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TNO report

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Real-world impacts of truck driving with Adaptive Cruise Control on fuel consumption, driver behaviour and logistics – *results from a hybrid field operational test and naturalistic driving study in the Netherlands*

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Summary

Introduction: increased automation logistics starting with ADAS systems
Digitization and automation are progressing fast in transport and logistics. Technological advancement is driving the level of automation and autonomy of vehicles, moving from driver-assisted technologies (Advanced Driver Assistance Systems; ADAS) to autonomous transport systems where driving tasks are taken over from the human driver by automated driving system (ADS). More and more vehicles are equipped as standard with Adaptive Cruise Control (ACC).
This ADAS system supports the driver in the longitudinal driving task by keeping a gap to preceding vehicles. This system is considered as a first step towards Truck Platooning as a broad concept with varying levels of automation. Initially, Truck Platooning may materialize as Cooperative-ACC (C-ACC) Truck Platooning and subsequently evolve towards Highly Automated (unmanned) Truck Platooning in the future.

Aim of the research: measure impact of ACC driving on fuel consumption, driver and logistics
At the time of designing this research (2018), there was limited evidence or insight into the usage of ACC systems and C-ACC Truck Platooning systems in everyday road logistics operations. Therefore, this two-stage research project ‘Integrator Connected Truck Trials’ was established to provide insights into ACC driving (solo and convoy) in the 1st stage, and C-ACC truck platooning in the 2nd stage. This report represents on the result of the 1st stage, thereby answering the following research question: ***What is the impact of the usage of Adaptive Cruise Control – both solo and in planned convoys – on fuel consumption, professional truck drivers and logistics?*** By answering this question, we provide baseline measurements that will help the safe and sustainable development and implementation of more autonomous driving systems such as truck platooning in the future. Thereby it should be noted that truck platooning is not a goal in and of itself but rather an innovation that is expected to contribute to the safety, sustainability and efficiency of heavy-duty road transport.

Methodology: a hybrid field operational test and naturalistic driving study involving real-world logistics operations
To answer our research question, we test ACC driving, both in solo and in convoy formation, in everyday traffic integrated in logistical operations. The research design is a hybrid between a Field Operational Test (FOT) and a Naturalistic Driving Study (NDS) – in contrast to most earlier studies that are conducted on test tracks. In our study, drivers executed their normal routines as much as possible and measurement instruments were chosen to not hinder the drivers in doing so.
The trucks were equipped with various measurement instruments in order to record fuel data, track vehicle data and monitor the drivers. Furthermore, questionnaires and an online survey app were used to monitor the drivers. Logistics data is gathered in interviews with the transporters. Figure 1 provides an overview of the project in a nutshell. Data is gathered during various driving campaigns adding up to 15 weeks of data in total.

- **15** Weeks of experimental testing in various driving campaigns by a naturalistic driving study, 25 weeks of data logging
- **11 I**nvolved truck drivers
- **9 T**rucks equipped with measurement instruments

- ~ 353,000 kilometres logged
- ~ 100,000 litres diesel used
- ~ 274,000 kilometres logged on highways > 75 km/h
- 6,800 hours of data logged
- 57 surveys (63 sent, 9 per respondent)
- 840 effort ratings in app (120 per respondent)

Figure 1: Integrator Connected Truck Trials project (stage) I in a nutshell.

On average ACC-usage is likely to lead to a 4-6% reduction in fuel consumption, depending on following distance.

For all 9 vehicles that were logged, ACC driving is more efficient in terms of fuel consumption. ACC driving is more fuel efficient than when ACC is switched off in the control condition, or at distances not associated with the relevant ACC mode. Note that for these 9 vehicles, no significant fuel reduction was seen at following distances less than 33 metres. The real-world data does show a spread in the results. Figure 2 plots the results of the individual trucks (Truck 1a-Truck 5b) in this study (diamond symbols), the average results of this study (red-dotted line) and results from earlier studies (dots). Our average results are lower than those presented by Veldhuizen et al. (2019).

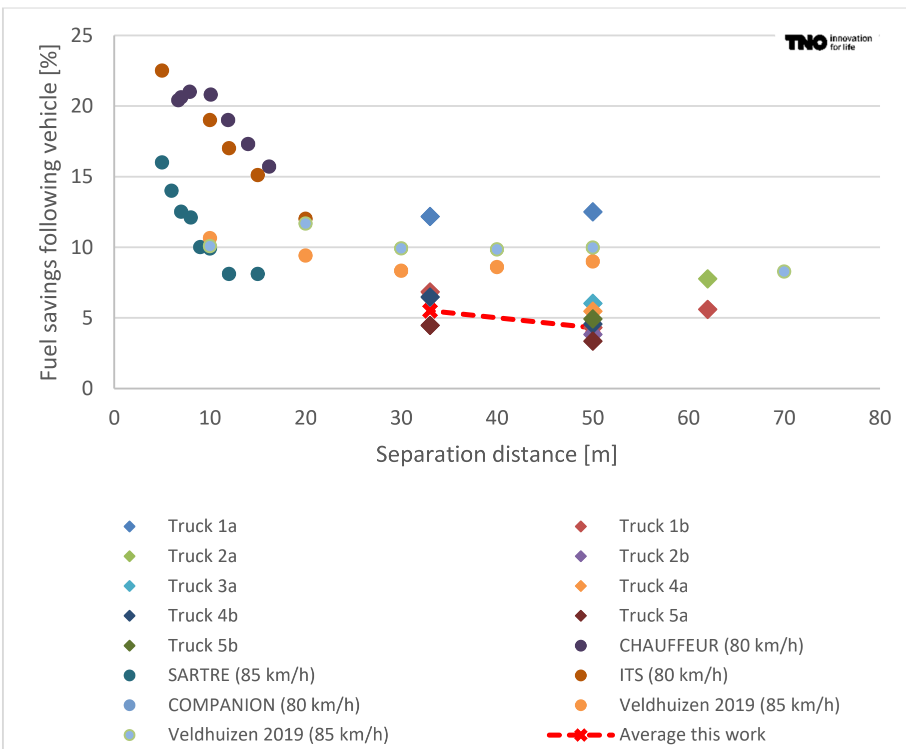

Figure 2: Fuel savings achieved during the real-world monitoring in this project, as compared to other platooning results obtained from literature: (Veldhuizen, Van Raemdonck, & van der Krieke, 2019).

High acceptance and trust of drivers in ACC systems

Based on the gathered data (regular surveys and informal conversations), it be can concluded that acceptance and trust in the ACC system is high. The most commonly used ACC setting was ACC setting 3 (+/- 50 m. gap distance at 80 km/h), also when the drivers had not received any driving instructions. Furthermore, drivers reported effort for each trip they made. Over time, no significant differences among the various driving campaigns were found. However, during the conversations drivers indicated that they experienced driving without ACC as unpleasant.

Logistics integration: transporters consider on the fly 'multi-fleet' convoys or platoons as most realistic future scenario

During two driving campaigns in total 41 (two-truck) convoys were formed (single and multi-fleet), driving approximately 5,177 kilometres. Less convoys than aimed for were formed due to challenges with respect to synchronizing planning of two vehicles (due to time pressure in the supply chain, the available transport volume on the same corridor or a combination of these). With respect to the logistics business case - at this point of the developments of more automated driving systems - the fuel savings allow for limited waiting times to form planned convoys. Transporters consider 'multi-fleet convoys or platoons as the most realistic future scenario. An important precondition is that trucks are equipped with the needed technology by default so that matching can take place 'on the fly' rather than planned or scheduled.

Outlook: truck platooning shifting focus from private monetary business model potential towards driving societal safety and sustainability benefits

In the past years fuel savings were expected to contribute to a large share of the savings potential of truck platooning, which in its own right was considered a potential monetary business model for road transport operators. While there are fuel savings reported in this study (4-6%), based on insights from recent studies and the findings in this work we deem the likelihood of truck platooning turning out to be a feasible financial business model to be limited if the business case stems from fuel savings alone, as the majority of fuel savings is already captured with current systems such as the ACC systems tested in this study.

Van Ark et al. (2017) report in the value case of truck platooning other elements that lead to positive value, more centred at the societal level (e.g., safety, reduced CO_2 emissions, traffic flow improvements). Once we consider ACC driving – and ADAS systems in general – as a step towards further automating the driver task and reducing human error, the increased use of ACC and ADAS systems may improve safety and therefore create positive societal value. More and more, ACC, C-ACC Truck Platooning and ADAS systems in general may therefore be considered as drivers of societal value in creating more safety and sustainability in road transport, bringing progress for the Vision Zero on road casualties[1] and Zero-Emissions[2] as target from Paris Climate Agreement. Further research is required to assess the order of magnitude of these effects of these advances in technology.

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[1] Reduce road deaths to almost zero by 2050 (European Commission, 2021)

[2] The EU aims be climate-neutral (net-zero greenhouse gas emissions) by 2050 (European Commission, sd)

Contents

1 Introduction

This first chapter introduces the project, the main motivation of the project and scopes the main research questions.

1.1 Background of the project

Digitization and automation are developing fast road transport. Technological advancement is driving the level of automation and autonomy of vehicles, moving from driver-assisted technologies (Advanced Driver Assistance Systems, ADAS) to autonomous transport systems where driving tasks are taken over from the human driver by an automated driving system (ADS).
Part of the interest is within the commercial vehicles industry on the topic of Truck Platooning. A widely accepted definition of Truck Platooning is still lacking, but truck platooning typically refers to heavy-duty trucks driving in convoy formation at motorway-oriented design domains with short time gaps between them (typically around 1.0 seconds at 80 km/h), made possible by cooperative automated driving systems providing at least longitudinal and possibly also lateral control. The level of automation considered for truck platooning ranges from driver-assisted truck platooning (SAE Level 1 for longitudinal control) to highly automated truck platooning (SAE Level 4), for which the latter might entail unmanned following vehicles (SAE, 2018).

Truck platooning is typically thought to have the potential to reduce fuel consumption and may also bring many societal benefits such as improved traffic safety, more efficient use of the road infrastructure and increased traffic flow (Van Ark, et al., 2017). The spike in interest in truck platooning coincides with various high-profile events that took place such as the European Truck Platooning Challenge in 2016, which was the first large public road trial of truck platooning functionality across Europe (Dicke-Ogenia et al., 2020). Subsequently, projects around truck platooning surfaced in various European countries to demonstrate the technical feasibility and assess the impact of truck platooning such as the HelmUK project, Sweden4Platooning, and the MAN EDDI project with many more low-profile projects taking place too.

Figure 3: European Truck Platooning Challenge 2016.

1.2 Motivation for this project

Previous projects were typically focused on demonstrating the physical aspects and technical feasibility of truck platooning. However, **limited attention has been paid to quantifying the impacts of truck platooning in real-world conditions and comparing the potential of truck platooning against the usage of current generation ADAS systems, in particular Adaptive Cruise Control (ACC)**. Especially ACC, being a longitudinal control technology, can be considered a precursor to future Cooperative-ACC (C-ACC) Truck Platooning and Highly Automated Truck Platooning technologies, and therefore it is interesting to investigate its use in everyday road transport operations to establish a baseline to compare future truck platooning systems to.

Therefore, in this study, we investigate the application of current generation ACC systems in everyday transport operations to establish a baseline to compare against a future extensive field trial of truck platooning in the Netherlands. We do so by assessing impacts on fuel consumption, driver behaviour and logistics from usage of ACC systems, driving both in solo and convoy formation in everyday traffic and integrated in logistical operations. The study as such supports the preparation for deployment of truck platooning in the Netherlands.

1.3 Project stages

The research is conducted in two stages, that jointly make up the *URSA MAJOR neo Truck Platooning* project:

Stage 1: *ACC Truck Trials* *[this report]*
Driving trucks – in solo and convoy formation – equipped with Adaptive Cruise Control (ACC), executed in 2019/2020.
Internal project reference: Integrator Connected Truck Trials

Stage 2: C-ACC *Truck Platooning Trial*
Driving trucks – in solo and convoy formation – equipped with Cooperative-Adaptive Cruise Control (C-ACC), to be executed in 2021
Internal project reference: Ursa Major neo Truck Platooning Trial

This report provides the results of Stage 1 of the research, the ACC Truck Trials: the baseline of truck driving (solo and in convoy formation) with Adaptive Cruise Control. During Stage 1, multiple conditions are investigated during which data is collected on a second-by-second basis, under varying experimental conditions such as application of driver-assistive technology, driving in solo and convoy configurations, etc. In the first stage, ACC is used and monitored to evaluate real-world effects of ACC driving, which provides a baseline scenario for the C-ACC truck platooning trials in the second stage.

1.4 Partners and roles

Figure 4 shows the project partners for both stages of the URSA MAJOR neo truck platooning project.

The Stage 1 ACC-subproject is executed by TNO (coordinator) and 7 logistics service providers: De Rijke Transport, DHL Global Forwarding, Getru Bedrijven, GVT Group of Logistics, Overbeek Int. Transport, Starmans Transporten, and Koninklijke Van der Slot Transport. TNO executes the research, based on data acquired in the transport operations of the 7 transport firms. The transport firms – active in either the container or the flower transport sector – provide (ACC-equipped) vehicles, trailers, drivers and operational data to the project. Across the seven transport firms in total 9 ACC-capable vehicles were outfitted with measurement equipment and 11 professional truck drivers participated in the project. Stage 1 is sponsored by NWO, the Dutch Science Organisation and TKI Dinalog, the Dutch Institute for Advanced Logistics.

The Stage 2 C-ACC subproject is currently in progress. In this C- subproject 3 C-ACC capable trucks are outfitted with measurement equipment. TNO is lead contractor and executor of Stage 2. Rijkswaterstaat, the Dutch Road Authority is the main sponsor of Stage 2. The second stage of the project is supported either directly or indirectly by the Netherlands vehicle approval authority RDW, DAF Trucks, and the Port of Rotterdam Authority. Results of Stage 2 will become available at the end of 2021.

Figure 4: URSA MAJOR neo project partners for both sub projects.

1.5 Reading guide

This report describes the results of the ACC Truck Trials: the baseline of truck driving (solo and in convoy formation) with Adaptive Cruise Control – measuring the impacts on fuel consumption and emissions, human interaction and logistics integration. Chapter **2** describes the research questions, overall methodology and data collection. In the subsequent three chapters we describe the impact domains in more detail by a concise literature overview, methodology specifics and the results; Chapter **3** Fuel consumption and emissions, Chapter **4** Human Interaction and Chapter **5** Logistics integration and business case. We conclude in Chapter **6** with conclusions and an outlook.

2 Research Questions, Methodology, Data Collection

In this chapter, we introduce the main research questions, the research design and methodology, and the data collection and vehicle instrumentation and data processing strategies. Also, we provide information on the human-research approach and post-hoc adjustment of data collection and analysis procedures.

2.1 Overarching research questions

We aim to evaluate the real-world impacts of ACC driving and C-ACC truck platooning. As ACC functionality is these days readily available on many commercial vehicles, we consider it a fair baseline situation to compare it to a future state of truck platooning, for which the first implementation is Cooperative-Adaptive Cruise Control (C-ACC).

Following the line of Van Ark et al. (2017) in the value case of truck platooning, the main research questions are formulated around three themes:
fuel consumption, human interaction and logistics business case.

RQ 1 What is the impact of ACC truck driving – both solo and convoy – on fuel consumption and CO_2 emissions?
RQ 2 What is the impact of ACC truck driving – both solo and convoy – on professional truck drivers?
RQ 3 What is the impact of ACC truck driving – both solo and convoy – on logistics integration and business case?

Each of the research themes is elaborated in the following chapters. For clarity and brevity, literature reviews of the three topics are included in the results-chapters of this report. We introduce the research themes in a little bit more detail with sub research questions next.

2.1.1 *Fuel consumption and CO_2 emissions*

We examine the impact of current ACC systems on fuel consumption and CO_2 emissions. Many claims have been made about the possible reduction in fuel consumption and CO_2 emissions when driving in truck platoon formation at short gap distances between the vehicles. With regard to following distances of less than 10 meters, a fuel consumption reduction of up to 16% has been reported (Van Ark et al., 2017),[3] however, current generation ACC systems only allow for a minimum following interval of 1.4 seconds, which corresponds to 31 m at 80 km/h. We are, therefore, interested in usage of ACC and the impact it has on fuel consumption and CO_2 emissions. Specifically, we aim to investigate what the effects are of using various ACC modes/settings, and whether the truck drives in convoy formation. These research questions are addressed monitoring multiple trucks during real-world driving.

[3] For an extensive discussion of available fuel savings figures at the start of 2019 see also Veldhuizen et al, 2019.

