinates of all the weaving sections/bridges along the route. For bridges, the method is to manually select the bridges and save the coordinates. For the weaving section, open street map (OSM) data are used. The identification process is shown in Figure B.3.

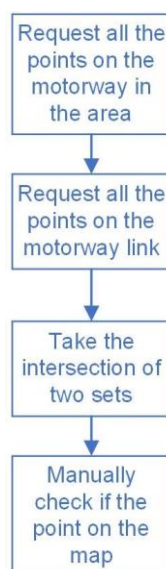


Figure B.3: Ramps identification

The overpass-turbo is used to request the coordinates of all the on- and off-ramps along the truck platooning routes from OSM. To match the coordinates of all the on-ramps/off-ramps with platoons, The latitude and longitude of the trucks for each time step are compared with the location of the ramps, weaving sections, and bridges. If the trucks' coordinates are closer than a certain threshold to one of these section types, the associated section type is added to the field of the truck platooning data. The attached weaving section is shown in Figure B.4.

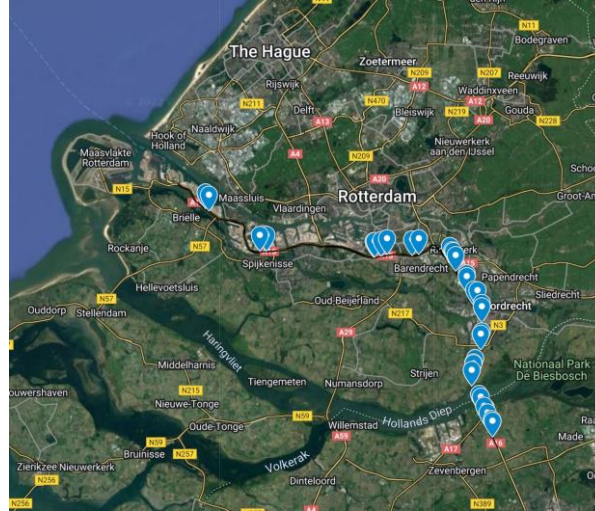


Figure B.4: Weaving sections of et2 2022-07-22_A16toRdam_conditionB5

B.2.2 Statistical Analysis

For the statistical analysis of truck platooning, we first characterize traffic along the experiment routes. Then we use time gap distribution to differentiate the performance of the truck platooning under various conditions. Afterward, we study the acceleration and deceleration of trucks under different driving modes, and finally, we explore the manoeuvring behaviour of truck platoons. The method used for each of these analyses is explained in the following sections.

B.2.2.1 Traffic conditions

To decide the categories of traffic conditions, the fundamental diagrams have to be estimated. All parts of the road are the motorway. Due to the consistency of the route, it can be assumed that the fundamental diagram of each part of the road is similar. Here, we assume a triangular fundamental diagram. The jam density and the free flow speed are fixed and the critical density is estimated using the flow and speed data. To find the critical density, the least square method is used to fit the triangular fundamental diagram to the flow-density data.

B.2.2.2 Time gap distribution

The space gaps between the ego vehicle and the follower, which are given in the dataset, are used to calculate the time gap distribution. The time gaps are calculated with the following equation:

$$Time_gap = \frac{LongPosition - 2.5m}{V_{follower}}$$

Long-Position is the relative position collected by the MIO sensor. The 2.5m constant is the distance between the sensor and the front bumper, and $V_{follower}$ is the speed of the follower.

The distribution can help to compare the performance of the truck platoon under different traffic conditions and between different types of roads.

Time-gap distributions are calculated under different traffic conditions because the performance and impact of the truck platooning might be different when the traffic flow of the road is different. As for the road types, the time gap distributions of trucks are studied in weaving sections, tunnels & bridges, and regular motorways.

To compare the time gap distributions under various conditions, a Two-sample Kolmogorov-Smirnov Test (K-S) is used to test whether the distributions of the two samples are significant or not by generating the cumulative probability of two distributions and finding the largest distance along the y-axis.

B.2.2.3 Acceleration and deceleration

In this study, we also explore the acceleration/deceleration distribution of truck platoons. This would shed light on the driving experiences and safety under various driving modes. The shape of cumulative distribution curves allows exploration of the difference in acceleration and deceleration rates between manual driving, ACC, and CACC.

B.2.2.4 lane changing

The lane-changing behaviour is also an important part of this data analysis. The manoeuvring behaviour is detected using the steering angle of the leading truck. During the lane change behaviour, the shape of the steering angle should look like a sine function or cosine function. According to Esmaeili et al. (Esmaeili, Kazemi, & Tabatabaei Oreh, 2019), at 60km/h the peak steering angle during the lane change process should be about 3 degrees and the lane change behaviour should last not more than 30 seconds. Then the gap distributions between different manoeuvring behaviour, i.e. lane changing and lane keeping, are compared.

B.3 Results and discussion

B.3.1 Data Fusion

As part of the data fusion process, initial insights into the speed and flow of surrounding traffic are demonstrated in Figures B.5 and Figure B.6.

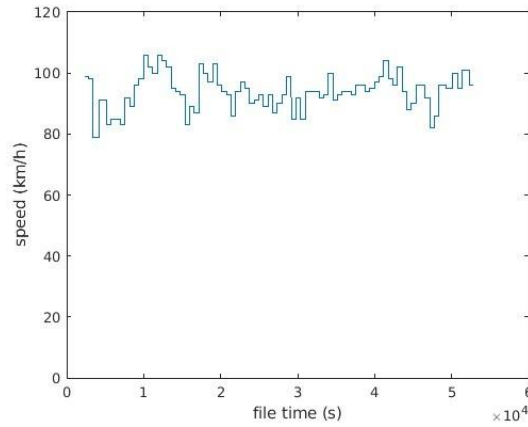


Figure B.5: Speed of the surrounding vehicles of et2 2022-07-22_A16toRdam_conditionB5

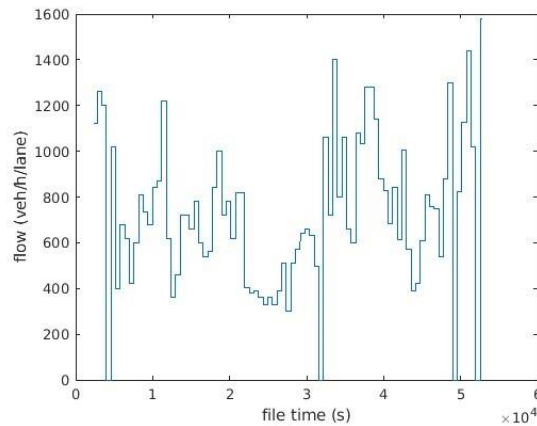


Figure B.6: Flow of the surrounding vehicles of et2 2022-07-22_A16toRdam_conditionB5

B.3.2 Fundamental diagram estimation

The flow and density data from the loop detector of one day are used to estimate the fundamental diagram. In Figure B.7, it can be observed that the value of critical density is 29 veh/km when the sum of squared differences between data points and the estimated diagram is minimum.

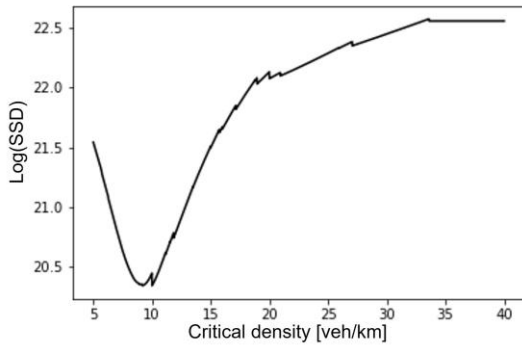


Figure B.7: SSD for different k^{cr}

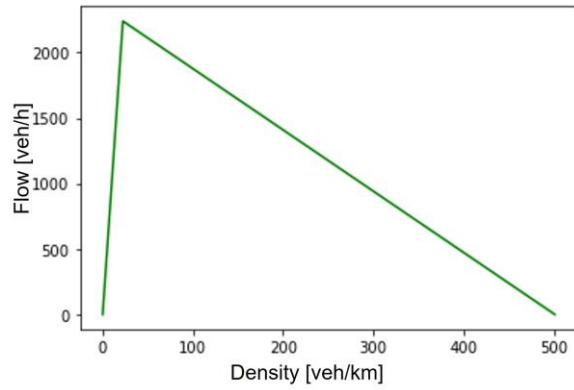


Figure B.8: Estimated FD

The estimated FD of the motorway is shown in Figure B.8. The critical density is relatively low because the high-density or congested sample is relatively small. This fundamental diagram is used to identify the categories of traffic conditions.