This results in the following sub questions:

- RQ 1.1 What is the impact of using ACC (or not) on fuel consumption and CO_2 emissions?
- RQ 1.2 What is the impact of using different ACC modes and settings on fuel consumption and CO_2 emissions?
- RQ 1.3 What is the impact of trucks driving in convoys on fuel consumption and CO_2 emissions?

2.1.2 *Human interaction*

Truck platooning is thought to reduce the workload of the driver, especially at higher levels of automation (De Winter et al., 2014). Even ACC is shown to reduce workload for drivers. However, our understanding of the impact of current generation ADAS systems such ACC in real-world driving is limited. Therefore, we investigate the interaction between truck drivers and ACC driving. This interaction is investigated as part of a Naturalistic Driving Study approach, in which the truck drivers are observed while driving in their natural environment, that is by being on their daily job driving the heavy-duty trucks. We examine the impact of ACC on professional truck drivers dependent on the mode of ACC employed (if it is employed) and whether the truck drives in convoy.

The following sub questions are formulated:

- RQ 2.1 How is ACC used and under what circumstances?
- RQ 2.2 What is the impact of using (or not using) ACC on the behaviour of professional truck drivers?
- RQ 2.3 What is the impact of using different ACC modes and settings on the behaviour of professional truck drivers?
- RQ 2.4 How do professional truck drivers experience the use (or non-use) of different ACC modes?
- RQ 2.5 What is the impact of trucks driving in convoys (or not) on the behaviour of professional truck drivers?
- RQ 2.6 How do professional truck drivers experience convoy (or non-convoy) driving?

By answering these questions we assess whether the mental and physiological condition of the truck drivers differs from a baseline scenario when ADAS systems are not being used and/or available. The confidence (trust and acceptance) of drivers in systems and technologies and the possible influence on driver behaviour is also considered.

2.1.3 *Logistics integration and business case*

Logistics parties across the supply chain network need a viable logistics business case if they are to successfully scale up deployment of truck platooning. Van Ark et al. (2017) show that positive business cases are possible under the right circumstances. Verifying these scenarios by real-world experimentation and testing is the next step. Once it can be proven with real-world data that the business case is positive, a step can be made towards deployment of truck platooning. Which is especially interesting since major commercial truck manufacturer Daimler Trucks has recently cancelled their future investments in platooning technology, citing unfeasible business cases (from disappointing real-world fuel savings) as main reason for doing so (Lopez, 2019).

In order to assess the impact of ACC driving on logistical integration and business case, the following sub questions are formulated:

- RQ 3.1 What are the requirements for the operational processes for preparation, formation and arrival at final destinations of truck convoys?
- RQ 3.2 What are the potential cost savings of ACC driving based on fuel consumption and CO_2 emissions (RQ1) and impact on the professional truck drivers (RQ2)?
- RQ 3.3 What are potential measures to improve the logistics business case?
- RQ 3.4 What are boundary conditions for implementation of ACC convoy driving (and truck platooning)?

Note that in this stage we are not researching truck platoons, but develop a baseline by assessing the impacts of (ACC-based) solo and convoy driving. Though, by researching sub question 3.4, we aim to give an indication or an outlook for the implementation of truck platooning.

2.2 High-level overview of the methodology: hybrid field operational test and naturalistic driving study

The main aim of this project is to research the real-world effects and impacts of using Adaptive Cruise Control, as an Advanced Driver Assistance System, on fuel consumption and emissions, driver behaviour, and logistics integration and business case.

Especially the focus on ‘real world impacts’ gives some requirements to the type of data collection necessary for the research. Most importantly, we envisaged to collect data from drivers and vehicles which were active in their normal daily logistical operations in everyday driving situations. We were particularly interested in observing how drivers would use the ACC systems in their trucks while driving, when they were turning the systems on or off, the amount of time they used the system, et cetera. This requires an approach based on observations and together with the focus on everyday driving situations yields a Naturalistic Driving Study (NDS) approach (Bärgman, 2015).

However, the NDS approach is strictly observational in nature. Given the nature of the research questions, we have some experimental requirements as we are interested in investigating how drivers would respond to certain treatments, for instance a request to use the ACC system as much as possible, or alternatively to not use the ACC at all for a while. Therefore, we also required an experimental methodology that allowed baseline/treatment conditions to be included, which is typical for a Field Operational Test. Figure 5 lists some differences between the FOT and NDS approaches.

Therefore, the study has been setup as a hybrid between a Field Operational Test (FOT) and a Naturalistic Driving Study (NDS), sometimes referred to as Naturalistic Field Operational Test (NFOT) (Bärgman, 2015).

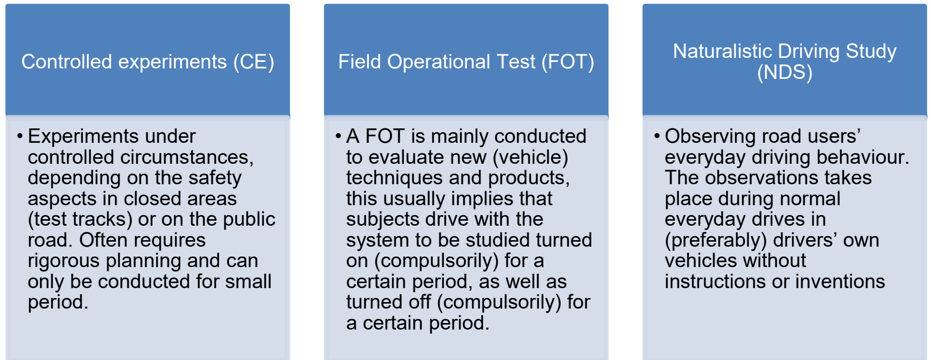

Figure 5: A hybrid field operational test and naturalistic driving study: the naturalistic field operational test (NFOT).

For the Naturalistic Field Operational Test, we sought the participation of various transport companies. The transport companies supplied multiple heavy-duty vehicles to the project which were instrumented with logging equipment and data collection tools such as CAN loggers, an emission measurement system and cameras. Also, drivers were invited to participate in the study. The drivers were added to an experimental scheme of baseline-treatment conditions, which we referred to as driving campaigns. Across the treatments, we requested the participating drivers, for instance, to enable or disable the ACC and drive with various ACC settings. Additionally, drivers were invited to fill in various surveys, both long and short, and heart-rate data was collected using a wristband device.

Overall, the 9 vehicles and 11 drivers were monitored (observed) for a total of 25 weeks, with 15 weeks having some sort of treatment and with the other 10 weeks being naturalistic driving-oriented. Subsequently, data was analysed and reported.

2.3 Research approach and methodology

The overall research methodology is summarized in Figure 6. It starts with instrumentation of the trucks. This is followed by an iterative cycle of driver involvement, driving campaigns as core of the measurement condition and data analysis. Once all driving campaigns (conditions) are finished, the analyses of the different driving campaigns can be compared and conclusions are drawn.

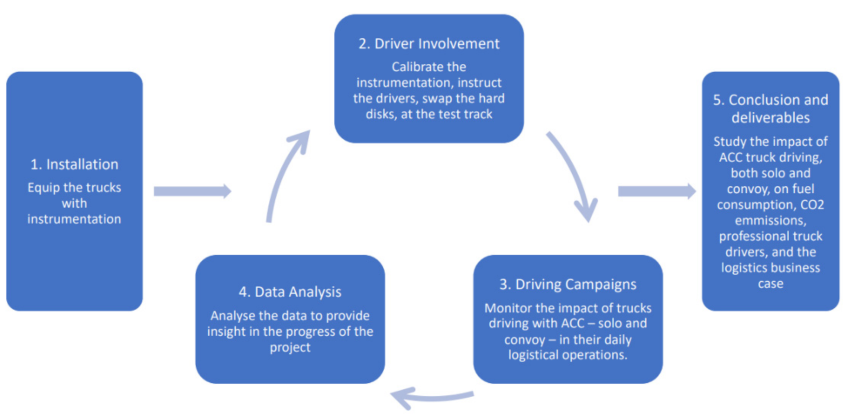

Figure 6: Research methodology.

2.4 Vehicle instrumentation

In order to answer the research questions as specified in Chapter 2, the trucks of the transporters are instrumented with specific sensors and equipment. This paragraph provides an overview of the vehicles and tools used in order to collect the required data. First, we give a description of the instrumented vehicle. Subsequently, details on assessing fuel consumption and CO_2 emissions, monitoring professional truck drivers, and the logistics business case are provided.

2.4.1 Vehicles in the trial

Within this project, the transport companies have supplied their vehicles to be used in the project. These days, all trucks from the DAF brand are outfitted with Adaptive Cruise Control as standard, which of course was an important feature for the vehicles to be considered. Also, to reduce complexity – for instance when capturing CAN data - we have ensured all vehicles were DAF Trucks.
All nine DAF trucks in the trial were either of the XF or CF model line and from model year 2015 or newer, equipped with Euro VI engines (VI-a, VI-b and VI-c) and rated powers between 320 kW and 350 kW. Data collection was started at ignition-on and data was being uploaded at ignition-off to a secured TNO database environment.

Figure 7: One of the DAF XF trucks participating in the project.

2.4.2 Background on Adaptive Cruise Control[4]

This section provides some background on the Adaptive Cruise Control (ACC) present in the instrumented DAF vehicles participating in the project.

Adaptive Cruise Control is an extension of Cruise Control. Cruise Control keeps the vehicle speed constant. This supports the driver in case of less dense traffic. However, in more dense traffic, the driver has to constantly adapt its vehicle speed to the surrounding traffic. Adaptive Cruise Control copes with this disadvantage of Cruise Control by adapting the speed of the vehicle to the traffic in front of the vehicle.

A radar sensor behind the grill detects front objects of the vehicle and checks their relative speed and distance. Three radar beams in combination with an integrated yaw rate sensor enable the system to distinguish between vehicles on the same lane and vehicles on other lanes.

[4] Information retrieved from DAF brochure on Adaptive Cruise Control.

The driver sets a desired driving speed and tracking distance to the vehicles in front of its own vehicle. In order to maintain the set distance, the vehicle speed is adapted by active intervention of ACC in the vehicle systems: gas control, engine brake, automatic gear switching, and secondary retarder. If a slower moving predecessor (that is, a vehicle with lower velocity) is detected, ACC maintains a safe distance by braking the vehicle. If the lane is clear again in front of the vehicle, it will accelerate until the set speed has been reached.

The ACC in the DAF vehicles has 5 settings that a driver can select, using buttons on the steering wheel (Figure 8): setting 1 provides the shortest gap distance whereas setting 5 is the longest distance to a predecessor. Table 1 displays the gap time and gap distances for the different ACC settings.

Figure 8: ACC setting 1 selected in the instrument cluster of a DAF vehicle.

Table 1: DAF ACC modes: Following time and distances.

Distance setting	**Following time (speed < 80 km/h)**	**Distance (speed ≥ 80 km/h)**
1	1,4 s	33 m
2	1,8 s	40 m
3	2,4 s	50 m
4	3,0 s	62 m
5	3,6 s	75 m

The ACC is automatically enabled on engine start and it automatically set at setting 3. At freeflow speed of 80 km/h, this results in a following distance of approximately 50 meters, which is the current (legally mandated) minimal gap distance in in various European countries such as Germany. After ignition-off, the ACC resets to setting 3 even if the driver finished their trip on another distance/time setting.

Finally, the ACC system works in various modes ‘under-the-hood’:

- **Distance**: vehicle detected in front of the truck, following other vehicle;
- **Speed**: traditional cruise control;
- **Finish**: transition from vehicle following (Distance) to normal cruise control (Speed);
- **Hold**: system maintains last speed when following another vehicle which is no longer present;
- **Overtake**: user accelerates with ACC engaged (user overrides system);
- **Disabled**: ACC system is in error mode, is not available, cannot be engaged;
- **Off**: system turned off.

2.4.3 *Schematic of the vehicle instrumentation*

Figure 9 shows a schematic representation of an instrumented vehicle and the tools used to answer the research questions. The instrumentation follows from the research questions from the beginning of this chapter.

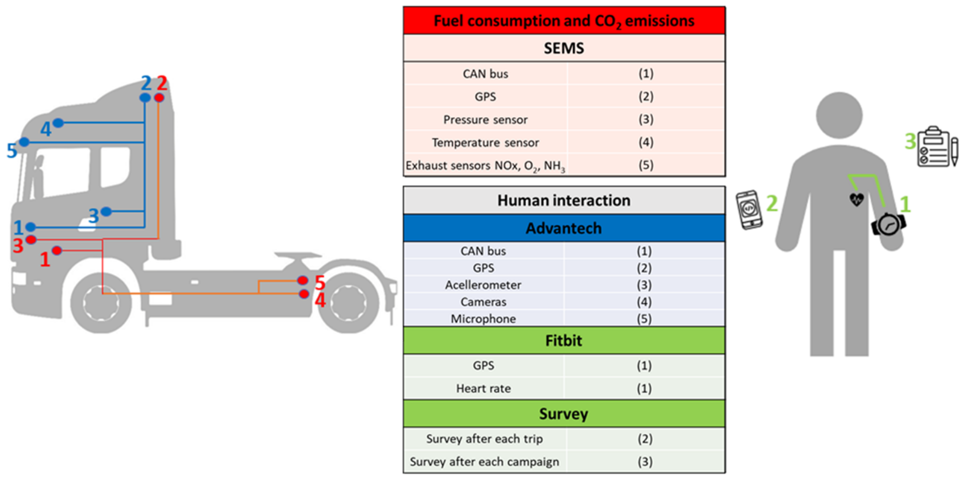

Figure 9: Schematic representation of an instrumented vehicle and the tools used to answer the questions associated with the professional truck driver.

Due to commitments of the participating transport companies and budgetary constraints, it was not possible to equip all vehicles with the complete sensor set, which is why it was decided to define three different 'configurations' (see Figure 10). In total 10 trucks were instrumented, with 1 truck not completing the trial and therefore its data has been discarded.

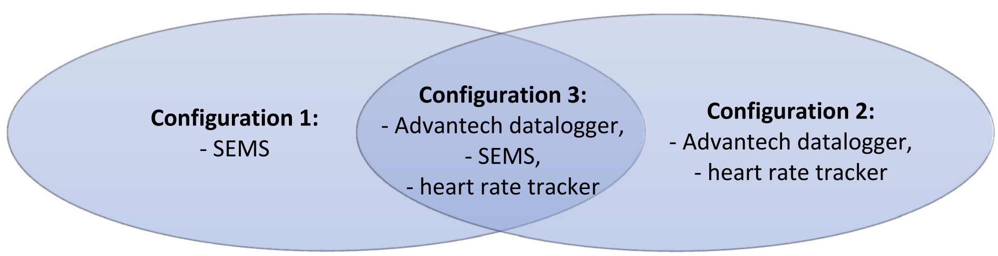

Figure 10: Instrumentation configurations.

2.4.4 *Logistics business case*

For establishing the logistics business case, there is no need to equip trucks with additional sensors as already described above. However for answering the research questions there is an additional data need that is summarized in Table 2. This research question builds further on the outcomes of the fuel consumption and human interaction research questions and as such requires input from the transporters on the monetary value of the impacts.

Table 2: Logistics business case: Research aim, Data type and source.

Research aim	Data type	Data source
Determine how the process of convoy preparation looks like	Information on planning procedure, boundary conditions, agreements made with final receiver.	Semi-structured interviews with planners and management.
Determine when convoys are planned	Overview of planned convoys	Excel-template to be filled in by planners.
Determine when convoy formation took place.	Information on realized convoys. Create insight in waiting times.	Survey after each trip (drivers). See section **4.3.4**, **Figure 24**.
Determine how convoy formation took place.	Information on how formation was established. Create insight in waiting times.	Semi-structured interviews with drivers.
Determine how arrival at final destinations took place.	Information on whether both trucks of the convoy were handled at the same time at final destination. Create insight in waiting times.	Semi-structured interviews with drivers
Determine the monetary value of fuel consumption increase/decrease as a result of convoy driving	€/ Litre	Management of transporters
Determine the potential corridors where convoys will be formed	Corridors and related kilometres that can be driven in convoy	Management of transporters
Determine the monetary value of workload increase/ decrease as a result of convoy driving	€/ hour	Management of transporters
Determine the monetary value of waiting time	€/hour	Management of transporters
Determine factors that can be modified for improving the business case	Views on possible relevant factors of the business case that can be changed/ influenced.	Semi-structured interviews with management of transporters
Determine boundary conditions for implementation of ACC convoy driving.	Views on opportunities and barriers for implementation of ACC convoy driving.	Semi-structured interviews and/ or focus groups with planners, truck drivers and management of transporters

2.5 Driver involvement

Driver involvement was very important for this project. Since the experiments were going to last over quite some time and we required to monitor the drivers quite extensively, quite some effort was given in involving the drivers properly.
Most importantly, all drivers were invited to participate in a Driver Experience Day at a test track facility (Figure 11).