B.3.3 Time-gap distribution among different traffic states

The time gap distributions among four different traffic states are shown in Figure B.9.

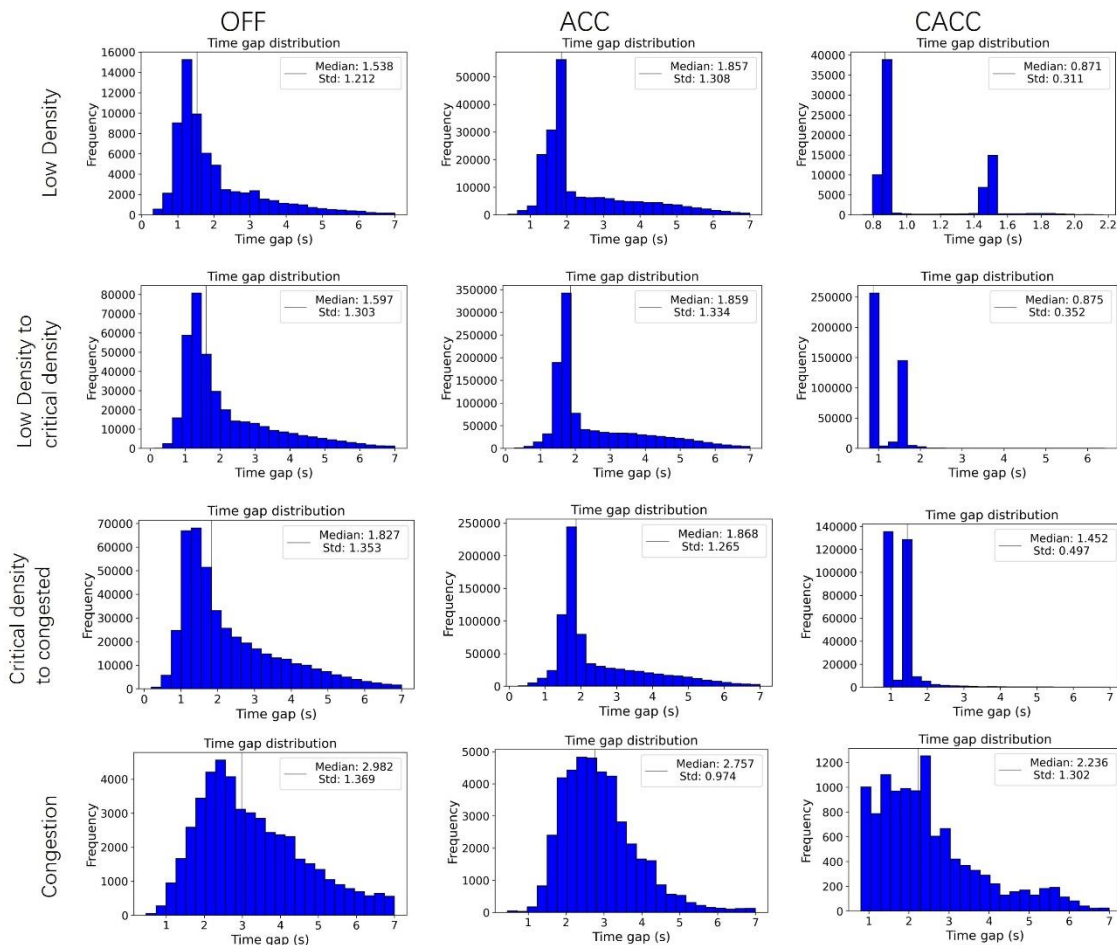


Figure B.9: Time-gap distributions among different traffic states

The four categories of traffic conditions are 1) low-density, 2) low-density to critical density, 3) critical density to congestion, and 4) congested density. For each time-gap distribution, the median is calculated to represent the overall situation. Standard deviation is used to represent the stability of the driving process. The Two-sample Kolmogorov-Smirnov Test is used to test if the two distributions are similar. Some of the results of the KS test are shown in Table B.1.

Table B.1: Two-sample Kolmogorov-Smirnov Test result

Sample 1	Sample 2	Statistic	P-value
OFF(Low density)	OFF(Low density to critical density)	0.043344	0.000
OFF(Low density)	OFF(Critical density to congestion)	0.129564	0.000
OFF(Low density)	OFF(Congestion)	0.49578	0.000
OFF(Low density)	ACC(Low density)	0.348355	0.000
OFF(Low density)	ACC(Low density to critical density)	0.352749	0.000
OFF(Low density)	ACC(Critical density to congestion)	0.349163	0.000
OFF(Low density)	ACC(Congestion)	0.506405	0.000
OFF(Low density)	CACC(Low density)	0.59203	0.000
OFF(Low density)	CACC(Low density to critical density)	0.539214	0.000
OFF(Low density)	CACC(Critical density to congestion)	0.410032	0.000
OFF(Low density)	CACC(Congestion)	0.264287	0.000
OFF(Low density to critical density)	OFF(Critical density to congestion)	0.099438	0.000
OFF(Low density to critical density)	OFF(Congestion)	0.460963	0.000
OFF(Low density to critical density)	ACC(Low density)	0.318235	0.000

From table B.1, it can be observed that all the distributions are significantly different (the p-values are all smaller than 0.01). Performance differences exist between the modes. And for the same mode, the performance of the system is different under different traffic conditions. For all other test results, no p-value is larger than 0.01, which means that there are no similar time gap distributions.

Then the performance difference can be concluded from the median and standard deviation of the distributions. When the driving mode is manual driving, the distribution figures are quite similar. The median of the time gaps is near 1.5s for uncongested traffic. The median of the time-gap distribution is 1.827s. This means that the overall time gap is larger. When in congestion, the median of the time gap increased to 2.982s and the standard deviation is smaller, which means that the time gaps are more distributed. When manually driving, the driver will keep the space headway not shorter than a certain distance, even if the speed is very slow. Thus, when in congestion, the space headway did not vary much; the speed changed within a certain boundary, which results in a more even distribution of time gap.

For the ACC mode, the results are similar. The median is about 1.8. Since the time gap settings of the ACC driving mode are 1.5s and 2.0s, most of the data points are within this range. There are also some points where the ACC failed to maintain the time gap. The percentage of these points is higher for the higher density category; since the standard deviation of the time-gap distribution 6 is higher than the time-gap distributions 5 and 4. In terms of the high-density situation, the median is larger and the standard deviation is smaller. In a congested situation, the ACC will also try to maintain a fixed safety distance. For the same reason as manually driving, the distribution is more even.

In terms of the CACC driving mode, the low density distribution has a fairly small standard deviation, which means that the CACC system performed better in maintaining time gaps. It can be observed that there are two clusters of time gaps. Since the time gap settings of the CACC are 1s and 1.5s, the two clusters are close to 1.0s and 1.5s. When the density is high, the standard deviation increases. The CACC has pretty good performance, and the time gap is stable when the density is low. When the density of the road is high, the CACC sometimes failed to maintain the time gap, so the standard deviation is much larger.

Since there are different time gap settings during the trial, the time gap needs to be specified to draw a further conclusion. The median and standard deviation of the ACC and CACC with different gap settings are shown in Table B.2.

Table B.2: Empirical gap times under different time gap settings and traffic types

		ACC			CACC		
Setting:		1	2	3	1	2	3
Low Density	Median	1.8317	1.6420	1.8710	0.8626	1.2780	1.4898
	Std	1.4949	1.2909	1.2149	0.1118	0.0749	0.0890
Low Density to critical density	Median	1.9372	1.6566	1.8681	0.8637	1.2581	1.4902
	Std	1.4881	1.3272	1.2435	0.2148	0.1655	0.1177
Critical density to congested	Median	1.8228	1.6935	1.8796	0.8644	1.4449	1.4923
	Std	1.4472	1.3037	1.1597	0.4648	0.2751	0.3232
Congestion	Median	2.0039	2.9785	2.4236	1.3019		2.5484
	Std	0.9096	0.9706	0.8617	0.7210		1.2123

We also conducted a K-S test for every two distributions. Part of the result is shown in Table B.3 to show the pair of distributions that are statistically different.

Table B.3: Two-sample Kolmogorov-Smirnov Test result

Sample 1		Sample 2		Statistic	P-value
OFF(Low density)	setting 1	OFF(Low density)	setting 2	0.036946	0.000
OFF(Low density)	setting 1	OFF(Low density)	setting 3	0.046717	0.000
OFF(Low density)	setting 1	OFF(Low density to critical density)	setting 1	0.374576	0.000

OFF(Low density)	setting 1	OFF(Low density to critical density)	setting 2	0.944395	0.000
OFF(Low density)	setting 1	OFF(Low density to critical density)	setting 3	0.936947	0.000
OFF(Low density)	setting 1	OFF(Critical density to congestion)	setting 1	0.870351	0.000
OFF(Low density)	setting 1	OFF(Critical density to congestion)	setting 2	0.486293	0.000
OFF(Low density)	setting 1	OFF(Critical density to congestion)	setting 3	0.401876	0.000
OFF(Low density)	setting 1	OFF(Congestion)	setting 1	0.400324	0.000
OFF(Low density)	setting 1	OFF(Congestion)	setting 2	0.382469	0.000
OFF(Low density)	setting 1	OFF(Congestion)	setting 3	0.440428	0.000
OFF(Low density)	setting 1	ACC(Low density)	setting 1	0.572215	0.000
OFF(Low density)	setting 1	ACC(Low density)	setting 2	0.596263	0.000
ACC(Congestion)	setting 3	OFF(Critical density to congestion)	setting 2	0.808951	1.000

There is only one pair that does not pass the K-S test; the time gap distribution of ACC when in congestion (gap setting = 1.5 s) and the time gap distribution of CACC when truck platoons are in congestion (gap setting = 1.5s). Although the median and standard deviation of ACC are smaller in this situation, this K-S test indicates that there is no performance difference between ACC and CACC during congestion.

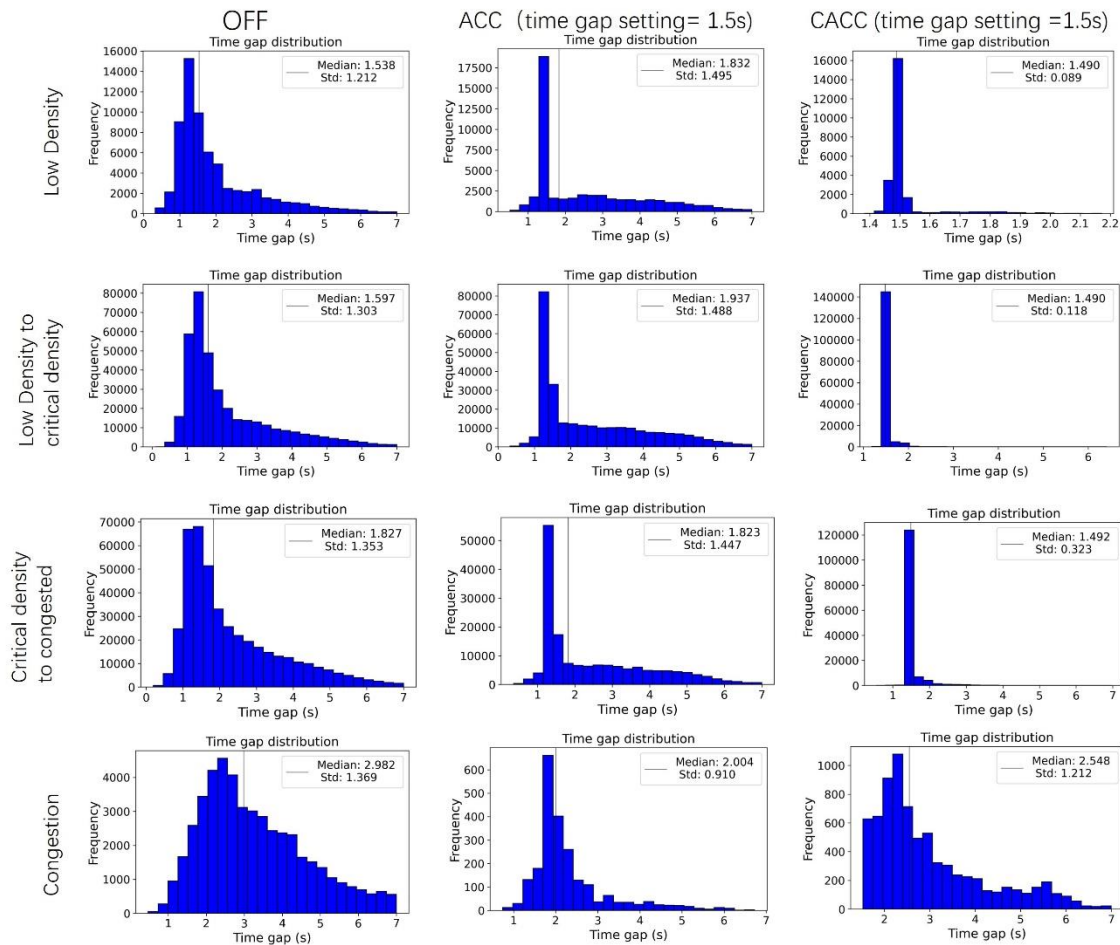


Figure B.10: Time-gap distributions among different traffic states (time-gap setting = 1.5s)

When the density is low, the standard deviation of CACC is much smaller and the median is quite close to the time gap setting. The same thing happened when density is high. It can be concluded that the CACC performs better when not in congestion. While the traffic is congested, there will be no performance difference anymore. By comparing the standard deviation of manual driving and the ACC, it can be observed that manual driving performs better in maintaining time-gap when traffic is not congested. Manual driving can keep the time gap within a specific boundary, while there the time gap for maintaining failure is more evenly distributed.

B.3.4 Time-gap distribution among different infrastructure

The time-gap distributions among different types of roads are shown in Figure B.11.

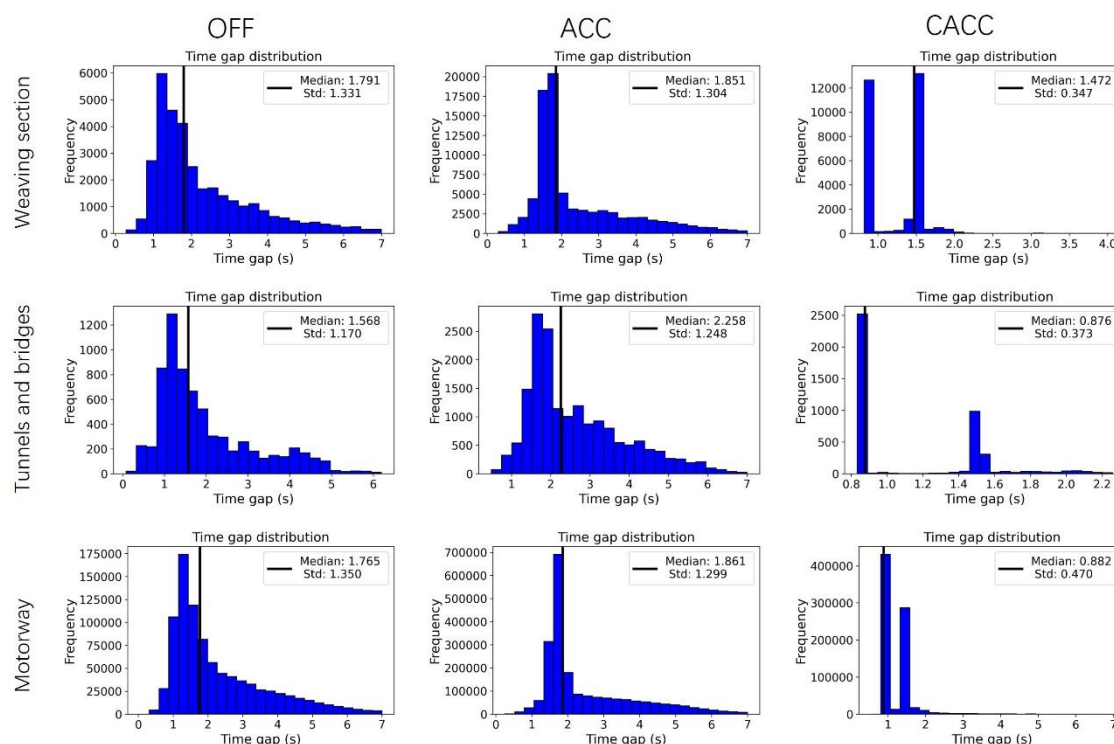


Figure B.11: Time-gap distributions among different road types

The result of the K-S test shows that the time gap sample of manual driving and CACC while driving is likely to be from the same distribution. It can be concluded that there is no performance difference between manual driving and CACC in tunnels and bridges.