Figure 11: Photo of drivers and research staff during the Driver Experience Day to aid driver involvement.

During the Driver Experience Day, the drivers received an extensive explanation of the project, its aims and ambitions and their role as drivers. The experience day was split in three parts: the first part was used to give presentations about the project itself, safety instructions, privacy considerations, and data processing. The second part of the data was devoted to doing test track trials. The aim here was twofold: (1) familiarizing the drivers with the different experimental driving conditions and (2) calibrating the instrumentation and systems. Every test track trial was modelled as a sample of the driving campaigns, so the drivers could gain acquainted with the various ACC settings and on-board measurement devices.

Finally, the third part of the day was to ensure enough moments throughout the day to get to know each other and to answer questions. During the day, the drivers were also invited to sign voluntary participation documents (full consent participation), which they received prior to the test track day.

After this driver experience day, driver involvement was insured by the use of a buddy system. A buddy – a staff member of the research organisation - was assigned to each truck driver. At the end of each week during the driving campaigns, the buddy would call the driver to see how the driver feels about the project and whether there were any particularities that he wants to share. As such, it is ensured that that they can raise their opinion and share their concerns if needed.

2.6 Experimental conditions: driving campaigns for baseline and treatment conditions

The driving campaigns are the core of the data collection periods to gather experimental data. Table 7 provides an overview of the experimental conditions and their order. Typically, the duration of the conditions was approximately two full week per condition, with 15 weeks of experimental conditions in total.
Before the start of A1 and after finishing A3, drivers were driving without any instruction or condition, therefore considered as naturalistic driving.

Table 3: Driving campaigns and characteristics.

Label	Solo/ Convoy driving	ACC	Duration (weeks)
A1	Solo	ACC mode as a driver would normally use it ('naturalistic driving').	3
A2	Solo	ACC switched off as much as possible	2
A3 Post	Solo	ACC mode as a driver would normally use it ('naturalistic driving').	2
B1	Solo	ACC setting 3	2
B2	Solo	ACC setting 1	2
C1	Convoy	ACC setting 3	2
C2	Convoy	ACC setting 1	2

The first driving campaign A1 started with a warming up period of naturalistic driving, such that the truck drivers could get used to the installed equipment present in their vehicles. Also, the drivers did not receive any instruction in this condition, for the researchers to be able to gather naturalistic driving.

After A1, starting with condition A2 the drivers would receive an instruction – an experimental condition or treatment – to change something. Before the start of each new campaign (condition), the drivers were instructed about the upcoming campaign. It is always emphasized that safety comes first.
In A2, the condition and instruction was to switch off the ACC as much as possible.

For driving campaigns A1, B1 and B2, the label ‘solo’ might be somewhat confusing as when ACC is switched on, the truck keeps a fixed distance to its predecessor and one might consider this a convoy. However, in these campaigns, the leading trucks are random trucks on the road and are not planned as opposed to driving campaigns C1 and C2. For driving campaigns C1 and C2 that involve convoy driving, the planners of the transport companies are instructed to plan the equipped trucks in such a way that they can form a convoy together (scheduled convoy driving). This driving campaign is established to learn how scheduled platooning, that is, planning platoons before the start of the trip could look like.

2.7 Monitoring and maintenance during driving campaigns

During the driving campaigns, it was important to monitor whether the sensors were still active and collecting the required data. Therefore, regular checks were carried out by the team. In case adjustments had to be made, action was taken. Actions could include amongst others: repositioning the cameras or reminding the drivers to fill in the ‘after trip survey’. In the first week of the driving campaigns all data sources were checked on a daily basis.

After that the monitoring schedule was the following:
- Fuel Consumption and Emissions: weekly;
- Human Interaction – Cameras and Advantech: weekly;
- Human Interaction – Fitbit and Survey: daily.

One of the issues that was checked was the free capacity of the hard disks of the Advantech logger (Human Interaction). As video data required a lot of hard drive space, it was expected that the two TB disks needed to be changed at the end of every campaign. The buddies were in charge of the monitoring and maintenance duties. This had the positive effect of both building up a good relation between driver and buddy, and the ability to quickly solve any problems.

2.8 Data pre-processing

In this section we discuss how we transform our raw data to data that is suitable for analysis. We start with the analysis of fuel consumption and CO_2 emissions. Subsequently, we focus on the human interaction part of the research, and we end with the analysis of the logistics business case.

2.8.1 Fuel consumption and CO_2 emissions

To answer our research questions related to fuel consumption and CO_2 emissions we divide our analysis in two parts. In the first analysis we look at the impact of different settings of ACC. In the second analysis we look at the impact of drafting. In Table 4 we describe the different data sources we need in order to calculate the impact for that specific subtopic.

Table 4: Data sources needed for the specific subtopics related to fuel consumption and CO_2 emissions.

Subtopic	Data source
Fuel consumption and CO_2 emissions dependent on ACC mode	CAN bus data (fuel rate, ACC mode, ACC setting, ACC set speed) Sensor data (exhaust mass flow rate)
Fuel consumption and CO_2 emissions dependent on drafting	CAN bus data (fuel rate, distance to leading vehicle, speed of leading vehicle) Pressure sensor data from two sensors (one placed on the front, and one on the underside, of the truck) Sensor data (exhaust mass flow rate)

In order to determine the relative impact of different modes of ACC we compare different driving scenarios. Care must be taken to ensure that the driving conditions are similar during real-world driving. For example, urban driving fuel consumption should not be directly compared to motorway driving. We narrow the scope of our research questions to include only the situations where the velocity of the vehicle is higher than 75 km/h. This should be the case for the bulk of normal use.

Via our SEMS device we gather our different data sources. The SEMS device is synchronized via a 4G connection such that the data is send to our SEMS database in real time. The database is hosted by an external party called Linqhost. This is depicted in Figure 12.

The raw CAN bus data for the ACC signals is converted from binary code to the corresponding assignment using the J1939 Digital Annex . We note that although in J1939DA ACC Distance mode #1 is defined as the largest distance, in the vehicles examined here ACC mode 1 is the shortest distance. The state of operation by the ACC device is also recorded. Where available, the CO_2 mass flow rate is used to calculate the fuel consumption in L/100km, otherwise the fuel rate signal from the CAN bus data is used.

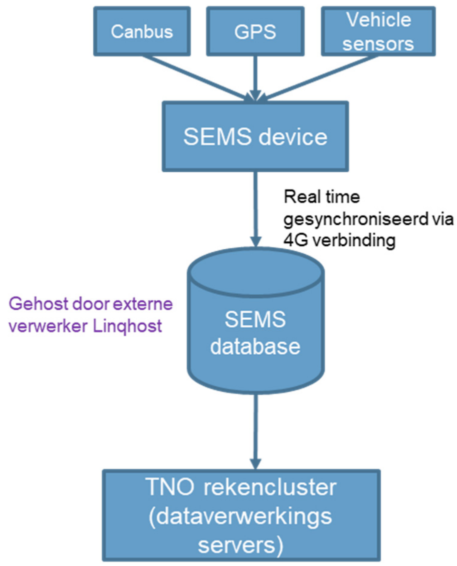

Figure 12: Data gathering and processing in order to answer the fuel consumption and CO_2 emissions related research questions.

2.8.2 *Human interaction*

All sensors (cameras, microphone) that are needed to record the required data are connected to the Advantech logger. Human behaviour data (heart rate, perceptions) is collected via the heart rate tracker and the surveys. This data is connected to the 'truck' data based on GPS and timestamp. This is all done within the confidential TNO environment. The overview is given in Figure 13.

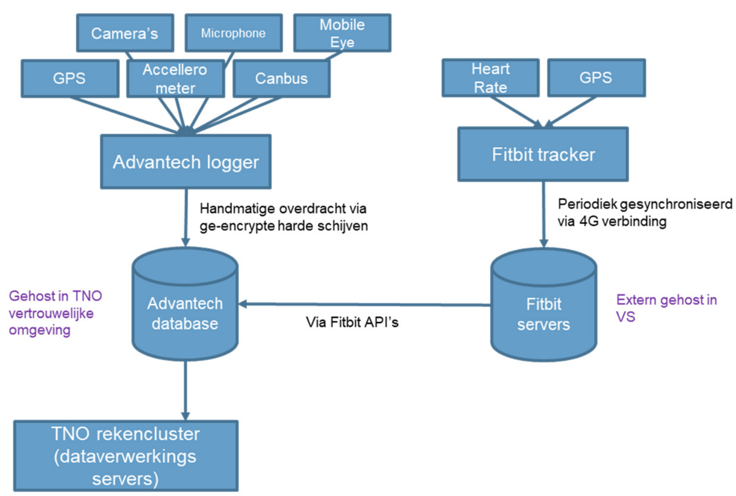

Figure 13: Data gathering and processing in order to answer the human interaction related research questions.

For the data analysis an event-based method is adopted. So not all video material will be analysed, only the events of significance will be taken into account.

This implies that video data are only consulted in case (a combination of) one of the following events is observed (see Table 5).

Table 5: Observed events that demand manual action.

Observed event	Data source
Hard braking (i.e. deceleration)	CAN-bus data
Special remarks by driver	Survey after trip/survey after driving campaign/personal communication

The first part of the human interaction analysis, is verifying if the obtained data are valid. The CAN data are used to detect differences between campaigns, for example in driving speed. Events that are detected in the CAN data will be verified with the collected video data. Besides linking the CAN data to different data, the CAN data itself is analysed (for example ACC settings, distance settings and speed).

It is very important that careful attention is given to potential outliers. If a potential outlier is detected it should be validated with video data, heart rate data, or the driver himself.

Survey data that are collected are used to detect trends as a result of adaptation of the technology. Survey data are used to determine if there is a difference between campaigns. The answers that the truck drivers provide in the surveys are also linked to the CAN data and heart rate data. When outliers are detected in the filled-in effort survey, the video data are checked for explanations.

2.8.3 Logistics business case

To answer our research questions related to the logistics business case, the analysis is split into three parts. The first two parts are summarized in Figure 14. First of all, based on the interviews with the planners and transport management, we determine whether there is extra effort and time involved in preparing and planning the ACC convoys. Also we analyse the data that is gathered through the survey after each trip on waiting time. We triangulate these outcomes with the driver interviews. Subsequently, based on information given by transport management, we link this to a monetary value.

The second part in our analysis is determining the improvement potential of the business case. We do so by calculating the unexploited potential of kilometres driven in ACC-convoy. First, we determine the potential corridors where convoys can be formed based on the interviews with transport managers. Subsequently, from the fuel consumption analysis we derive the kilometres that could have been driven in ACC-convoy (i.e. km's that ACC was switched of, while at the same time a vehicle in front drives within ACC-convoying distance). Lastly, the planned and the realized convoys will be compared. Based on these three inputs the Business Case improvement potential will be set up.

The third and final part consists of synthesizing the results from the interviews with planners, drivers and transport managers. In this part, we come up with general boundary conditions and requirements for (operational) processes for the implementation of ACC-convoy driving.

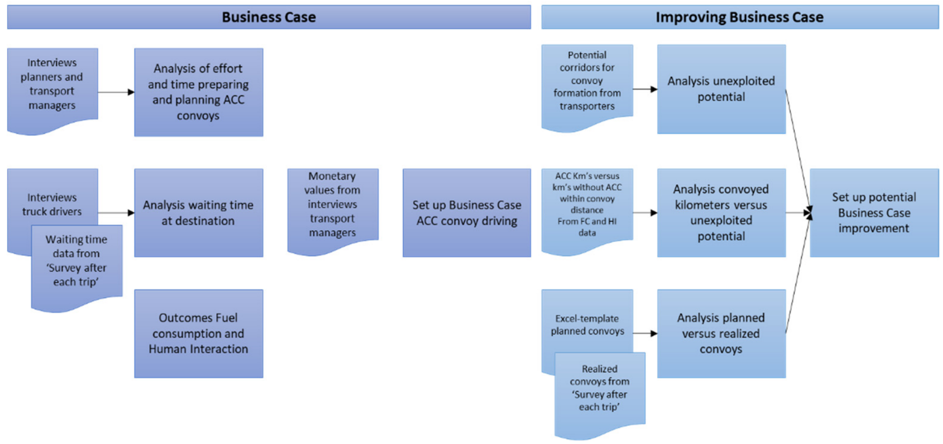

Figure 14: Analysis steps Business Case and Improving Business Case.

2.9 Human-related research

In this project, personal data is collected included special category data (see Table 6). In order to comply with General Data Protection Regulation (GDPR), TNO policy requires a positive advice from the (internal) Institutional Review Board on human-related research.

For this project we were required to provide the following documents:

- **Research proposal** – a summary of how the research will be carried out, including the purpose of the research, how and which measurements are performed, and what (personal) data is collected.
- **Quick scan Data Protection Impact Assessment (DPIA)** – a quick scan is performed in order to assess whether the project is obliged to perform a full DPIA. It resulted from this quick scan that this project is required to do so, because location data is processed, flexible camera surveillance is used and personal data in which the behavior of natural persons is systematically monitored.
- **Data Protection Impact Assessment (DPIA)** – includes, amongst others, the potential risks and ethical obligations to the data used in this project and the measures taken to mitigate these.
- **Data Management Plan (DMP)** – aims to clearly record the agreements concerning the safe and confidential handling of information within the project.

Furthermore, this project was required to get full consent of the participants. The participating truck drivers were informed by providing them with understandable information about the purpose of the research, why their data is used, how their data is collected, and how their privacy is protected.

Participant-information documents were drafted that include information for the participants on what is expected from them, what participating in this project entails, and the rights they have as a participant. If thereafter the truck drivers agree to participate, they signed a participant-agreement.

Table 6: Classification data types.

Sensor	Personal data	Special category
CAN bus	No	No
GPS	**Yes**	No
Accelerometer	No	No
Cameras	**Yes**	No
Microphone	**Yes**	No
Mobile Eye	No	No
Pressure sensor	No	No
Temperature sensor	No	No
Exhaust sensor	No	No
Heart rate tracker (Fitbit)	**Yes**	**Yes**

2.10 Adaptions to the original research set-up

Inherent to the nature of research, some steps did not work out as projected in the planning phase of the research. In this chapter we shortly describe the adjustments we made to our methodology and data collection approach.

2.10.1 Changes to the Instrumentation

In order to log the gap (headway) distances we initially planned to use a Mobile Eye to collect CAN-information on headway distance and lane keeping behaviour. Reality proved to be more challenging and unfortunately it was not feasible to use the Mobile Eye. Instead, we used the CAN bus signals that recorded the headway distance from the radar sensor available in the trucks.

The trucks that were instrumented according to configuration 2 (see Figure 10), were in the end also equipped with offline SEMS systems to record the CAN-data. Hereby we mitigated the fact that retrieving the CAN-data with the Advantech computer was not possible.

Also, we had planned on visiting all professional drivers after each driving campaign. This would have been an ideal moment to swap the hard disks, conduct the extensive surveys in person, and gather some personal feedback. However, finding suitable moments to meet the truck drivers at a convenient location and time turned out to not be that simple. This, in combination with the fact that the hard disks did not need to be replaced yet, made us decide to distribute the surveys via mail and allowing the drivers to fill in the surveys at their own. By this, there was a bit less influence on whether surveys were filled in directly after the campaigns.

2.10.2 Changes to the Analysis

Video data was planned to be analysed by automatic image recognition.
For instance, we envisaged to automatically recognize what the viewing behaviour for the drivers was, the usage of pedals, or other activity in the cabin. However, due to limited resources, time constraints, and technical difficulties, the video database is only used as a basis for validation and not all video data was processed.

Also, in the analysis of the data, the initial plan was to look for safety-critical events (e.g. hard braking movements or overtaking).

However, due to the fact that data was collected in a lower sampling frequency than intended (1 Hz obtained versus 10 Hz planned), limited resources and time constraints, these safety-critical situations were not found in the data. Because these safety critical events were not found, audio signals as recorded with the microphone in the “feet camera” (for capturing beeps from the lane departure warning system), were not automatically detected and therefore not analysed.

The trucks were fitted out with pressure sensors in order to aid the analysis with regards to drafting behind another vehicle. However, it was decided to primarily use the gap (headway) distance as recorded on the CAN bus for this topic.

An investigation regarding the impact of using ACC on the variability of engine speed has not been addressed here, but remains an opportunity for future investigation.