Table B.4: Two-sample Kolmogorov-Smirnov Test result

OFF(Weaving section)	OFF(Tunnels and bridges)	0.14561	0.000
OFF(Weaving section)	OFF(Motorway)	0.034369	0.000
OFF(Weaving section)	ACC(Weaving section)	0.199261	0.000
OFF(Weaving section)	ACC(Tunnels and bridges)	0.250127	0.000
OFF(Weaving section)	ACC(Motorway)	0.232704	0.000
OFF(Weaving section)	CACC(Weaving section)	0.56401	0.000

OFF(Weaving section)		CACC(Tunnels and bridges)	0.549537	0.000
OFF(Weaving section)		CACC(Motorway)	0.565282	0.000
OFF(Tunnels and bridges)		OFF(Weaving section)	0.14561	0.000
OFF(Tunnels and bridges)		OFF(Motorway)	0.12959	0.000
OFF(Tunnels and bridges)		ACC(Weaving section)	0.320905	0.000
OFF(Tunnels and bridges)		ACC(Tunnels and bridges)	0.368541	0.000
OFF(Tunnels and bridges)		) ACC(Motorway)	0.353998	0.000
OFF(Tunnels and bridges)		CACC(Tunnels and bridges)	0.500954	1.000

For manual driving, there is no major difference between the three types of roads. However, the median of time gaps is smaller in the tunnels and the standard deviation during tunnels and bridges is minor. For the ACC driving mode, the peak of driving on the motorway is much higher, and this indicates that the ACC system performs better compared to driving in the weaving sections or tunnels. Since there are different time gap settings during the process, the time gap settings need to be specified before drawing any further conclusion. As for CACC, the two time-gap settings can be observed from all the distribution figures. And the standard deviation is much smaller compared to manual driving or ACC.

To compare the time-gap distribution between different driving modes, the standard deviation and median of the categories with different gap settings are shown in Table B.5.

Table B.5: Empirical gap times under different time gap settings and road types

		ACC			CACC		
Setting:		1	2	3	1	2	3
Weaving sections	Median	1.6829	1.6457	1.8657	0.8648	1.3318	0.4918
	Std	1.4735	1.2911	1.2356	0.1214	0.2143	0.1584
Tunnels and bridges	Median	2.3672	2.0888	2.2406	0.8636		1.5069
	Std	1.2579	1.4038	1.1789	0.2257		0.1729
Motorway	Median	1.8884	1.6644	1.8733	0.8639	1.2786	1.4913
	Std	1.4732	1.3001	1.2025	0.3278	0.2738	0.3754

Figure B.12 shows the distributions of the time gap under different road types when the time-gap setting equals 1.5s.

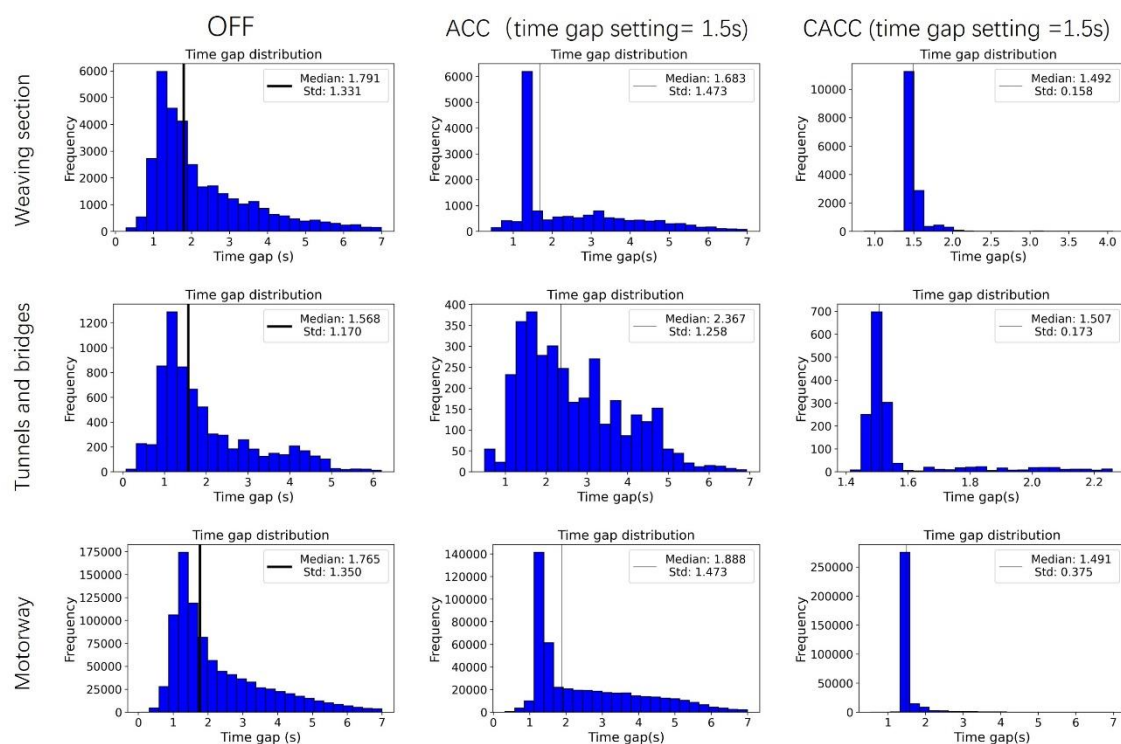


Figure B.12: Time-gap distributions among different road types (time-gap setting = 1.5s)

The results of the K-S test are shown in Table B.6.

Table B.6: Two-sample Kolmogorov-Smirnov Test result

Sample 1		Sample 2		Statistic	P-value
OFF(Weaving section)	setting 1	OFF(Weaving section)	setting 2	0.277976 785	0.000
OFF(Weaving section)	setting 1	OFF(Weaving section)	setting 3	0.047429 519	0.000
OFF(Weaving section)	setting 1	OFF(Tunnels and bridges)	setting 1	0.903727 694	0.000
OFF(Weaving section)	setting 1	OFF(Tunnels and bridges)	setting 2	0.884911 926	0.000
OFF(Weaving section)	setting 1	OFF(Tunnels and bridges)	setting 3	0.886242 436	0.000
OFF(Weaving section)	setting 1	OFF(Motorway)	setting 1	0.371926 278	0.000
OFF(Weaving section)	setting 1	OFF(Motorway)	setting 2	0.286863 348	0.000
OFF(Weaving section)	setting 1	OFF(Motorway)	setting 3	0.405073 437	0.000
OFF(Weaving section)	setting 1	ACC(Weaving section)	setting 1	0.572833 001	0.000
OFF(Weaving section)	setting 1	ACC(Weaving section)	setting 3	0.466356 685	0.000
OFF(Weaving section)	setting 1	ACC(Tunnels and bridges)	setting 1	0.367695 19	0.000
OFF(Weaving section)	setting 1	ACC(Tunnels and bridges)	setting 2	0.395015 525	0.000
OFF(Weaving section)	setting 1	ACC(Tunnels and bridges)	setting 3	0.421947 766	0.000
OFF(Weaving section)	setting 1	ACC(Motorway)	setting 1	0.451609 631	0.000

All pairs pass the test, which means that there are statistical differences between any two distributions. For all three categories, the CACC performs better in time gap maintenance than the ACC driving mode. The percentage of gap maintenance failure of the CACC (tunnels and bridges) is higher than in the weaving section and the regular motorway. This conclusion also holds for the ACC driving mode. There are more gap maintenance deviations of ACC while driving in tunnels or bridges compared to other road types.

B.3.5 Acceleration distribution

The cumulative distribution functions of acceleration are shown in Figure B.1B. And the CDFs of deceleration is shown in Figure B.14.

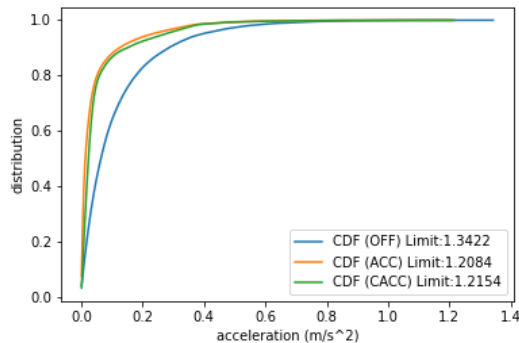


Figure B.13: Cumulative distribution functions of acceleration

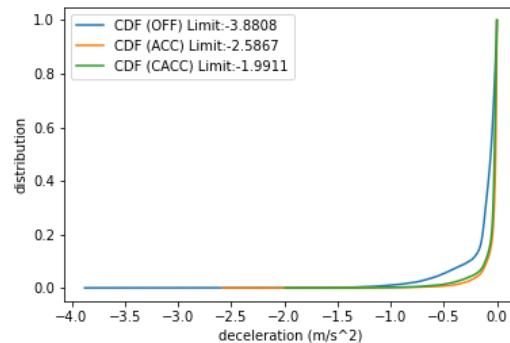


Figure B.14: Cumulative distribution functions of deceleration

The shape of the CDFs is similar. However, it can be observed that the curves of ACC and CACC are steeper. The steeper CDF means that acceleration and deceleration are within a smaller scope. The acceleration CDF and deceleration CDF of ACC and CACC are much steeper than the manual driving CDF, indicating that the experience of driving in a truck platoon with ACC or CACC is better. It is safer for the vehicle behind the CACC truck platoon compared to following the manual driving trucks or ACC platoon since there is no extreme braking(the limit of CACC is smaller).

B.3.6 Manoeuvring behaviour

The lane-changing behaviour is In the truck platooning trial, most of the manoeuvring behaviours are performed to follow the route. Before executing the lane-change behaviour, the driver needs to consider whether to accept the gap. Since gap data are unavailable, the gap within the truck platoon can be used to analyse the overall impact of the truck platoon on traffic flow. A larger gap means that the platoon will need more space to change lanes, which indicates a more profound negative impact on the traffic flow. The gap distributions of the manoeuvring are shown in Figure B.15, Figure B.17 and Figure B.19.

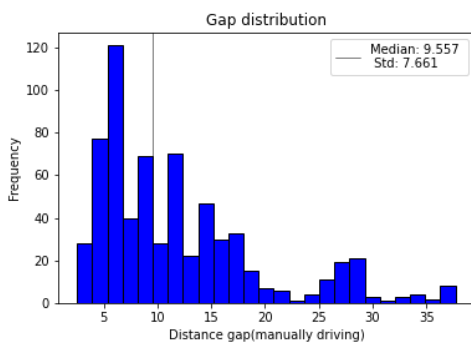


Figure B.15: Gap distribution of manual driving (during
manoeuvring)

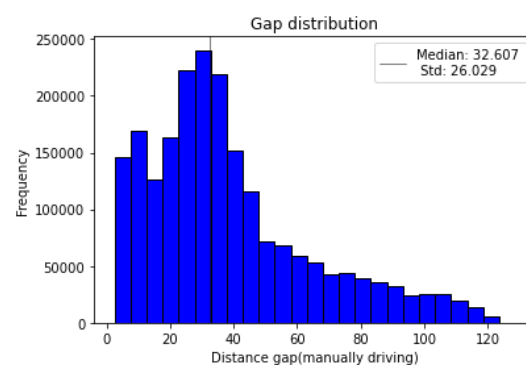


Figure B.16: Gap distribution of manual driving

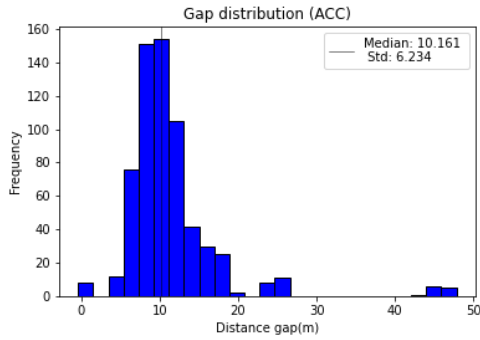


Figure B.17: Gap distribution of ACC (during manoeuvring)

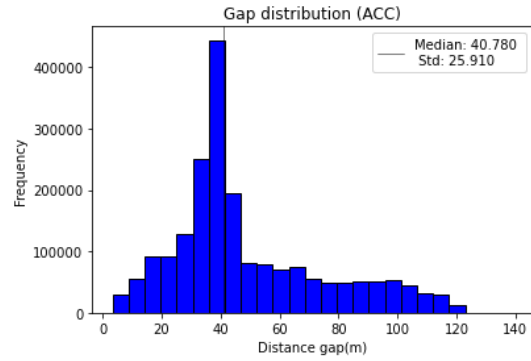


Figure B.18: Gap distribution of ACC

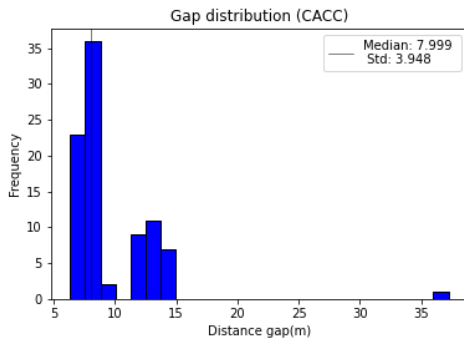


Figure B.19: Gap distribution of CACC (during manoeuvring)

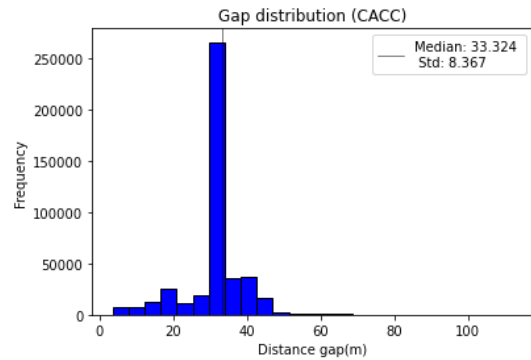


Figure B.20: Gap distribution of CACC

We Conducted a K-S test between the gap distributions while drivers are manoeuvring and keeping their lane (the steering angle is small). The results shown in Table B.7 indicate that the difference between the lane-keeping and lane-changing manoeuvring is significant.

Table B.7: Two-sample Kolmogorov-Smirnov Test result

	Statistic	P-value
Manual driving	0.64273	0
ACC	0.87976	0
CACC	0.94436	0

It can be observed that the CACC system can maintain a relatively small gap during lane-changing behaviours, and the gaps are more centrally distributed for the CACC system. This result indicates that the CACC truck platoon performs better than ACC and manual driving. The lane-changing behaviours of the CACC truck platoon are less likely to have a negative effect on traffic flow since the platoon occupies less space in the longitudinal direction. There are no significant differences in the median and standard deviation between ACC and manual driving. This indicates that ACC could not improve the negative effect of lane change behaviour compared to manual driving.

B.4 Conclusions

The analysis in this section focuses mainly on the distributions of the time gaps under different traffic conditions and road categories. The two-sample Kolmogorov-Smirnov Test is used to verify the statistical difference between the two distributions. On the basis of the empirical data, it is concluded that there is no performance difference between ACC and CACC during congested traffic. With CACC, the platoon performs better in maintaining time gaps when traffic is not

congested. In tunnels or on the bridges, the ability to maintain the desired time gap is diminished for both the ACC driving mode compared to the CACC driving mode.

The other two parts of the analysis relate to the acceleration distributions and the manoeuvring behaviour. From the acceleration/deceleration distribution plots, the distribution of the CACC driving mode is within a smaller boundary meaning that there is no sudden braking. The driving experience of the truck platoon with the CACC system is better compared to manual driving or ACC. And from the result of manoeuvring behaviour analysis, the CACC system could help to maintain a relatively small gap during lane changes. However, ACC mode could not improve the negative effect of lane change behaviour compared to manual driving.

In this study, all conclusions are based on empirical data. For further analysis and better reasoning of the phenomena, we recommend calibrating a simulation model based on the empirical evidence provided by this study. With such a model, more detailed conclusions can be drawn. For example, the impact of longer truck platoons or any other conditions that are pretty hard to implement in real-life trials.

Appendix C Contents of C-ITS messages

C.1 Vehicle-to-infrastructure communication

For the infrastructure to be able to detect and distinguish platooning c-its vehicles from other road traffic, uniquely identifiable information needed to be available. To that extend, TNO and Swarco agreed upon using the below defined information with the ETSI CAMv2 messages that were send out by the platooning trucks for the purpose of the Ursa Major project.

The following special ETSI CAMv2 containers were used when the trucks have their platooning function switched on, underlined:

- SpecialTransportType ::= BIT STRING {heavyLoad(0), excessWidth(1), excessLength(2), excessHeight(3)} (SIZE(4))
- AccelerationControl ::= BIT STRING {brakePedalEngaged (0), gasPedalEngaged (1), emergencyBrakeEngaged (2), collisionWarningEngaged (3), accEngaged (4), cruiseControlEngaged (5), speedLimiterEngaged (6)} (SIZE(7))

When the platooning function was disengaged, these fields were not used within the CAMv2 messages and the CAMv2 messages were transmitted without them.

C.2 Infrastructure-to-vehicle communication

For the platoon to be able to receive instructions from the infrastructure, specifically regarding the automated driving and platooning functions, the latest ETSI IVIM message standard (NEN-CEN ISO/TS 19321:2020) contains an 'Automated Vehicle Container'.