3 Fuel consumption and emissions[5]

3.1 Introduction

We examine the impact of current ACC systems on fuel consumption and CO_2 emissions. Many claims have been made about the possible reduction in fuel consumption and CO_2 emissions when driving in truck platoon formation at short gap distances between the vehicles. With regard to following distances of less than 10 meters, a fuel consumption reduction of up to 16% has been reported (Van Ark et al., 2017),[6] however current generation ACC systems only allow for a minimum following interval of 1.4 seconds, which corresponds to 31 m at 80 km/h. We are, therefore, interested in usage of ACC and the impact it has on fuel consumption and CO_2 emissions. Specifically, we aim to investigate what the effects are of using various ACC modes/settings, and whether the truck drives in convoy formation. These research questions are addressed monitoring multiple trucks during real-world driving.

This results in the following sub questions:

- RQ 1.1 What is the impact of using ACC (or not) on fuel consumption?
- RQ 1.2 What is the impact of using different ACC modes (and settings) on fuel consumption?
- RQ 1.3 What is the impact of trucks driving in convoys on fuel consumption?

3.2 Literature

In this section we provide an overview of the developments with respect to fuel consumption and truck platooning. We do this by highlighting the most important studies and presenting the latest developments in the European ENSEMBLE project.

From an early stage in the development of truck platooning, one of the expected benefits of the technology is reduced fuel consumption. As trucks are driving at a closer gap distance, the aerodynamic drag coefficient of each vehicle decreases depending on its position in the platoon (Tsugawa, 2016). Also, automatic speed control and cooperative vehicle following control can smooth speed variations in traffic, which can save energy and as such reduce fuel consumption and related CO_2 emissions.

Van Ark et al. (2017) summarised the results of various studies on truck platooning and the effect on fuel consumption (PROMOTE, Auburn-Peleton, Japan – Energy ITS, PATH, SARTRE). They report team savings – the average savings of all vehicles in a platoon – up to 16%. These numbers are mainly based on experimental test-track studies such as SARTRE. Van Ark et al. (2017) estimated team fuel savings for several platooning capabilities with varying gap distances (at a speed of 80 km/h): 6% at 1.0 s. or 22m., 8% at 0.6 s. or 13 m. and 10% at 0.3 s. or 6.7 m.

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[5] The analysis reported in this chapter is co-funded by the CATALYST Living Lab

[6] For an extensive discussion of available fuel savings figures at the start of 2019 see also Veldhuizen et al, 2019.

Since the Van Ark et al. (2017) literature summary however, newer insights have been emerging. For example fuel consumption effects of truck platooning at larger gap distances (20-70 m.) were researched (Veldhuizen et al., 2019). Figure 15 summarizes the fuel consumption results of the leading and the following vehicle in a 2-truck platoon in the study of Veldhuizen et al. (2019) relative to earlier studies. For the following vehicle, at the largest distance of 50 m savings of 9.0 ± 2.8% were achieved. Decreasing the distance to 40, 30 and 20 m did not yield any significant savings over a following distance of 50 m. The authors conclude that for the following vehicle at European legal distances (50 m) the savings of platooning are significant, and that the potential for increasing the savings by reducing the separation distance is rather limited.

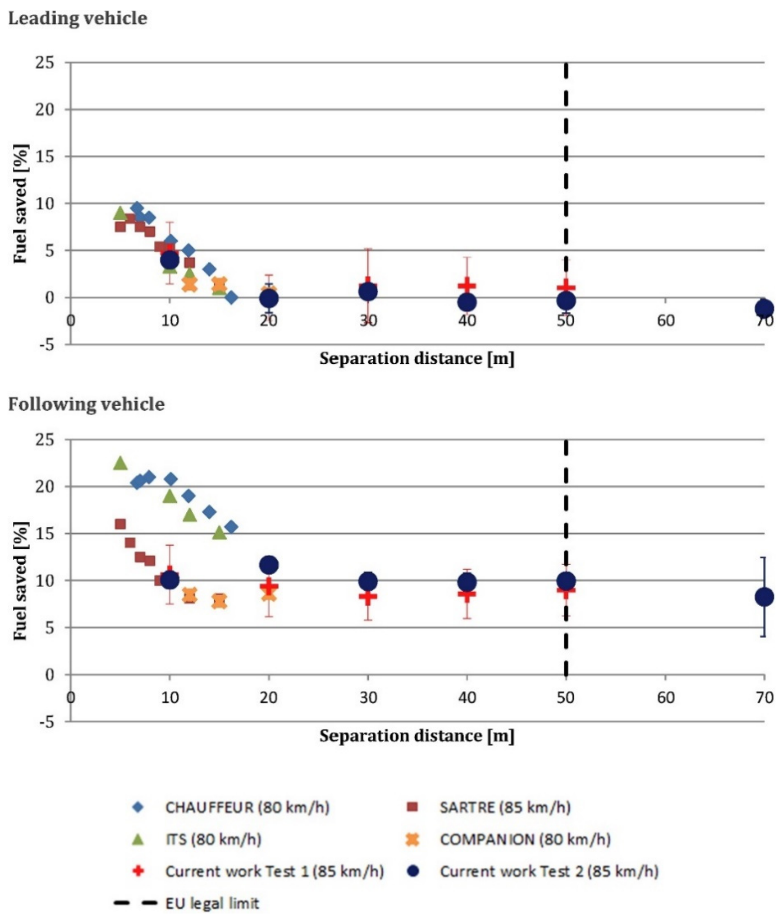


Figure 15: Fuel economy platooning results Veldhuizen et al. (2019) compared to earlier studies (Adapted from: Veldhuizen et al.,2019).

It should be remarked that comparing these studies is challenging, since testing conditions (test track versus real-world), weather conditions, testing protocols (no clear protocol versus SAE J1321 Type II fuel economy protocol) and truck vehicle profiles (EU cab-over versus USA torpedo model) vary across studies (see Table 7). Also, information on conditions such as weight and load of the vehicles were not equally available. Lastly, most studies researched short gap distances, below 20 meters (less than 1.0 second at a speed of 80 km/h).

Table 7: Positioning of this research with respect to previous studies and study conditions.

Project/ Research	Test protocol	Speed (km/h)	Gap distance (m).	Truck platoon	Truck profile	Load	Weather
Auburn – Peleton (2017)	SAE J1321 Type II fuel economy protocol	105	9,12,15, 23,45.	2 truck platoon	Articulat-ed tractor-trailer	30t. / truck-trailer	
CHAUFFEUR/ PROMOTE (2000-2003)	By flow measurem ent (3% reliability)	80	8,10,12,14	2 truck platoon	No wind deflector s on tractors	Lead truck 14.5t.; following truck 28t.	
EDDI (2019)	Real-world	80	15	2 truck platoon		Dummy and actual goods (from sept.)	Varying summer, autumn, winter: Aug-Dec.
ITS (2013)	No clear protocol	80	5,10,15,20	3 truck platoon	Rigid body	Empty-loaded	
PATH (2004)	No clear SAE protocol mentioned	80, 89	3,4,6, 8,10.	2 truck platoon	Articulat-ed tractor-trailer	Empty-loaded. 14-28 t. / truck-trailer	
SARTRE (2013)	Extensive description (not SAE)	85	5, 12, 20, 25.	2 truck platoon	Rigid body	Unknown	Describe d
Veldhuizen et al. (2019)	SAE J1321 Type II fuel economy protocol	85	10,20,30, 40,50,70.	2 trucks, ACC	EU truck over cab	Unknown	January (1-4°C); August (12-24°C).
This research: Integrator Connected Truck Trials, ACC	Real-world (naturalisti c driving, field operational test)	80	33, 50.	2 truck ACC convoy	EU truck over cab	Loaded, mean weight 38t	Varying autumn, winter: Sept-Feb

Next to the test track results of Veldhuizen et al. (2019), real-world platooning tests have been conducted. The EDDI project (MAN, DB Schenker) shows the results of real-world platooning at a gap distance of 0.7s. or 15m. (at a speed of 80 km/h). The fuel savings are 1.3% for the leading truck and 3-4% for the following truck. These are considerably lower than the expected fuel savings reported in earlier studies and can be explained by the fact that real-world conditions are more diverse than tests on a test track. Also, trucks on the road often undershoot the safe driving distance and as a result the net fuel savings effects of platooning in real traffic are lower (Brandt, 2019).

Lastly, the European Horizon 2020 project ENSEMBLE, where the six large OEMs collaboratively work on multi-brand platooning, closely follows the developments with respect to expected fuel savings as a result from platooning. ENSEMBLE recognises the potential fuel savings of 4-10% for the following vehicle at a following distance of 1.5 s. or 33 m. at a speed of 80 km/h. ENSEMBLE expects the same savings when following the SAE testing protocol on a test track. However, when implemented in real-world driving a negligible effect is expected due to the distances already driven (including risky tailgating). The ENSEMBLE consortium now focuses on a platooning technology that adopts a gap distance of 1.4-1.6 s. or 33 meter, comparable to the current DAF ACC mode 1 settings.

This implies that expected savings at following distances shorter than 30 m. as reported by Van Ark et al. (2017) and displayed in Figure 15 will not be of relevance in the implementation as foreseen by ENSEMBLE.

3.3 Methodology specifically for fuel consumption and emission analysis

In order to determine which sensors to use for data collection, we first determine the data needs for answering our research questions related to fuel consumption and CO_2 emissions. Table 1 shows what data needs to be logged, by which data type this is gathered, and which sensor is used for this purpose.

Table 8: Fuel consumption: Research aims, the related data type and sensors, and the research questions which use the resulting conclusions.

Aim	Data type	Sensor	Question
Determine whether ADAS systems such as the ACC are enabled/engaged and at what speed	Information on ACC mode and vehicle speed	CAN bus	RQ 1.1 – 3
Determine real-world emissions of trucks	Vehicle emissions in the exhaust	Exhaust sensors	RQ 1.1 – 3
Determine distance and time headway to preceding vehicle	Radar distance information from the on-board radar sensor	CAN bus	RQ 1.2 – 3
Determine when convoy formation took place.	Calculation of inter-vehicle distances	CAN bus	RQ 1.3
	Relative truck GPS locations	CAN bus	
	Information on realised convoys	Information supplied by drivers/planners	
Determine the road type on which a vehicle is located	Location data: GPS longitude and latitude	GPS and map-matching using OpenStreetMap	*See Section 3.4*
Determine whether driving in convoy formation affects the aerodynamic resistance of the vehicle	Air pressure measurement in front of and under the vehicle	Pressure sensors	*See also Appendix A - 8.1.3*

For collecting the data as specified in Table 8, the Smart Emissions Measurement System (SEMS) is used (see Figure 16) which logs data at 1 Hz resolution.
This system is developed by TNO for the purpose of logging real-world emissions, that is vehicles in natural driving conditions (as opposed to a controlled, laboratory environment) (Vermeulen, Spreen, & Vonk, 2014; Spreen, et al., 2016).

Figure 16: Smart Emissions Measurement System (SEMS), with sensors in the exhaust.

Fuel consumption data was only used when the engine was at regular (hot) operating temperature, that is, when the engine coolant temperature was above 70 °C. The average fuel consumption was determined by dividing the total fuel used per subset of data, then dividing by total distance driven. This distance is calculated by integrating the speed of the vehicle over time. Fuel consumption can be determined either via the CAN bus (via the fuel rate signal), or via a sensor mounted in the exhaust. This sensor measures the mass flow in the exhaust, which can then be used to determine the CO_2 mass flow. For the five vehicles examined there is a deviation of around 1% between the total fuel calculated via the CAN bus signal, and the sensor (see Table 22 in Appendix A). The median and interquartile range of fuel consumption is determined from the 1 Hz fuel consumption, which is subject to more fluctuation. The 1 Hz fuel consumption is determined per second, using the CO_2 mass flow (or fuel rate signal) and vehicle velocity.

3.4 Results

The measurement period ran over a period of six months, from 10/09/2019 to 29/02/2020. Routes were driven as usual, which included trips throughout the Netherlands, but also across Europe (Figure 17). During this time, the 9 vehicles (Trucks 1a, 1b, 2a, 2b, 3a, 4a, 4b, 5a, 5b) drove more than 325 000 kilometres and used around 100 000 L of fuel (Table 9). We note that Truck 2a has logged significantly less kilometres, in retrospect likely due to faulty hardware.
Most of the time is spent either idling at low speeds, or at speeds above 75 km/h (Figure 18). Map matching was used to categorise the road types on which the trucks drove on during this time period. 1% of the distance was driven on urban roads, 3% on rural roads, 40% on motorways, and 56% on roads that could not be categorised (for more information see Table 23 in Appendix A).

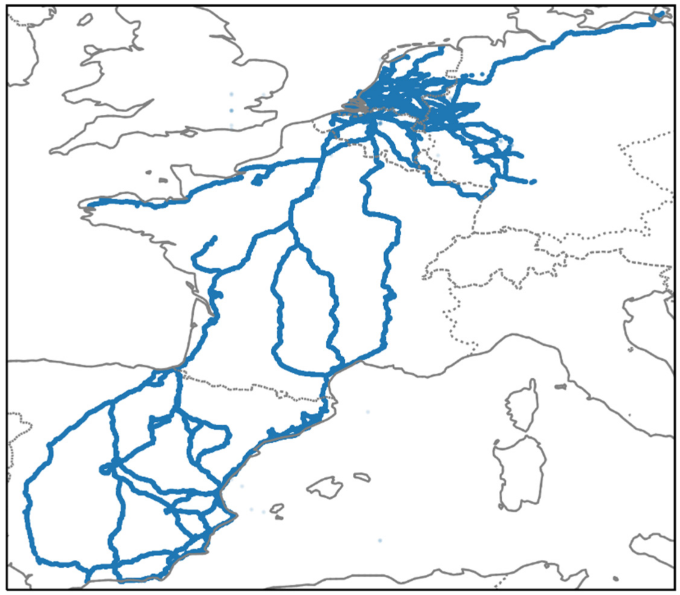


Figure 17: Routes driven over the measurement period.

Table 9: Different statistics determined for the measurement period 10/09/2019 – 29/02/2020. Note that Truck 4a – 5b were not fitted with sensors; the fuel use is determined using OBD signals.

Name	Distance [km]	Time [h]	Average Speed [km/h]	Total Fuel [L]	Average Fuel [L/100km]
Truck 1a	30 930	700	44	9 152	29.6
Truck 1b	51 848	913	57	14 895	28.7
Truck 2a	13 368	276	48	5 076	38.0
Truck 2b	56 559	1 180	48	20 026	35.4
Truck 3a	39 378	549	72	10 930	27.8
Truck 4a	46 294	958	48	11 165	24.1
Truck 4b	36 312	728	50	9 247	25.5
Truck 5a	31 375	677	46	7 973	25.4
Truck 5b	46 704	900	52	11 156	23.9
Total	**352 767**	**6 880**	**51**	**99 621**	**28.2**

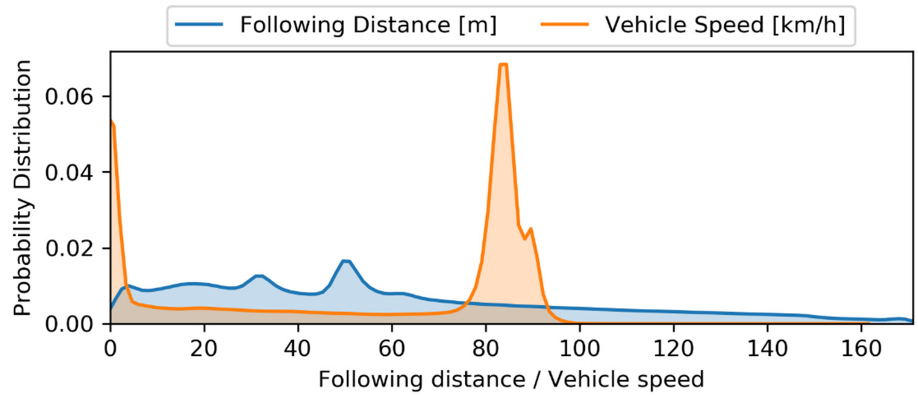


Figure 18: Distribution of the following distance (or distance to the vehicle in front, blue) and vehicle speed (orange), for all driving during the campaigns.

In the examination of the effects of ACC on real-word fuel consumption, we would primarily want to consider the effects based on the situations where this is most used: during long distance driving on the motorway. However, as more than half the kilometres driven were on roads that could not be classified, it is decided to used speed as a cut-off point: we will primarily consider driving at speeds higher than 75 km/h (referred to from here on out as high speed). We note here, that the mean fuel consumption for all vehicles (at all speeds) during this study is calculated as 28.2 L/100 km, which is slightly lower than the 29 L/100 km previously published by TNO in 2016. (Ligterink, Zyl, & Heijne, 2016), perhaps due to loading conditions. On motorways the average fuel consumption is 27.5 L/100 km, while at high speeds, the average fuel consumption is 27.0 L/100km.

3.4.1 *Implications of real-world driving*

During real-world driving, vehicles are subject to large variations in driving conditions. The vehicles drive on various routes, with differing traffic, weather, and road conditions. Furthermore, the payload also varies per trip. Especially driving dynamics (speed and acceleration during driving) and payload have a significant impact on fuel consumption. An initial examination of the correlation between fuel consumption and ACC modes and convoying was performed (as documented in Appendix A - 8.1.2). However, without accounting for the payload and driving dynamics, the observed effects can be biased by operating conditions with a heavy payload, or conditions on specific routes with specific payloads.

The influence on fuel consumption by the factors payload and driving dynamics are considered and accounted for in the following analysis. The payload, or the total vehicle weight, is estimated from the data itself. Payload can be considered the largest fuel consumption influencing factor. To estimate the vehicle weight, one can consider the high power consumption at hard acceleration. Furthermore, the power consumption at constant speed provides an estimate of the driving resistance, which also depends on vehicle weight. Using the calculated total mass, and the velocity and acceleration at each second of each trip, the expected CO_2 emission can be estimated. Investigating the difference between the actual fuel consumption and that expected based on the physical factors mentioned above, highlights fuel consumption dependencies besides these factors.

3.4.2 *Percentages reduction in fuel consumption for different ACC settings*

The fuel consumption dependency of ACC modes is investigated by examining the dependence on the headway (or following) distance, i.e. the distance between the truck in question and the vehicle in front of it. The residuals showing the effect of distance, and the typical distances of the ACC modes, can be combined with the average emissions to show the influence of these settings.

As shown in Figure 19 (top panel) there are significant decreases in fuel consumption at following distances corresponding to the ACC modes 1, 3, and 4: 33, 50, and 62 m.[7] Furthermore, Figure 20 shows differences in how ACC is employed by the different drivers. Truck 1b shows clear decreases in fuel consumption at 33 and 50 m, while Truck 2a only shows a decrease at 62 m.

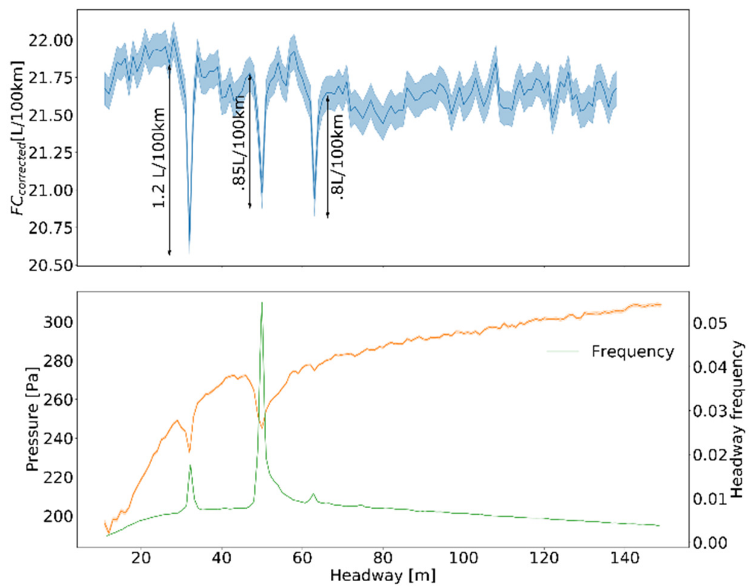


Figure 19: Aggregated results for the fuel consumption and front pressure for the four vehicles equipped with pressure sensors. On the top panel the fuel consumption (blue) and the headway frequency (green) as a function of the distance headway are shown. The shaded blue region denotes the standard error of the fuel consumption. On the bottom panel the pressure as a dependence on the headway is depicted. The relative extrema correspond to headway distances around 33, 50 and 62 m (associated with ACC mode 1, 3 and 4).

To further examine these decreases, the pressure differences on the front of the vehicle is investigated, as shown in the lower panels of Figure 19 and Figure 20. The general trend shows a decrease in the pressure with respect to decreased following distance (as one might expect), with sharp decreases at the distances corresponding to the ACC modes.

[7] Note that ACC 4 was not part of the driving campaigns but is included here for completeness.

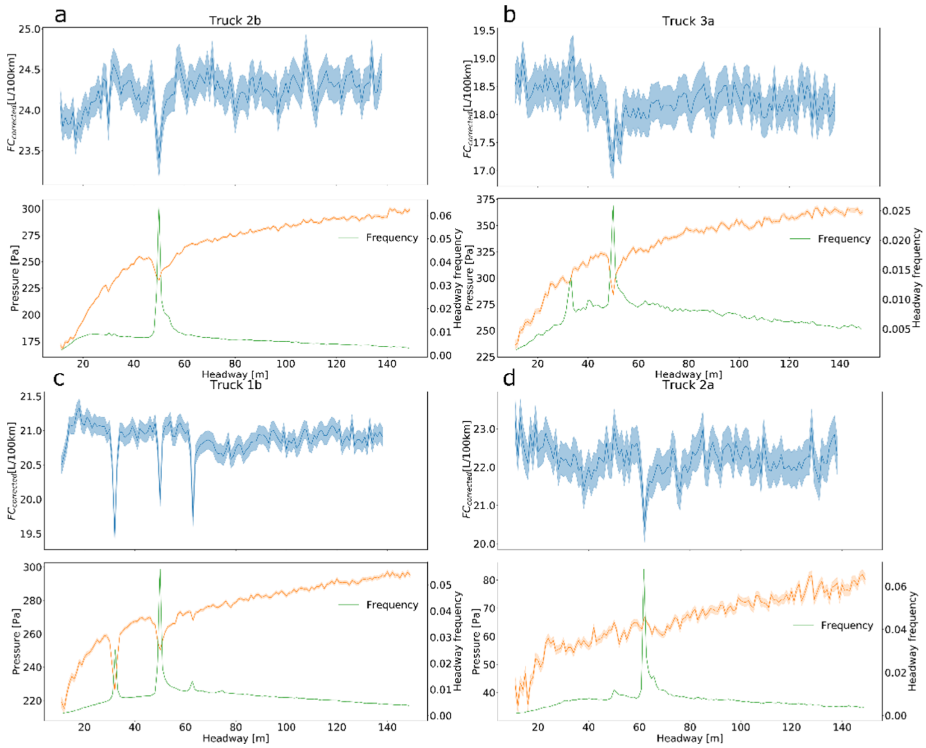


Figure 20: Fuel consumption, front pressure and headway distribution for the four trucks equipped with sensor pressure separately. In each subfigure a) to d) the top panel shows the fuel consumption in blue. The thick line stands for the mean value whereas the shaded area indicates the standard error. The bottom panel shows the pressure measured at the front of the vehicle (orange) and headway frequency distribution (green). A reduction in fuel consumption and pressure is observed for the most frequent headway distances, which correspond to the headway distances associated with various ACC modes.

The reduction of fuel consumption is best expressed in terms of absolute numbers, as it is related to the change in air drag, and only partly to the change in dynamics. The reduction varies from 0.8 to 1.2 L/100 km, from the largest (62 m) to the smallest (33 m) headway. Given a typical fuel consumption of 22 L/100km for constant velocity on the motorway, the fuel consumption reduction is 4.3 to 5.6% from 50 metres to 33 metres headway respectively. Among the trucks there is about 30% variations in the reduction percentages and about 20% variations in the absolute reductions in litres per 100 km for the cases were the ACC mode was applied amply. Some ACC modes were applied less in certain trucks and no significant conclusions can be drawn for these cases. The variations, to a great extent, are likely related to the baseline, which is dependent on driver, payloads, and routes.

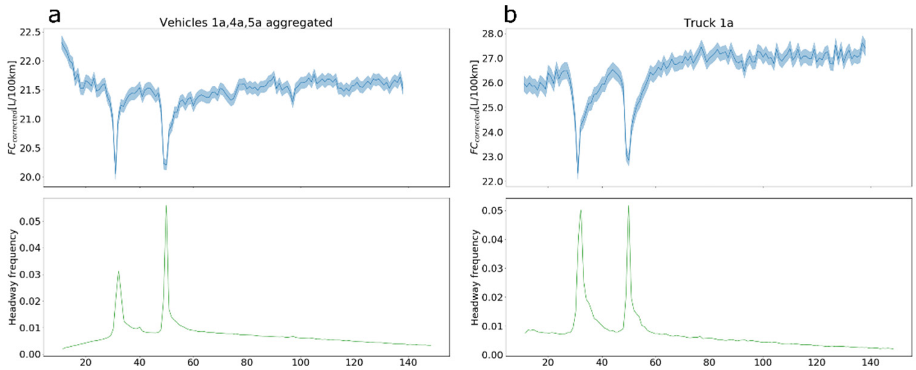


Figure 21: Corrected fuel consumption and headway frequency distribution for the vehicles without air pressure system installed. Both panels a) - b): on top in dark blue the mean fuel consumption and the standard error (shaded area). The bottom plot in green shows the headway distance density distribution. a) shows the data for the Trucks 1a, 4a, 4b, 5a and 5b together whereas panel b) shows the data for Truck 1a only. Truck 1a had the most equally distributed headway frequency between 33 and 50 m.

In Figure 21 we also show the corrected fuel consumption for Truck 1a only (Figure 21 b). Truck 1a had the most equally distributed headway frequency between 33 and 50 m, i.e. the most equal distribution between time spent at 33 m and 50 m. However, Figure 21 b) shows that Truck 1a has an unusually high reduction in corrected fuel consumption due to ACC use (around 4 litres). For this truck, the difference in reduction from 50 m to 33 m was around 2%.

3.4.3 *Change in fuel consumption with the headway*

The pressure differences with the headway (as shown in the lower panels of Figure 19 and Figure 20) give an estimate of the fuel consumption variation with headway alone. The change in pressure is most notable between 30 metres and 10 metres headway. The observed drop in air pressure of 50-100 Pa can be associated with changes in the air drag of 150 to 300 Newtons, based on an effective frontal area of 3 m^2. The effective frontal area is roughly related to the C_d*A in aerodynamics, where the frontal area is A = w * h = 2.4 * 3.4 = 8.16 m^2. The force difference due to the drop in air pressure is roughly related to 1 to 2 litres per 100 km reduction in fuel consumption, for the shortest headway of 10 metres.

Sharp drops in air pressure are also observed at distances corresponding to the use of ACC. This seems to suggest that the lower air drag is, in part, related to the stable air flow conditions in the convoying situation. The effect on the pressure of ACC, at the same headway, is about a quarter of the effect of reducing the distance to 10 metres headway. More appropriately, in normal use, the use of ACC appears to reduce air drag as much as a decrease in headway of 10 metres.

From the pressure measurements it may be concluded that a short headway (shorter than the settings of the different ACC modes) would reduce air drag further. However, the corrected fuel consumption at these short distances does not show the reductions expected from this decrease in pressure. I.e. based on Figure 19 (risky) tailgating at short distances does not result in fuel consumption reductions equal to those achieved when ACC is used.

It is therefore estimated that if the headway can be reduced to 10 metres, *in combination with an ACC mode*, the fuel consumption reduction can be about 2 litres per 100 km, as compared to a headway of 70 metres or more. This is based on the force exerted on the front of the cabin, as measured by the pressure sensor. The pressure sensor gives a proper indication of the variation of the air drag with the distance. It must however be noted that these results vary about a factor two in absolute levels. One truck, Truck 2b, has deviating results. If this vehicle is excluded the remaining variation in observed air drag is about 20%. This is probably related to the actual tractor and trailer aerodynamic configurations and wind conditions, or the placement of the pressure sensor on this truck, as absolute values are also lower than for the other trucks.

3.5 Conclusions

The impact of using ACC
To ensure that payload and driving dynamics do not bias conclusions about the use of ACC, the fuel consumption is corrected for these factors. The correlation between the *uncorrected* fuel consumption and ACC use is shown in Appendix A - 8.1.2. Clear decreases in the corrected fuel consumption are observed at distances associated with the ACC modes 1, 3 and 4. This reduction varies from 0.8 to 1.2 L/100 km, from the largest to the smallest headway.

Reduction due to different headway distances
Given a typical fuel consumption of 22 L/100km for constant velocity on the motorway, the *average* fuel consumption reduction is 4.3 to 5.6% from 50 metres to 33 metres headway. ACC driving is more fuel efficient than when ACC is switched off in the control condition, or at distances not associated with the relevant ACC mode. The real-world data does show a spread in the results when comparing the fuel savings of the individual trucks; for the 50 metres headway (ACC 3) this ranges from 3.3-5.5% and for a 33 metres headway (ACC 1) this ranges from 3.0-5.7%. The variations, to a great extent, are likely related to the baseline, which is dependent on driver, payloads, and routes.

Influence of planned convoys
Sharp drops in air pressure are observed at distances corresponding to the use of ACC. This seems to suggest that the lower air drag is, in part, related to the stable air flow conditions in the drafting/convoying situation. Pressure measurements suggest that a short headway (shorter than the settings of the different ACC modes) would reduce air drag further. It is estimated that if the headway can be reduced to 10 metres, in combination with an ACC mode, the fuel consumption reduction could be about 9% (2 litres per 100 km) as compared to not following another vehicle. Note that when comparing this to a headway of 33 metres (ACC 1), the fuel consumption reduction could be about 4%.

4 Human interaction

4.1 Introduction

In this chapter, the use of ACC and its impact on the driver is evaluated.

Specifically, we investigated the following research questions:

RQ 2.1 How is the ACC system used? With the following sub questions:

a. How often were the different ACC distance settings used by the drivers?
b. What was the distribution of ACC modes (see Table 3: Driving campaigns and characteristics, Chapter 2) in which the ACC system operated?
c. At which driving speeds was ACC used?
d. Did ACC use differ between campaigns with different instructions regarding ACC use?

RQ 2.2 Did the drivers' evaluation of the ACC system and of the overall driving experience differ between campaigns?
RQ 2.3 Is there a relationship between acceptance of and trust in the ACC system and how often this system has been used?
RQ 2.4 Does reported workload[8] differ between campaigns with different instructions regarding ACC use?
RQ 2.5 Is the reported workload related to how often ACC has been used?
RQ 2.6 Is the reported workload related to driving speed?
RQ 2.7 Is the reported workload related to heart rate?
RQ 2.8 Does the mean driving speed differ between different campaigns?
RQ 2.9 Do acceleration distributions differ between campaigns?
RQ 2.10 Is maximum deceleration related to ACC use?
RQ 2.11 Does ACC use depend on the weather?

4.2 Literature

In the current study, the interaction between truck drivers and ACC driving was investigated in a field study where professional truck drivers drove their trucks on the road in regular transport schemes with or without ACC and with different ACC distance settings. Moreover, ACC was used in convoy driving (two trucks) as well.

As ACC keeps a set distance to a lead vehicle, the driver drives more relaxed and displays less symptoms of fatigue, according to DAF (DAF Trucks, n.d.).
In everyday driving, truck drivers already frequently make use of ACC and are very positive about the technology (Van Engelen et al., 2018). The step to ACC convoy driving seems nowadays feasible on the road, but highly automated driving in Truck Platooning is still in the future.

The use of ACC in trucks brings up several important human factors questions and issues.

[8] Workload: the perceived amount or intensity of work that has to be performed given the available cognitive resources.

Firstly, it is important to know to what extent drivers trust and accept advanced driver assistance systems such as ACC, as this may impact their actual use of these systems. Secondly, does the use of ACC actually improve the comfort of the driver while driving? And thirdly, the use of ACC may reduce the involvement of the driver in the driving task and induce him/her to engage in non-driving-related tasks (Jones, 2013; De Winter et al., 2014). Therefore, it is important to investigate this.

Measures
While it is quite common to apply physiological measurements, eye-movement equipment, cognitive workload and vigilance measurements in controlled experimental environments such as driving simulators or driving on a test track (e.g. Brookhuis & De Waard, 2010), a natural setting puts restrictions on what is feasible and bearable for the truck driver for relatively long periods of time. Therefore, the main focus of this study with respect to Human Interaction was on the analysis of (longitudinal) driving behaviour. Moreover, several questionnaires were filled in by the truck drivers after their experience with ACC in different distance settings, as defined by the different campaigns. The use of physiological measures was rather limited for practical reasons. The possibility to measure heart rate by a device such as for example a Fitbit smart watch was explored in this study (see Figure 23). Heart rate variability would be a better indicator for mental workload as heart rate in itself is rather sensitive to physical effort, but in the context of this on-the-road study it was not feasible to measure heart rate variability, leaving heart rate as the only option. Brookhuis and De Waard (2010) reported differences in mental effort based on heart rates for different road types (for example built up area versus quiet motorway).