The purpose for the Automated Vehicle Container is to contain information associated with real or virtual road signs which is specific for automated vehicles to support use cases like Cooperative Adaptive Cruise Control or Platooning.

For each of the scenarios as described earlier, different field in the IVIM message are applicable in order to instruct the platoon of trucks. Below these fields are summarized.

AutomatedVehicleContainer:

detectionZonelds	The zone(s) stream-upwards of the area where the scenario has to be effective.
relevanceZonelds	The zone(s) where the scenario is effective.
direction	0 (same direction)
platooningRules	See below.

Fields used for the 'platoon disengage' scenario:

platooningRule

priority 1 (contextual)

allowedSaeAutomationLevels 0 (only level 0 allowed).

Fields used for the 'increase gap distance' scenario:

platooningRule

priority 1 (contextual)

allowedSaeAutomationLevels 2

minGapBetweenVehicles 30

Appendix D Average fuel consumption, emissions per trip

This appendix provides trip averages of fuel consumption, CO₂ and NO_x emissions at a velocity range of 80 km/h +/- 5 km/h. It supports chapter 3 – Macro Topic 3 Emissions.

Date	Block	Vehicle	Position	Time gap setting [s]	Control Mode	Time captured [h]	Distance gap [m]	Velocity [km/h]	Fuel [l/100 km]	CO ₂ [g/km]	NO _x [mg/km]
28-6-22	C	ET3	Leader	Manual	Manual	0.009	96.1	80.06	30	801	698
28-6-22	C	ET3	Leader	2.0	ACC	0.012	72.7	79.95	27	704	2675
28-6-22	C	ET2	Trailer	Manual	Manual	0.004	16.4	79.29	62	1638	3977
28-6-22	C	ET2	Trailer	2.0	ACC	0.013	37.3	80.37	41	1093	5110
28-6-22	D	ET3	Leader	Manual	Manual	0.136	43.0	79.85	19	498	94
28-6-22	D	ET3	Leader	2.0	ACC	0.520	50.6	80.00	21	549	195
28-6-22	D	ET2	Trailer	Manual	Manual	0.073	20.2	79.83	21	565	39
28-6-22	D	ET2	Trailer	1.75	ACC	0.003	20.5	80.21	10	275	1
28-6-22	D	ET2	Trailer	2.0	ACC	0.559	38.8	79.70	25	661	227
29-6-22	A	ET2	Leader	Manual	Manual	0.035		79.01	21	565	28
29-6-22	A	ET2	Leader	2.0	ACC	0.101	74.8	78.51	23	603	184
29-6-22	A	ET3	Trailer	Manual	Manual	0.022	33.2	79.10	27	716	113
29-6-22	A	ET3	Trailer	1.0	CACC	0.109	19.0	78.83	23	608	325
29-6-22	B	ET2	Leader	Manual	Manual	0.096	15.6	79.07	20	535	88
29-6-22	B	ET2	Leader	Manual	Manual	0.008	11.8	79.16	16	436	18
29-6-22	B	ET2	Leader	1.5	ACC	0.526	49.2	79.22	21	555	189
29-6-22	B	ET2	Leader	1.75	ACC	0.000	9.7	79.18	17	451	11
29-6-22	B	ET2	Leader	2.0	ACC	0.001	11.0	79.18	16	423	23
29-6-22	B	ET3	Trailer	Manual	Manual	0.008	8.0	79.22	14	369	59
29-6-22	B	ET3	Trailer	Manual	Manual	0.006	28.0	79.09	16	411	43
29-6-22	B	ET3	Trailer	1.5	ACC	0.001	13.5	78.93	20	534	119
29-6-22	B	ET3	Trailer	1.75	ACC	0.001	12.6	79.22	13	349	153
29-6-22	B	ET3	Trailer	2.0	ACC	0.035	28.1	79.10	20	536	238
29-6-22	B	ET3	Trailer	1.0	CACC	0.184	19.2	79.43	23	610	159
29-6-22	B	ET3	Trailer	1.25	CACC	0.005	6.6	79.12	18	482	41
29-6-22	B	ET3	Trailer	1.5	CACC	0.383	24.5	79.19	19	514	286
29-6-22	C	ET2	Leader	Manual	Manual	0.031	36.9	80.48	19	507	9
29-6-22	C	ET2	Leader	1.5	ACC	0.135	48.8	80.67	21	553	275
29-6-22	C	ET3	Trailer	Manual	Manual	0.030	23.7	80.31	26	682	332
29-6-22	C	ET3	Trailer	1.5	ACC	0.027	27.8	80.33	22	595	385
29-6-22	C	ET3	Trailer	1.0	CACC	0.110	20.3	80.57	22	590	184
29-6-22	D	ET2	Leader	Manual	Manual	0.008	28.7	81.83	18	485	56
29-6-22	D	ET2	Leader	1.75	ACC	0.280	45.8	81.75	22	588	95
29-6-22	D	ET3	Trailer	Manual	Manual	0.003		76.03	36	949	1059
29-6-22	D	ET3	Trailer	2.0	ACC	0.285	43.7	81.55	23	601	183
1-7-22	A	ET2	Leader	Manual	Manual	0.004	26.5	76.11	22	579	289
1-7-22	A	ET2	Leader	1.5	ACC	0.180	59.3	78.33	24	645	165
1-7-22	A	ET3	Trailer	1.5	ACC	0.009	20.7	77.22	25	667	157
1-7-22	A	ET3	Trailer	1.0	CACC	0.178	20.0	79.11	25	658	368
1-7-22	B	ET2	Leader	Manual	Manual	0.006	85.1	77.68	23	601	739
1-7-22	B	ET2	Leader	2.0	ACC	0.195	60.9	78.55	21	567	423
1-7-22	B	ET3	Trailer	2.0	ACC	0.197	40.8	77.89	21	556	606
1-7-22	C	ET2	Leader	Manual	Manual	0.444	42.2	78.68	25	650	423
1-7-22	C	ET3	Trailer	Manual	Manual	0.368	26.9	77.30	25	669	435
1-7-22	D	ET2	Leader	Manual	Manual	0.015	17.2	78.96	17	452	326
1-7-22	D	ET2	Leader	2.0	ACC	0.087	72.8	78.99	23	608	957
1-7-22	D	ET3	Trailer	Manual	Manual	0.011	27.6	77.72	26	691	343
1-7-22	D	ET3	Trailer	2.0	ACC	0.001	31.5	76.82	49	1287	2333
1-7-22	D	ET3	Trailer	1.5	CACC	0.075	33.2	77.15	26	683	1380
6-7-22	A	ET2	Leader	2.0	ACC	0.161	67.0	79.41	23	617	97
6-7-22	A	ET3	Trailer	2.0	ACC	0.161	41.2	79.69	26	681	278
6-7-22	B	ET2	Leader	Manual	Manual	0.028	59.3	79.76	27	716	136
6-7-22	B	ET2	Leader	2.0	ACC	0.765	64.4	79.93	22	591	166
6-7-22	B	ET3	Trailer	Manual	Manual	0.003	23.9	79.68	45	1181	1853
6-7-22	B	ET3	Trailer	Manual	Manual	0.018	57.0	79.13	25	655	137
6-7-22	B	ET3	Trailer	1.5	ACC	0.069	30.7	79.75	28	736	690