A commonly accepted, validated, and easy-to-use cognitive workload test is the RSME (Rating Scale Mental Effort) (Zijlstra, 1993). For measuring psychological job strain, the trucker strain monitor questionnaire as developed by De Croon et al. (2001), was used resulting in a fatigue and a sleeping-problem scale.
For acceptance and comfort issues a standardised checklist of acceptance of new technological equipment (Van der Laan et al., 1997) was used as a well-accepted approach. Hoedemaeker (1999) successfully applied this checklist in a driving simulator study on Adaptive Cruise Control. The same questionnaire approach was used in this study.

4.3 Methodology

In order to answer the research questions related to human interaction we used four different tools. After a brief description of our participants sample, we describe the Advantech logger for vehicle and video data and the heart rate tracker. Then, the surveys used to measure ACC evaluation and work load are described and the last two paragraphs describe the design of the study and the data analysis.

4.3.1 Participants

Seven drivers from three different transport companies volunteered to take part in the Human Interaction part of the study. All were male in the age range of 34 to 58 years (median 51 years). One of the drivers used the same trucks as two of his colleagues at night. However, it was not recorded when which driver was using a specific truck. All drivers had extensive experience in driving with ACC. During the study, they drove the same trucks they normally did for their work.

4.3.2 *Cameras and vehicle data*

For logging human-machine interaction, trucks were instrumented with a set of seven cameras (3 in-cabin views and 4 outside views) and a microphone. Figure 22 shows the views of the different cameras. Below, in Table 10, information of individual sensors is listed. Some of this data can (in combination with other traceable information) be used to analyse the performance of a truck driver. For this reason, transport companies were explicitly denied access to the raw data. An Advantech logger with hard disk was used to store the camera and vehicle data. The logger stored vehicle - and GPS data at 10 Hz.

Table 10: Vehicle sensors and cameras.

Research aim	Data type	Data source
Determine whether systems are enabled and how the vehicle performs under certain conditions	Information on vehicle performance, implicit driver behaviour	CAN bus
Determine the road type and its parameters on which a vehicle is located and check the (time) synchronization of the different measurement systems	Location data : GPS longitude and latitude	GPS
Determine safety critical events (e.g. strong braking)	Acceleration of the vehicle	Accelerometer
Determine viewing behaviour/ alertness of driver	Footage of viewing behaviour and automatic eye-blink movement recognition	1 Camera directed at the driver's face
Determine how drivers control the pedals	Foot positions and pedal use	1 Camera directed at the driver's feet.
Determine driver's positioning and activities in the cabin	Categorization of given set of actions	1 Camera providing an overview of the cabin
Determine presence and position of other vehicles	Overtaking or being overtaken behaviour	1 Camera located on/ near the left side mirror; 1 Camera located on/ near the right side mirror
Longitudinal and lateral control	Headway distance and lane keeping behaviour	2 Forward facing cameras (wide and narrow angle)
Retrace the audio signals (e.g. beeps from the Lane Departure Warning system)	Sound recordings by a microphone directed at the vehicle's dashboard.	Microphone, combined with the 'feet camera'

Figure 22: Camera views of the installed cameras. Clockwise from top left: top down cabin view, driver view, forward view wide, forward view narrow, pedals view, right side mirror, left side mirror.

4.3.3 *Heart rate*

In order to measure the drivers' heartrate, a heartrate tracker was used. This is a smart watch that is attached to the wrist of the professional truck driver.
To determine which sensors to use for data collection, we first determined the required data type for answering our research questions related to human interaction. This is shown in Table 10. To select an appropriate heartrate tracker for the purposes of our study, a comparison of four different devices was made (see Table 11) along four dimensions: quality of the heart rate monitor, level of detail, accessible API and the country of data storage. The country of data storage is relevant with respect to the sensitivity of storing personal data of our participants. Fitbit and Garmin have the best heart rate monitors and the most accessible API. Both devices store their data in America. Fitbit gives access to a finer level of detail in data, compared to the other solutions. Suunto is Chinese and does not have an easily accessible API. Polar stores data in the EU, but only publishes data at a general aggregated level, i.e., average heart rate per activity, which is insufficient for our research. Based on this comparison the Fitbit Ionic (Figure 23) was chosen for this study.

Figure 23: Fitbit Ionic.

Table 11: Heart rate monitor comparison.

	Fitbit	Garmin	Polar	**Suunto**
Quality of heart rate monitor	Best	Best	Good	Good
Level of detail	Good	Good	Best	Medium
Accessibility API	Good	Good	Medium	Insufficient
Country of data storage	USA	USA	Europe	Europe

4.3.4 *Effort ratings*

To measure self-rated work effort, short single question surveys were used. These surveys were presented via an app on a smartphone. All participants had the app installed on their phone with personal login codes. After each trip the participant was requested to open the app and use the slider as shown in Figure 24 to indicate the effort for that trip. The survey was in Dutch, as all participants were Dutch. Name, date, and time were filled in automatically. The short effort survey was based on the Rating Scale Mental Effort (Zijlstra, 1993) and measured self-rated effort on a visual scale from 0 (not the least effortful) to 110 (extremely effortful) to 150 (no label).

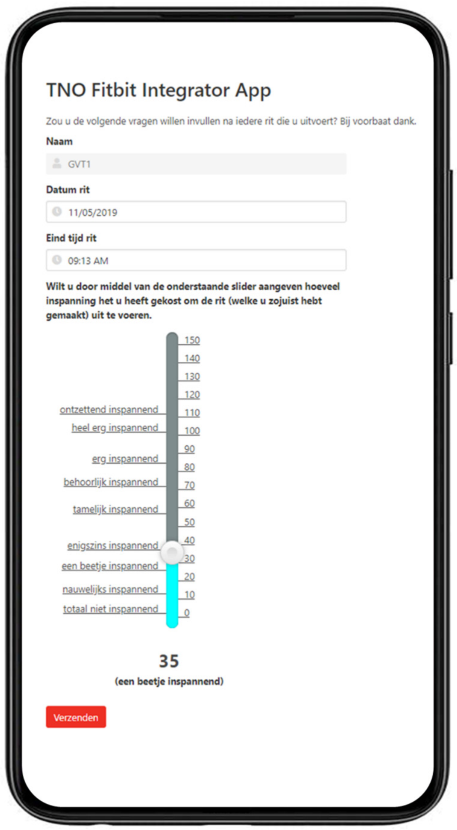


Figure 24: Effort survey, conducted after each trip.

4.3.5 *Long survey on ACC use and driving experience*

After each campaign, participants were requested to fill out an extensive survey on ACC use and general driving experience during the campaign. These surveys were sent by mail and could be filled out at the office of the transporter. In these surveys the trust in both Conventional Cruise control (CC) and Adaptive Cruise Control (ACC), the acceptance of ACC (Van der Laan et al., 1997), the advantages/disadvantages of ACC, the use of ACC, stress experience of participants and workload of participants (De Croon et al., 2001) were tracked over the different campaigns. The questionnaire can be found in Appendix B - 8.1.5.

4.3.6 *Comments during weekly contact participants*

Every week the participants were contacted through telephone by a project member. This project member was the same as the point of contact of the participant. During these weekly telephone calls, the truck driver's week was discussed. During these calls, participants also had the opportunity to give open comments regarding their experiences with the ACC system or about general driving conditions.

4.3.7 *Conditions*

The study consisted of seven campaigns, each implementing a different study condition by giving the participants different instructions concerning ACC use. Table 12 gives an overview. The first (A1) and last (A3) campaign served as baseline measurements. All participants drove their truck in these different campaigns. Participants were instructed to use the ACC system as they normally would. In the second campaign (A2), participants were instructed to use the ACC system as little as possible, to allow evaluation of the impact of ACC use. In campaigns B1 and B2, participants were instructed to use the ACC only in one specific distance setting, either setting 3 (medium distance) in B1 or setting 1 (short distance) in B2. In campaigns C1 and C2, participants received the same instructions, but were in addition asked to perform convoy drives, driving a large part of their route in convoy with one other truck. These campaigns served to evaluate the potential fuel savings by driving in convoy. Note that the participants of one company performed these campaigns in a different order for logistical reasons. Campaign A3 was added later to check on whether learning effects occurred.

Table 12: Campaigns and corresponding conditions. For one of the participating companies, the campaigns A1-A3 were performed on different dates, indicated between parentheses.

Campaign	Condition	Instruction	Period
A1	Baseline pre	Use ACC as normal	9-27/9/2019 (2-18/10/2019)
A2	No ACC	Do not use ACC	20/9-11/10/2019 (24/1-9/2/2020)
B1	ACC 3 solo	Use ACC setting 3	14-25/10/2019
B2	ACC 1 solo	Use ACC setting 1	28/10-8/11/2019
C1	ACC 3 convoy	Use ACC setting 3 while convoying	25/11-6/12/2019
C2	ACC 1 convoy	Use ACC setting 1 while convoying	13-24/1/2020
A3	Baseline post	Use ACC as normal	27/1-7/2/2020 (10-21/2/2020)

4.3.8 *Analysis*

In the next subparagraphs we discuss several important steps in the analysis: the pre-processing of the surveys (4.3.8.1), trip identification (4.3.8.2), vehicle data and cameras (4.3.8.3) and statistical analysis (4.3.8.4).

4.3.8.1 *Pre-processing of surveys*

Participants' responses were digitized and collected in an Excel file. Answers to five point scale questions were coded 2 (completely agree) to -2 (do not agree at all). For negatively phrased questions, the scale was mirrored to -2 to 2. The different questionnaires each contained multiple questions that reflected a few underlying dimensions. In order to analyse the results, the responses to individual questions were combined to reflect these dimensions.

For the questions related to Acceptance (question 3 in Appendix B- 8.1.5), the scores for the items 1, 3, 5, 7, 9 and 10 were averaged to produce an overall Usefulness score. Likewise, items 2, 4, 6 and 8 were combined to give a Satisfaction score (see Van der Laan et al, 1997). For the questions related to job strain (question 7 in Appendix B - 8.1.5), the scores for the items 1 to 6 were combined into one Fatigue score and the items 7 to 10 were combined into one Sleep problems score (see De Croon et al, 2001). For the questions related to trust (questions 1 and 2 in Appendix B - 8.1.5), the scores for the items 1, 2, 7 and 8 were combined into one Usage score and those for the items 4 and 6 and items 1 to 9 of question 2 into one Trust score.

4.3.8.2 *Trip identification*

A trip was defined as a driving period between turning ignition on and turning it off again. However, during data processing it was observed that drivers sometimes did not switch off the ignition between different trips (e.g., while sleeping on a parking lot). Therefore, trips were detected using two criteria. First, timestamp gaps of more than 10 min were taken to be caused by turning the ignition off and on with an interval of more than 10 min, indicating a new trip (no data was stored with ignition off). Second, long periods (> 10 min) with zero vehicle speed were also taken as separating different trips. Only trips identified by these criteria, that lasted more than 10 min, were considered in data analysis. From the data analysis, it became evident that effort ratings did not correspond one to one to the detected trips. Sometimes, less effort ratings were given than the number of trips detected, sometimes more. Therefore, both data sources were aggregated for different days. Hence, both the effort ratings and various vehicle parameters were averaged for each day and the relationship between these averages was analysed.

4.3.8.3 *Vehicle data and cameras*

It was planned to use the vehicle data recorded by the Avandtech dataloggers at 10 Hz to analyse driving behaviour in depth. This would allow us not only to look at the distributions of various driving parameters such as speed, acceleration and distance to lead vehicles, but also to identify critical incidents, for example strong braking or swerving. However, due to technical problems, the vehicle data turned out not to be available from the Avandtech dataloggers. Instead, the vehicle data from the SEMS dataloggers were used to analyse driving behaviour. However, since these only stored data at 1 Hz, this did not allow us to identify critical incidents. Moreover, it was not feasible within the scope of the project to analyse the video images for critical incident detection. Consequently, this part of the analysis was left out.

4.3.8.4 *Statistical analysis*

Where feasible, statistical significance was tested by means of Linear Mixed-Effects (LME) models. The advantage of this type of model over traditional methods such as ANOVA or linear regression is that it can deal with unbalanced data (different number of observations in different conditions) as well as with a combination of within- and between-subjects factors. Moreover, it suffers less from missing data. LME models were implemented in MatLab, using the *fitlme* function with restricted maximum likelihood (REML) estimation. Results were evaluated by using the *ANOVA* function with Satterthwaite approximation of degrees of freedom. Continuous fixed factors were centered by subtracting the mean value before entering them into the model.

4.4 Results

In this section we discuss the results of the survey data (4.4.1), vehicle data (4.4.2), and the heart rate data (4.4.3).

4.4.1 *Survey data*

The results from the survey data are subdivided in the sections presenting the *findings of the campaign surveys (4.4.1.1), self-rated effort surveys (4.4.1.2) and* the open comments (4.4.1.3). The campaign surveys paragraph discusses the various variables of interest: Acceptance (4.4.1.1.1), Trust (4.4.1.1.2) and Job strain (4.4.1.1.3) in consecutive order.

4.4.1.1 *Campaign surveys*

At the beginning and end of the entire study as well as at the end of each campaign participants were instructed to fill in a survey containing questions concerning acceptance of and trust in the ACC system, their perceived job strain[9], as well as their experiences with the ACC system (see Appendix B - 8.1.5). In total, 57 of the 63 distributed surveys were returned.

4.4.1.1.1 *Acceptance*

Participants' responses with respect to ACC acceptance were analysed in terms of the two underlying dimensions, Usefulness and Satisfaction. The distribution of responses across participants at each administration of the questionnaire is shown in Figure 25. The figure shows that acceptance of ACC was generally high, both for Usefulness (medians for different campaigns between 1.4 and 1.8) and for Satisfaction (medians for different campaigns between 1.75 and 2.0). More details can be found in Appendix 8.1.7.

To evaluate differences between the different campaigns, the difference scores between the responses after each campaign and that at the beginning of the study were determined. The differences between campaigns were then tested in a linear mixed-effects model analysis, in which the frequency of ACC use was included as a covariate as well. Participant was used as a random factor for the intercept. From this analysis, it could be concluded that neither the frequency of ACC use (Usefulness: $F(1,19) = 0.033$, $p = 0.86$; Satisfaction: $F(1,24) = 0.081$, $p = 0.78$) nor campaign (Usefulness: $F(6,19) = 1.63$, $p = 0.19$; Satisfying: $F(6,24) = 0.86$, $p = 0.54$) had a significant effect on the acceptance scale dimensions (see Appendix C).

[9] The job strain questionnaire asks about strain on a relatively long time scale and is therefore part of the campaign surveys. Workload is measured with the RMSE through self-rated effort, see section 4.4.1.2.

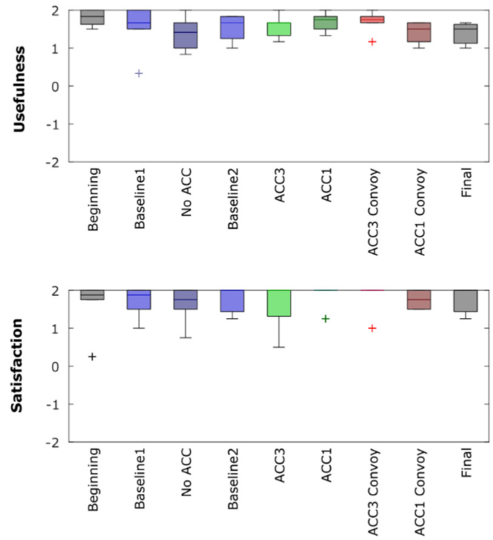


Figure 25: Acceptance scale dimensions “Usefulness” (top) and “Satisfaction” (bottom) concerning driving with ACC per campaign. Boxplots show the distribution of responses across 7 participants for the different campaigns, as well as for the beginning and end of the study. Box length indicates the interquartile range, with the red horizontal lines representing the median answer. Crosses indicate outliers beyond 1.5 * the interquartile range and whiskers extend to the last value that is not an outlier.

4.4.1.1.2 Trust

Participants’ responses with respect to trust in the ACC system were analysed in terms of the two underlying dimensions, Usage and Trust. The distribution of responses across participants at each administration of the questionnaire is shown in Figure 26. From the figure, it can be seen that trust in the ACC system was generally high (medians across campaigns between 1.5 and 2.0 for Usage and between 1.3 and 1.7 for Trust). Details can be found in Appendix C - 8.1.7.

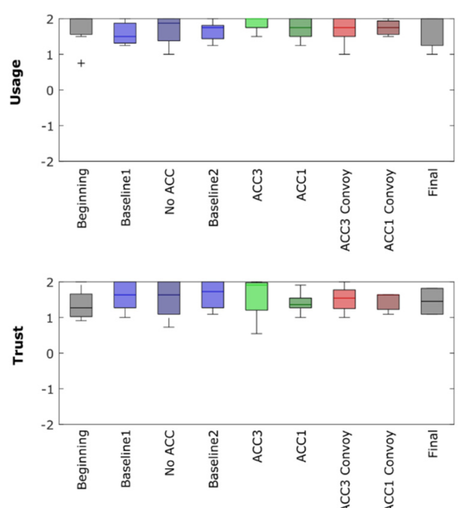


Figure 26: Trust ratings for the dimensions “Trust” and “Usage” per campaign as well as at the beginning and end of the study. Boxplots as in Figure 25.

To evaluate differences between the different campaigns, the difference scores between the responses after each campaign and that at the beginning of the study were determined. The differences between campaigns were then tested in a linear mixed-effects model analysis, in which the frequency of ACC use was included as a covariate as well. Participant was used as a random factor for the intercept. From this analysis, it could be concluded that neither percentage of ACC use on highways (Usage: $F(1,35) = 0.32$, $p = 0.57$; Trust: $F(1,32) = 1.23$, $p = 0.28$) nor campaign (Usage: $F(6,35) = 19.83$, $p = 0.10$; Trust: $F(6,32) = 0.11$, $p = 0.99$) did have a significant effect on the trust and usage dimensions (see Appendix C) for details).

Responses to the question "Driving with ACC gives me the opportunity to do other things besides driving" were analysed separately. A linear mixed-effects analysis, with Campaign and percentage of ACC use on highways as additive fixed factors and Participant as a random factor, showed that neither percentage of ACC on highways ($F(1,35) = 0.22$, $p = 0.64$) nor campaign ($F(6,35) = 1.65$, $p = 0.16$) had a significant effect on the answers to this question. In other words, answers to this question did not change significantly in different campaigns over the course of the study. In the final survey, participants were also asked which non-driving related activities they performed during driving with ACC engaged. The percentage of participants per activity is shown in Figure 27. As can be seen from the figure, all participants reported to engage in at least one other task while driving with ACC. Most frequently, participants listened to music while driving and/or eat/drink, in particular on motorways. Handsfree telephone calls were also reported by 67% of the participants.

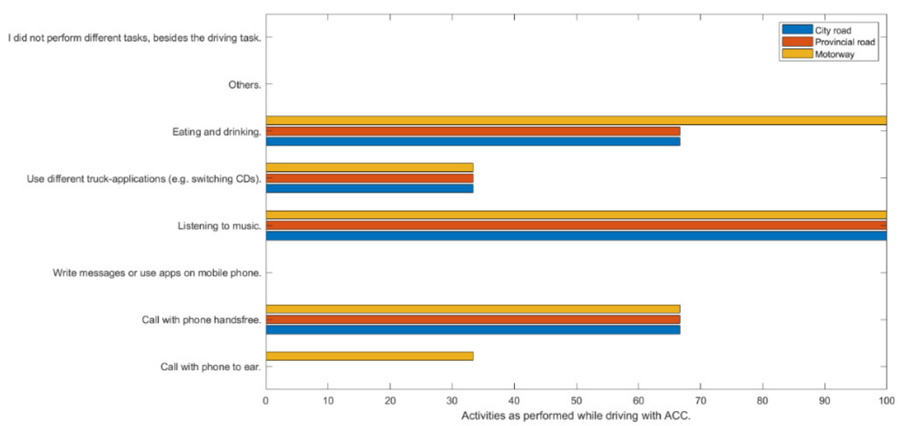


Figure 27: Percentage of truck drivers that performed other activities while driving with ACC. Different colours indicate different road categories.

4.4.1.1.3 Job strain

Participants' responses with respect to subjective job strain were analysed in terms of the two underlying dimensions, Work-related fatigue and Sleeping problems. The distribution of responses across participants at each administration of the questionnaire is shown in Figure 28. From the figure, it can be seen that in general scores on work-related fatigue (medians for different campaigns between 0.67 and 1.17) and sleeping problems (medians for different campaigns between 0 and 1.5) were low.

Note, however, that the variability in sleeping problems scores between different participants was considerably higher than that for fatigue. More details can be found in Appendix C - 8.1.7.

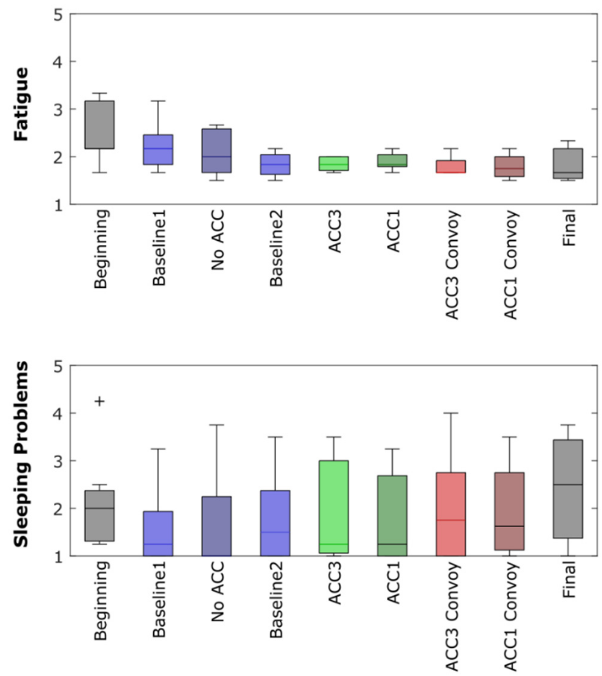


Figure 28: Trucker strain monitor ratings for “Work-related Fatigue” and “Sleeping problems”. For clarity, ratings have been inverted such that higher scores mean more fatigue or sleeping problems. Boxplots as in Figure 25.

To evaluate differences between the different campaigns, the difference scores between the responses after each campaign and that at the beginning of the study were determined. The differences between campaigns were then tested in a linear mixed-effects model analysis, in which the frequency of ACC use was included as a covariate as well. Participant was used as a random factor for the intercept. The results showed that neither the percentage of ACC on highways (Work-related fatigue: $F(1,33) = 2.09$, $p = 0.16$; Sleeping problems: $F(1,33) = 0.28$, $p = 0.60$) nor Campaign (Work related fatigue: $F(6,33) = 1.31$, $p = 0.28$; Sleeping problems: $F(6,33) = 0.71$, $p = 0.65$) had a significant effect on trucker strain monitor dimensions (see Appendix C).

4.4.1.2 *Self-rated effort – Work load*

Although participants were instructed to fill out the Effort survey after every trip they made, the results showed that they differed in their adherence to this instruction. Figure 29 shows the number of trips per day detected from the vehicle data and the number of effort ratings on that day for 6 participants (the data from the 7th participant could not be attributed unequivocally to one vehicle, i.e., specific logging data). As can be seen from this figure, most participants filled out the Effort survey at least once a day, but the number of effort ratings rarely matched the number of trips. This may have been due partly to unreliable trip detection, but also indicates that participants did not always rate their effort for every trip.

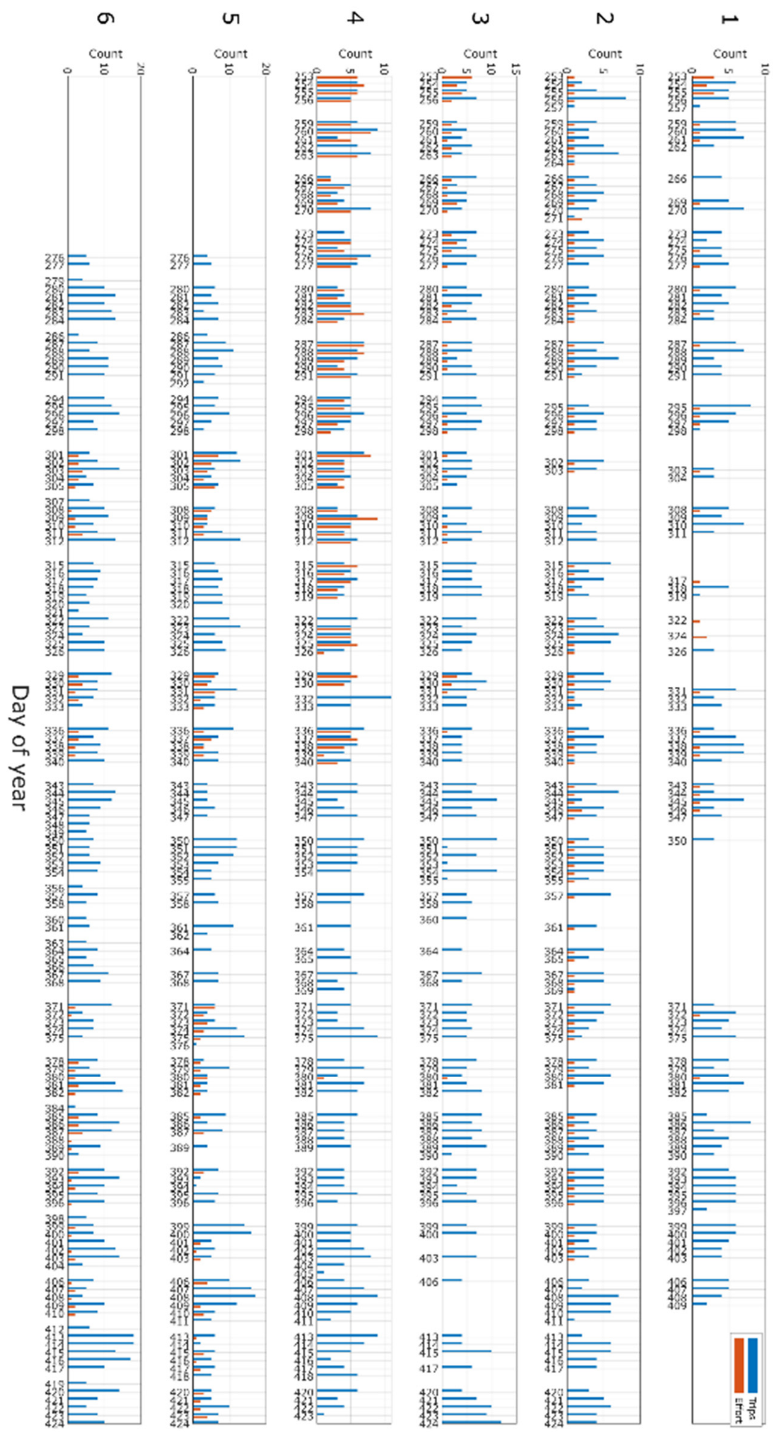


Figure 29: Number of effort ratings and of trips per day within the seven campaigns. Red bars indicate the number of times per day the Effort survey was filled out by 6 participants (different rows); blue bars represent the number of trips detected for that day. The horizontal axis gives the day number for 2019, continued into 2020 (day 366 = January 1st, 2020).

The average Effort rating per condition is shown in Figure 30. The ratings were mostly on the lower side, with maximum ratings going up to approximately 60, or ‘moderately effortful’ (150 was the maximum possible value). Average Effort ratings tended to decrease for consecutive conditions, as was confirmed by analysis with a linear mixed-effects model, including Participant and Day nested within Participant as random effects for the intercept and Condition as fixed effect ($F(6, 252.01) = 6.25$, $p = 3.89e-06$). All conditions showed significantly lower Effort ratings than condition A1, except for conditions A2 and B1 (parameter estimates are given in Table 34, in Appendix D). Rather than reflecting changed effort due to different ACC use, this probably represents changing effort ratings over time, since the lowest average effort was measured in condition A3, which was defined by the same instruction as condition A1 (use ACC as normal).

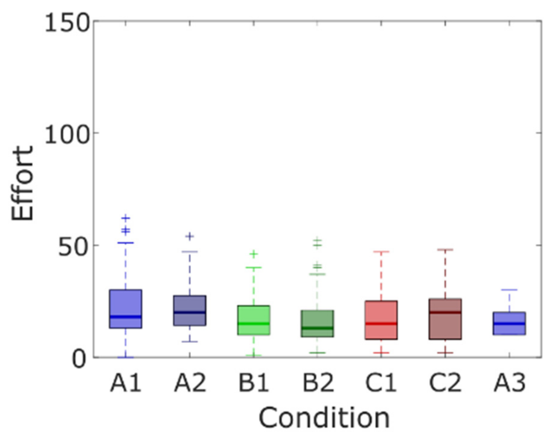


Figure 30: Self-rated Effort in each condition. Boxplots are based on aggregated data across participants and trips. Box length indicates the interquartile range, with the fat horizontal lines representing the median Effort scores. Crosses indicate outliers beyond 1.5 * the interquartile range and whiskers extend to the last value that is not an outlier.

Figure 31 shows the mean effort rating per day as a function of four different vehicle parameters: A). The proportion of time that ACC was active; B). The mean driving speed; C). The number of times ACC was turned on per hour driving (the number of switches from ACC off to ACC on is counted per trip and divided by trip duration); D). The proportion of time that the windscreen wiper was turned on (as a proxy for weather conditions). None of these parameters showed a clear relationship with self-rated effort. This was confirmed by a linear mixed-effects model analysis of Effort as outcome measure and Condition, mean Speed, proportion ACC on and proportion Wiper on as additive fixed factors, combined with Participant and Day nested within Participant as random factors. Only Condition had a significant effect on self-rated Effort ($F(6,295.7) = 5.39$, $p = 2.61e-05$), while none of the vehicle parameters had a significant effect on Effort (all $p > 0.22$). Mean Effort ratings were significantly higher in condition A2 than in A1, lower in A3, C1 and C2 and there was no significant difference with Effort in A1 in conditions B1 and B2. However, the largest difference by far was that in Effort between the two baseline conditions, A1 and A3, suggesting that it was not so much the difference in ACC use instructions that caused effort to vary, but other factors that varied over time. Parameter estimates are given in Appendix D.

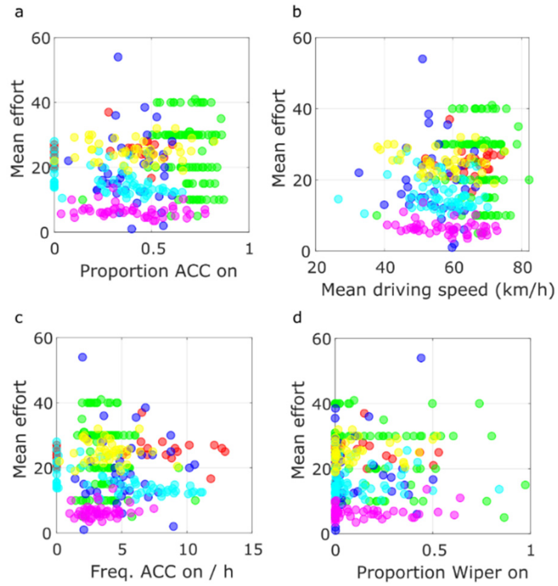


Figure 31: Mean effort per day as a function of a. proportion of time that ACC was turned on; b. mean driving speed; c. the number of times ACC was turned on per hour; d. proportion of time that windscreen wiper was turned on. Different colours represent data from different participants.

4.4.1.3 Open comments

The participants were contacted every week by phone to discuss the participants' experiences.

The general opinion of the participants about driving with ACC was that it was not very special. The reason for this was that the participants usually were already driving with ACC turned on. Furthermore, the participants usually drove a restricted set of routes, as customers remained largely the same from week to week. The participants commented that they usually used ACC setting 3 or 4. One participant indicated that he usually did not use ACC setting 3 on urban and rural roads, because in some cases the system actively brakes to reduce speed instead of just releasing the gas pedal.

Another participant remarked that he typically selected setting ACC3/ACC4, because it provides a bigger distance to the vehicle in front. This participant indicated therefore during the ACC1 campaign, that the distance was too close and that he was inclined to brake himself instead of relying on the ACC system. However, other participants commented that they did not experience a lot of difference between ACC3 and ACC1, and therefore used the ACC1 setting more often when instructed to do so.

Due to the fact that the participants were already used to driving with ACC, the participants were not looking forward to the campaign where no ACC was to be used. The reason for this was that they had the feeling that driving without ACC was less safe, because they should pay more attention to the speed they were driving at. The participants indicated that driving without ACC was very exhausting, especially when the amount of traffic was limited.

When the participants were asked about their experience with driving in convoy, some participant reacted that the convoys were planned in the early morning, earlier than normal workday beginning, which led to a dissatisfaction with driving in convoy. Some participants commented that they usually form an unplanned convoy with trucks that they meet by accident on a road.