Date	Block	Vehicle	Position	Time gap setting [s]	Control Mode	Time captured [h]	Distance gap [m]	Velocity [km/h]	Fuel [l/100 km]	CO2 [g/km]	NOx [mg/km]
6-7-22	B	ET3	Trailer	1.75	ACC	0.003	23.3	80.18	14	369	173
6-7-22	B	ET3	Trailer	2.0	ACC	0.070	41.5	79.91	20	535	149
6-7-22	B	ET3	Trailer	1.0	CACC	0.578	19.8	79.98	22	575	245
6-7-22	B	ET3	Trailer	1.25	CACC	0.003	24.8	79.77	24	647	260
6-7-22	B	ET3	Trailer	1.5	CACC	0.031	33.3	80.13	28	747	549
6-7-22	C	ET2	Leader	Manual	Manual	0.003		78.36	34	896	5
6-7-22	C	ET2	Leader	Manual	Manual	0.012	32.7	80.34	21	560	63
6-7-22	C	ET2	Leader	1.5	ACC	0.516	68.4	78.77	21	556	159
6-7-22	C	ET2	Leader	2.0	ACC	0.009	74.3	80.46	18	475	95
6-7-22	C	ET3	Trailer	Manual	Manual	0.014	30.7	79.90	20	527	49
6-7-22	C	ET3	Trailer	1.5	ACC	0.519	30.3	78.82	21	564	141
6-7-22	C	ET3	Trailer	1.75	ACC	0.000	30.9	80.50	21	556	0
6-7-22	D	ET2	Leader	Manual	Manual	0.652	58.7	78.92	21	553	57
6-7-22	D	ET3	Trailer	Manual	Manual	0.636	30.3	78.82	21	545	277
6-7-22	D	ET3	Trailer	1.5	ACC	0.005	21.2	78.79	16	416	67
8-7-22	A	ET2	Leader	1.75	ACC	0.171	65.0	79.82	22	571	63
8-7-22	A	ET3	Trailer	2.0	ACC	0.003	28.6	79.98	31	817	289
8-7-22	A	ET3	Trailer	1.5	CACC	0.150	33.4	79.88	23	619	115
8-7-22	B	ET2	Leader	Manual	Manual	0.012	29.8	79.84	23	602	12
8-7-22	B	ET2	Leader	1.75	ACC	0.388	60.0	77.69	22	592	140
8-7-22	B	ET3	Trailer	2.0	ACC	0.057	41.8	79.60	22	584	222
8-7-22	B	ET3	Trailer	1.5	CACC	0.343	33.5	79.51	24	648	670
8-7-22	C	ET2	Leader	Manual	Manual	0.006	61.7	76.66	21	549	126
8-7-22	C	ET2	Leader	2.0	ACC	0.110	62.9	76.62	21	566	310
8-7-22	C	ET3	Trailer	Manual	Manual	0.006	24.6	80.42	17	457	113
8-7-22	C	ET3	Trailer	1.5	ACC	0.003	20.7	79.38	15	402	36
8-7-22	C	ET3	Trailer	1.0	CACC	0.101	19.5	79.52	26	692	1474
8-7-22	D	ET2	Leader	Manual	Manual	0.040	35.1	79.61	24	641	67
8-7-22	D	ET2	Leader	2.0	ACC	0.236	68.9	79.63	21	566	142
8-7-22	D	ET3	Trailer	Manual	Manual	0.039	17.0	79.68	20	520	163
8-7-22	D	ET3	Trailer	1.75	ACC	0.234	35.7	79.65	21	564	304
15-7-22	A	ET2	Leader	Manual	Manual	0.009	41.8	78.52	23	621	36
15-7-22	A	ET2	Leader	1.75	ACC	0.208	55.6	78.93	22	585	161
15-7-22	A	ET3	Trailer	Manual	Manual	0.003		79.57	20	536	68
15-7-22	A	ET3	Trailer	1.75	ACC	0.215	35.5	79.50	23	611	410
15-7-22	B	ET2	Leader	Manual	Manual	0.591	60.4	78.95	22	580	134
15-7-22	B	ET3	Trailer	Manual	Manual	0.556	33.6	79.35	23	621	352
15-7-22	C	ET2	Leader	Manual	Manual	0.109	28.5	79.17	23	598	358
15-7-22	C	ET2	Leader	2.0	ACC	0.041	76.8	79.31	21	563	238
15-7-22	C	ET3	Trailer	Manual	Manual	0.088	22.5	79.17	20	540	381
15-7-22	C	ET3	Trailer	2.0	ACC	0.066	38.1	79.01	26	686	1887
15-7-22	D	ET2	Leader	2.0	ACC	0.140	61.9	79.72	21	557	68
15-7-22	D	ET3	Trailer	2.0	ACC	0.118	41.7	80.22	24	648	245
20-7-22	A	ET2	Leader	Manual	Manual	0.234	51.3	78.41	23	622	111
20-7-22	A	ET3	Trailer	Manual	Manual	0.204	35.0	78.73	23	617	186
20-7-22	B	ET2	Leader	Manual	Manual	0.013	42.3	81.16	22	587	147
20-7-22	B	ET2	Leader	1.75	ACC	0.300	14.4	80.55	24	637	231
20-7-22	B	ET3	Trailer	Manual	Manual	0.013	18.4	81.24	21	545	103
20-7-22	B	ET3	Trailer	1.75	ACC	0.296	14.1	80.06	25	672	562
20-7-22	C	ET2	Leader	Manual	Manual	0.004		79.92	12	319	28
20-7-22	C	ET2	Leader	2.0	ACC	0.288	40.2	79.38	25	651	147
20-7-22	C	ET3	Trailer	Manual	Manual	0.004	46.2	79.65	19	516	62
20-7-22	C	ET3	Trailer	2.0	ACC	0.270	38.9	79.06	25	672	354
22-7-22	A	ET3	Leader	Manual	Manual	0.029	20.1	78.45	29	768	1125
22-7-22	A	ET3	Leader	2.0	ACC	0.219	40.9	80.24	21	561	133
22-7-22	A	ET2	Trailer	Manual	Manual	0.031	59.0	78.89	31	810	442
22-7-22	A	ET2	Trailer	2.0	ACC	0.229	70.5	80.34	22	583	156
22-7-22	B	ET2	Leader	Manual	Manual	0.011	100.4	80.96	8	201	19
22-7-22	B	ET2	Leader	1.5	ACC	0.516	63.5	80.24	22	573	265
22-7-22	B	ET2	Leader	1.75	ACC	0.001		80.37	21	548	18
22-7-22	B	ET2	Leader	2.0	ACC	0.001		80.39	22	588	12
22-7-22	B	ET3	Trailer	Manual	Manual	0.008	7.9	78.99	32	851	253
22-7-22	B	ET3	Trailer	1.5	ACC	0.028	36.9	79.87	25	652	186

Date	Block	Vehicle	Position	Time gap setting [s]	Control Mode	Time captured [h]	Distance gap [m]	Velocity [km/h]	Fuel [l/100 km]	CO2 [g/km]	NOx [mg/km]
22-7-22	B	ET3	Trailer	1.0	CACC	0.489	19.6	79.91	22	591	240
22-7-22	C	ET2	Leader	Manual	Manual	0.012	72.6	80.34	19	506	5
22-7-22	C	ET2	Leader	Manual	Manual	0.089	33.9	80.34	19	495	41
22-7-22	C	ET2	Leader	1.75	ACC	0.190	53.7	80.21	22	582	196
22-7-22	C	ET3	Trailer	Manual	Manual	0.011	19.6	80.39	18	471	27
22-7-22	C	ET3	Trailer	Manual	Manual	0.020	29.2	79.94	17	445	87
22-7-22	C	ET3	Trailer	1.75	ACC	0.001	32.6	80.39	23	606	32
22-7-22	C	ET3	Trailer	2.0	ACC	0.081	29.1	80.29	27	704	426
22-7-22	C	ET3	Trailer	1.25	CACC	0.004	28.6	80.44	15	392	33
22-7-22	C	ET3	Trailer	1.5	CACC	0.169	31.9	80.19	24	633	333
22-7-22	D	ET2	Leader	Manual	Manual	0.141	65.9	78.88	20	531	86
22-7-22	D	ET3	Trailer	Manual	Manual	0.126	26.5	78.81	27	714	635
29-7-22	A	ET2	Leader	Manual	Manual	0.001		79.52	20	541	11
29-7-22	A	ET2	Leader	1.75	ACC	0.223	62.0	79.65	23	611	202
29-7-22	A	ET3	Trailer	2.0	ACC	0.009	28.1	79.41	18	475	162
29-7-22	A	ET3	Trailer	1.5	CACC	0.218	33.7	79.63	24	642	374
29-7-22	B	ET2	Leader	Manual	Manual	0.024	27.7	79.70	25	674	486
29-7-22	B	ET2	Leader	1.5	ACC	0.132	70.8	79.31	22	593	307
29-7-22	B	ET3	Trailer	Manual	Manual	0.001	26.9	78.35	59	1571	1299
29-7-22	B	ET3	Trailer	Manual	Manual	0.006	36.3	80.65	25	657	272
29-7-22	B	ET3	Trailer	1.5	ACC	0.005	27.2	79.48	22	581	191
29-7-22	B	ET3	Trailer	1.75	ACC	0.017	36.5	78.53	31	816	1077
29-7-22	B	ET3	Trailer	2.0	ACC	0.041	44.8	79.66	24	648	216
29-7-22	B	ET3	Trailer	1.0	CACC	0.054	21.3	80.03	33	880	809
29-7-22	B	ET3	Trailer	1.25	CACC	0.011	29.3	78.37	15	403	93
29-7-22	B	ET3	Trailer	1.5	CACC	0.020	32.8	80.24	21	556	109
29-7-22	C	ET2	Leader	Manual	Manual	0.000	47.6	83.20	21	549	32
29-7-22	C	ET2	Leader	1.5	ACC	0.010	46.6	81.54	28	748	180
29-7-22	C	ET2	Leader	1.75	ACC	0.036	35.4	80.21	22	583	1721
29-7-22	C	ET3	Trailer	2.0	ACC	0.027	37.6	79.56	35	917	2891
29-7-22	C	ET3	Trailer	1.5	CACC	0.012	31.6	78.67	39	1045	1371
10-8-22	B	ET2	Trailer	Manual	Manual	0.017	36.4	81.33	24	636	669
10-8-22	B	ET2	Trailer	2.0	ACC	0.052	40.8	78.53	25	670	747
10-8-22	C	ET3	Leader	Manual	Manual	0.408	63.2	77.60	24	636	192
10-8-22	C	ET2	Trailer	Manual	Manual	0.217	30.1	79.60	23	611	559
10-8-22	C	ET2	Trailer	Manual	Manual	0.001	47.1	82.28	9	234	292
10-8-22	C	ET2	Trailer	Manual	Manual	0.197	33.3	79.16	25	671	995
10-8-22	C	ET2	Trailer	1.5	ACC	0.003	40.1	79.95	11	297	200
10-8-22	D	ET2	Leader	Manual	Manual	0.016	32.1	81.77	27	707	474
10-8-22	D	ET2	Leader	Manual	Manual	0.004	45.6	80.72	13	355	317
10-8-22	D	ET2	Leader	2.0	ACC	0.041	73.8	78.90	20	531	280
10-8-22	D	ET3	Trailer	Manual	Manual	0.013	54.9	78.83	26	690	297
10-8-22	D	ET3	Trailer	2.0	ACC	0.002	48.4	78.76	13	344	298
10-8-22	D	ET3	Trailer	1.5	CACC	0.046	33.5	77.56	24	624	303
22-8-22	A	ET3	Leader	Manual	Manual	0.016	28.7	78.91	17	457	22
22-8-22	A	ET2	Leader	1.5	ACC	0.342	70.8	80.09	21	544	578
22-8-22	A	ET3	Leader	1.5	ACC	0.015	31.5	78.18	16	420	58
22-8-22	A	ET2	Leader	1.75	ACC	0.000		80.28	15	399	419
22-8-22	A	ET2	Leader	2.0	ACC	0.011	79.5	80.27	18	478	464
22-8-22	A	ET2	Trailer	1.5	ACC	0.008	100.4	77.56	30	797	2996
22-8-22	A	ET2	Trailer	2.0	ACC	0.027	63.6	80.26	19	495	369
22-8-22	A	ET3	Trailer	1.0	CACC	0.356	19.2	78.78	20	526	95
22-8-22	B	ET2	Leader	2.0	ACC	0.222	61.2	79.86	22	588	987
22-8-22	B	ET3	Leader	2.0	ACC	0.031	34.0	79.00	26	692	895
22-8-22	B	ET2	Trailer	2.0	ACC	0.039	52.2	79.81	33	883	2145
22-8-22	B	ET3	Trailer	1.5	CACC	0.194	33.4	78.85	26	692	585
22-8-22	C	ET3	Leader	Manual	Manual	0.006	25.2	79.04	24	639	131
22-8-22	C	ET3	Leader	2.0	ACC	0.476	40.9	79.15	21	559	281
22-8-22	C	ET2	Trailer	Manual	Manual	0.006		80.01	23	618	372
22-8-22	C	ET2	Trailer	2.0	ACC	0.477	64.4	79.96	23	598	910
22-8-22	D	ET2	Leader	Manual	Manual	0.002	81.6	80.04	23	602	795
22-8-22	D	ET3	Leader	Manual	Manual	0.043	26.4	79.07	19	505	176
22-8-22	D	ET2	Leader	1.5	ACC	0.353	66.5	80.02	22	575	620

Date	Block	Vehicle	Position	Time gap setting [s]	Control Mode	Time captured [h]	Distance gap [m]	Velocity [km/h]	Fuel [l/100 km]	CO2 [g/km]	NOx [mg/km]
22-8-22	D	ET3	Leader	1.5	ACC	0.012	31.4	79.09	20	530	183
22-8-22	D	ET2	Trailer	Manual	Manual	0.013	80.6	80.03	23	597	684
22-8-22	D	ET2	Trailer	Manual	Manual	0.019	24.6	80.06	22	573	542
22-8-22	D	ET2	Trailer	1.5	ACC	0.022	73.7	80.09	20	536	606
22-8-22	D	ET2	Trailer	1.75	ACC	0.001	26.6	79.94	27	709	1170
22-8-22	D	ET2	Trailer	2.0	ACC	0.001	23.2	79.97	25	666	1045
22-8-22	D	ET3	Trailer	1.0	CACC	0.354	19.8	79.04	20	531	247
20-9-22	A	ET2	Leader	1.5	ACC	0.080	67.0	80.36	23	611	911
20-9-22	A	ET3	Trailer	2.0	ACC	0.012	43.2	80.70	33	869	902
20-9-22	A	ET3	Trailer	1.5	CACC	0.061	33.3	79.81	25	653	233
20-9-22	B	ET2	Leader	Manual	Manual	0.011	43.1	78.90	17	441	601
20-9-22	B	ET2	Leader	2.0	ACC	0.590	54.3	79.17	21	553	878
20-9-22	B	ET3	Trailer	Manual	Manual	0.004	37.6	79.34	20	527	202
20-9-22	B	ET3	Trailer	2.0	ACC	0.574	41.4	79.43	22	591	399
20-9-22	C	ET2	Leader	Manual	Manual	0.001		79.40	40	1051	1595
20-9-22	C	ET2	Leader	1.5	ACC	0.336	60.3	79.81	22	590	950
20-9-22	C	ET2	Leader	1.75	ACC	0.000	97.0	82.09	0	0	13
20-9-22	C	ET3	Trailer	Manual	Manual	0.001	31.5	80.33	15	385	204
20-9-22	C	ET3	Trailer	1.5	ACC	0.337	30.1	80.45	22	581	576
21-9-22	A	ET2	Leader	Manual	Manual	0.004	44.8	78.71	33	885	1208
21-9-22	A	ET2	Leader	1.75	ACC	0.390	67.9	79.13	22	594	783
21-9-22	A	ET3	Trailer	1.75	ACC	0.387	36.0	79.33	23	619	396
21-9-22	B	ET2	Leader	Manual	Manual	0.010	58.4	79.24	16	425	389
21-9-22	B	ET2	Leader	Manual	Manual	0.000		79.58	17	449	374
21-9-22	B	ET2	Leader	1.75	ACC	0.006	34.5	79.04	23	600	560
21-9-22	B	ET2	Leader	2.0	ACC	0.496	64.5	79.07	22	582	782
21-9-22	B	ET3	Trailer	Manual	Manual	0.009	24.8	79.39	15	410	41
21-9-22	B	ET3	Trailer	2.0	ACC	0.481	41.1	79.55	24	624	577
21-9-22	C	ET2	Leader	1.75	ACC	0.203	60.8	79.35	23	607	1318
21-9-22	C	ET3	Trailer	1.75	ACC	0.200	35.8	78.71	22	596	465
21-9-22	D	ET2	Leader	Manual	Manual	0.058	31.5	79.35	22	594	208
21-9-22	D	ET2	Leader	1.75	ACC	0.389	64.6	79.15	22	575	238
21-9-22	D	ET3	Trailer	Manual	Manual	0.032	19.5	80.03	20	518	69
21-9-22	D	ET3	Trailer	Manual	Manual	0.018	28.2	78.80	18	487	22
21-9-22	D	ET3	Trailer	1.75	ACC	0.368	35.9	79.47	21	565	327
21-9-22	D	ET3	Trailer	2.0	ACC	0.026	44.0	78.72	20	534	38
28-9-22	A	ET3	Leader	Manual	Manual	0.003	30.8	78.67	53	1398	2087
28-9-22	A	ET3	Leader	2.0	ACC	0.342	69.9	79.00	23	603	298
28-9-22	A	ET2	Trailer	2.0	ACC	0.340	42.3	79.03	25	660	160
28-9-22	B	ET3	Leader	Manual	Manual	0.129	32.2	78.89	24	648	726
28-9-22	B	ET3	Leader	1.5	ACC	0.533	59.5	79.01	23	608	287
28-9-22	B	ET2	Trailer	Manual	Manual	0.081	24.0	79.15	28	736	43
28-9-22	B	ET2	Trailer	1.5	ACC	0.113	33.1	79.21	25	661	22
28-9-22	B	ET2	Trailer	1.0	CACC	0.421	19.2	79.12	24	648	104