Some participants also commented on the study procedure itself. They indicated that the cameras as installed in the truck were falling off. Another remark was that the Fitbit heart rate watches showed a high heart rate. Further, the battery life of the watches was too short for a complete working day. Finally, the participants indicated that they had to remember to fill in the survey after every ride. Because of this, some participants did not fill in the survey after every ride, but only once a day or only when something interesting happened. By the end of the study, several truck drivers indicated dissatisfaction with the study, because it took longer than expected.

4.4.2 *Vehicle data*

As described above, the ACC system could be turned on in five different distance settings, with ACC 1 being the shortest following distance and ACC 5 the longest. Figure 32 shows the proportion of time within a trip that different ACC settings were active, split for different conditions. Only data from highway driving were included. The figure shows that on highways the ACC system was active about 75% of the time for most conditions. Distance setting 3 was used most often, setting 1 mostly in conditions B2 (ACC 1 solo) and C2 (ACC 1 convoy), while settings 2, 4 and 5 were hardly used at all. The data show that, while the instructions for different conditions did not produce large differences in ACC use, they did change participants' behaviour in using the system. In condition A2 (no ACC use), the ACC system was (indeed) used less than in the other conditions, including the two baseline conditions (A1 and A3). In the conditions where participants were instructed to use ACC 1 (B2 and C2), this setting was indeed active more often than in the other conditions. As participants already used ACC 3 by default, the instruction to use this distance setting (conditions B1 and B2) did not result in more use of ACC 3 than in the baseline conditions (A1 and A3).

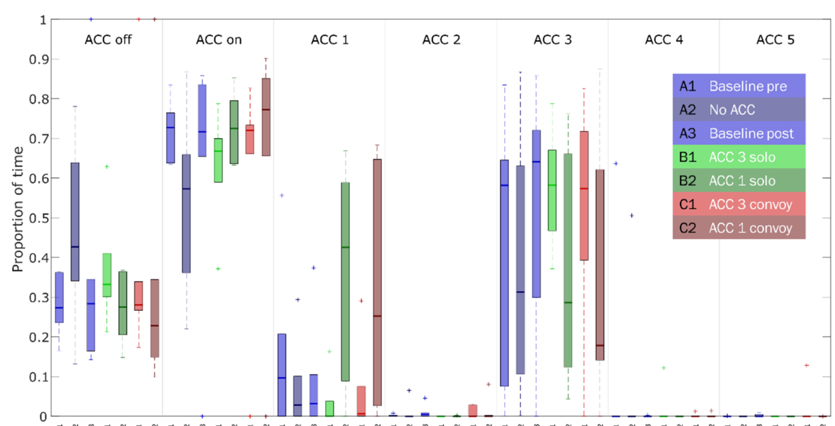


Figure 32: ACC use on highways in different conditions. Boxplots show the variation in proportion of measurement samples for different ACC settings across participants (n = 7). ACC on is all ACC settings (1-5) combined. Boxplots as in Figure 30.

Figure 33 shows the number of times the ACC system was turned on by the driver in trips that took place at least 50% of the time on the highway. As expected, ACC was turned on less often in condition A2 (no ACC use) than in the other conditions. Moreover, this frequency also tended to be less in the convoy conditions (C1 and C2), possibly because more time was spent behind a known other vehicle.

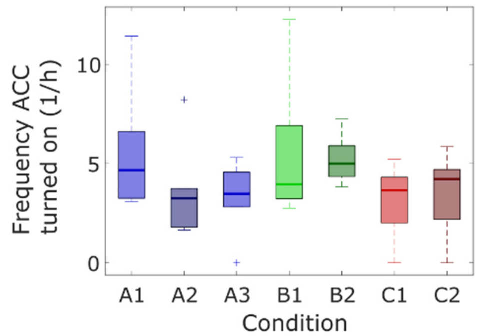


Figure 33: Frequency with which ACC was turned on (per hour) in trips with at least 50% of the time spent on the highway. Boxplots as in Figure 30.

Figure 34 shows the distribution of different ACC modes for each ACC setting. Most notably, when ACC was turned on, it was in Distance mode most of the time, indicating that the truck was following another vehicle and the system maintained the set distance, and in Speed mode, or normal cruise control mode, for most of the other time.

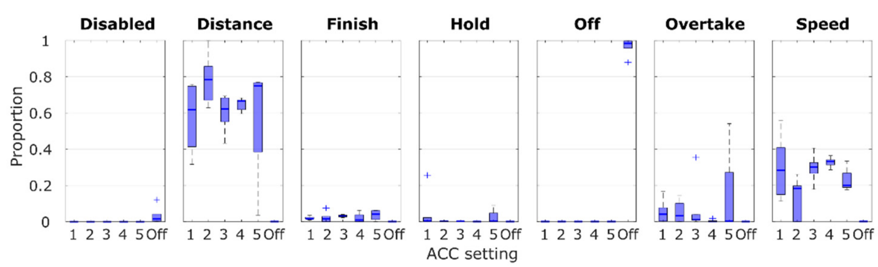


Figure 34: ACC modes at different ACC settings. Boxplots give the proportion of samples in a given ACC setting. Only samples during highway driving were used. Boxplots as in Figure 30[10].

The relationship between various driving parameters is shown graphically in Figure 35 for trips that took place for at least 50% of the time on highways. There was a clear relationship between the proportion of time the ACC system was active and mean driving speed in a trip (Figure 35a). This was confirmed by a LME analysis with mean speed as dependent variable and Condition, proportion ACC on and Speed limit as factorially combined fixed factors. Participant and Trip within Participant were used as random factors. Compared to the first baseline condition (A1), mean trip speed was higher in all other conditions, except B2 (ACC1 solo) ($F(6, 1237.2) = 23.655$, $p = 1.39e\text{-}26$).

[10] DAF ACC settings are explained in more detail in section 2.4.2.

Mean speed also increased significantly with proportion ACC on (F(1, 1238.2) = 337.02, p = 9.15e-67) and Speed limit (F(1, 1237.8) = 4.68, p = 0.03). Moreover, all interactions, except the one between proportion ACC on and Speed limit, were also significant. Details are given in Table 36 in Appendix D. Interestingly, the standard deviation (SD) of driving speed in a trip showed a curvilinear relationship with proportion ACC on (Figure 35b). Variation in driving speed was highest when ACC was active about 50% of the time, and lowest when it was on all the time. An LME analysis showed a significant difference in speed SD between conditions, with all conditions having a lower SD than A1, but this difference was not significant for conditions B2 and C1. The speed SD also decreased significantly with higher proportion ACC on. Speed limit did not have an effect. Details are given in Table 37 in Appendix D.

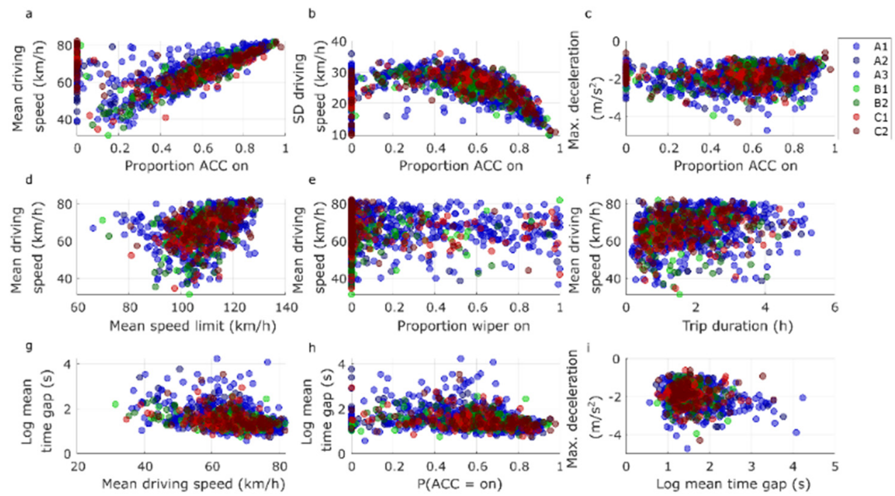


Figure 35: Driving parameters and ACC use across trips (only trips with at least 50% of the time highway driving). a. Mean driving speed versus proportion of time with ACC on; b. standard deviation of driving speed versus proportion of time with ACC on; c. maximum deceleration versus proportion of time with ACC on; d. mean driving speed versus mean speed limit during the trip; e. mean driving speed versus the proportion of time with windscreen wipers on; f. mean driving speed versus trip duration; g. log mean time gap versus mean driving speed; h. log mean time gap versus proportion of time with ACC on; i. maximum deceleration versus log mean time gap. Each dot represents data from one trip. Different colours represent different conditions (legend).

The final parameter that was investigated was the time gap, the distance between the truck and the vehicle it follows divided by the driving speed. This is often used as a measure of safety, with short time gaps implying little time to react in the case of an incident, for instance when the vehicle in front brakes unexpectedly. By definition time gap should be directly affected by the ACC distance setting, and this was indeed the case as shown in Figure 36 for driving speeds above 70 km/h. The most frequently found time gap was shortest when ACC 1 was used and longest with ACC 5. With ACC turned off, a broader distribution of time gaps was found, with a peak around the same time gap as for ACC 1, at 1.3 s. Note, however, that even shorter time gaps were much more frequent with ACC turned off than with ACC 1. These findings match those reported previously for truck driving on Dutch roads. A factsheet by the SWOV (2012) refers to a study by Hansen and Minderhoud (2003) and reports an average time gap of 1.3s.

A recent report by the Dutch Rijkswaterstaat (Dicke-Ogenia, et al. 2020) established that the most common time gap between trucks is between 1.2 and 1.4s (although the authors do not differentiate between driving with and without ACC).

The graphs in Figure 36 show that time gap distributions are strongly right skewed. Therefore, the log time gap was used in analyses. An LME analysis with Condition, mean driving speed and proportion ACC on per trip showed that log time gap on average was not affected by Condition ($F(6, 1163.4) = 0.90$) or proportion ACC on ($F(1, 1141.6) = 1.90$, $p = 0.17$), but decreased with mean driving speed ($F(1,1123.1) = 17.28$, $p = 3.48e-05$). For every km/h faster, log time gap decreased by 0.027 s. This is also visible in Figure 35g. Analysis details are given in Table 38 in Appendix D. It can be observed that the most common time headway for ACC 1 equals the most common time headway when ACC is switched off; namely 1,3 seconds.

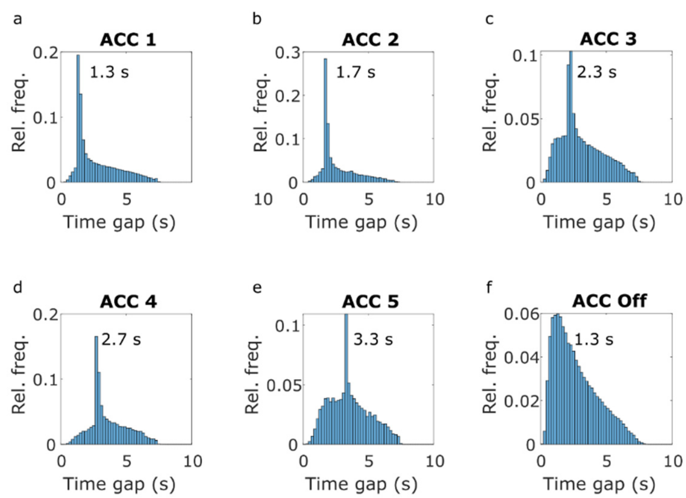


Figure 36: Time gap distributions for different ACC modes for driving speeds above 70 km/h. Numbers next to the peaks indicate the most common time headway for a given ACC mode.

4.4.3 *Heart rate data*

Fitbit Ionic smartwatches were used to measure heart rate in all seven participants during their daily work. The aim was to investigate the use of these devices to measure stress and workload responses to driving conditions, including the use of ACC and potential incidents. However, the devices turned out to produce highly unreliable data in all participants.

Figure 37 shows representative data from one participant. Numerous large jumps in heart rate up to 50 bpm can be seen that could not be related to changes in physical activity or driving circumstances as verified from the camera images. As shown in Table 13, average heart rate was close to 120 bpm for all participants, which is highly implausible for healthy persons in a sedentary job.

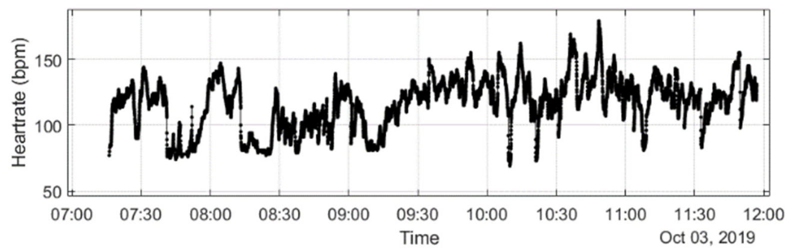


Figure 37: Exemplary Fitbit heart rate data from one participant.

Heart rate as measured with the Fitbit was compared to that measured with a Polar H10 breast belt in one participant. The previous model of the Polar device has been found to measure heart rate more accurately than wrist-worn devices (Passadyn, et al., 2019). As shown in Figure 38, the Polar device recorded a much lower heart rate than the Fitbit. Across the six days that both devices were worn by the same participant, median heartrate was 67 bpm as recorded by the Polar versus 125 bpm by the Fitbit. Therefore, we concluded that the Fitbit heart rate data was unreliable and could not be used to evaluate driver responses to incidents or ACC use. As yet, we do not have an explanation for this unreliability. We ruled out any errors in data processing by ascertaining that the high heart rates were indeed recorded by the Fitbit itself and did not arise from later processing steps. Possibly, despite our instructions, the Fitbit devices were not worn properly by our participants. However, visual inspection of the video images gave no reason to assume this. Alternatively, some factors in the truck cabin environment, such as vibration or electromagnetic radiation may have affected the reliability of the Fitbit measurements. Further research would be needed to pinpoint the exact causes. It must also be noted that participants objected to wearing a breast belt all the time, so using this type of heart rate monitor may not be a viable option for measuring heart rate in many participants either.

Table 13: Fitbit heart rate descriptive statistics. Nr Days: number of days during which heartrate was recorded; Min HR: minimum heart rate recorded; Max HR: maximum heart rate recorded; Median HR: median heart rate recorded.

Participant	Nr Days	Min HR	Max HR	Median HR
1	78	46	201	118
2	50	51	206	120
3	58	55	195	117
4	64	52	188	114
5	82	46	209	121
6	84	46	207	118
7	86	42	185	117

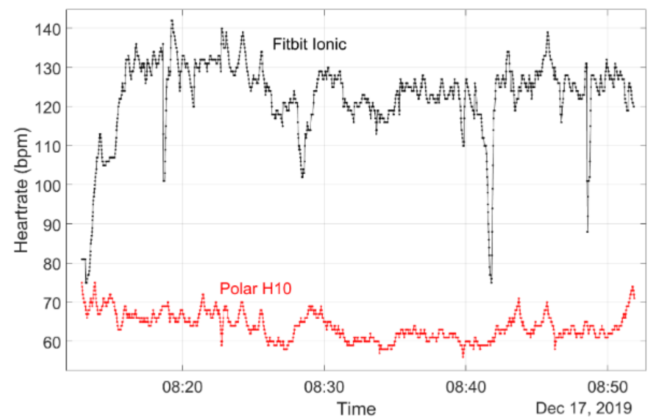


Figure 38: Sample heart rate data for one participant. Black: Fitbit Ionic; red: Polar H10.

4.5 Conclusions

RQ 2.1: How is the ACC system used?
Use of different ACC settings differed across conditions, indicating an effect of the instructions participants were given. On highways, ACC was turned on approximately 75% of the time. When the ACC system was active, it was mostly in Distance mode, indicating that the truck was following another vehicle. The most frequent time gap to the lead vehicle when driving without ACC was about 1.3 s, which was similar to the one with ACC at the shortest distance setting.

RQ 2.2: Did the drivers' evaluation of the ACC system and of the overall driving experience differ between campaigns with different instructions regarding ACC use?
Participants indicated a high degree of acceptance of the ACC system, both in terms of usefulness and satisfaction. They also indicated a high degree of trust in the ACC system, on both underlying dimensions (usage and trust). No significant differences in acceptance or trust between different conditions were observed. In general, participants were already used to driving with ACC. Some of them reported to find driving without ACC strenuous. Also, having the ACC distance set to the shortest distance was experienced by some drivers as uncomfortable.

RQ 2.3: Is there a relationship between acceptance of and trust in the ACC system and how often this system has been used?
Acceptance of and trust in the ACC system did not depend on how often ACC was used.

RQ 2.4: Does reported workload differ between campaigns with different instructions regarding ACC use?
Self-rated effort decreased over time, leading to significant differences between campaigns. However, since this also lead to a significant difference in self-rated effort between the two baseline conditions (pre and post), this effect of campaign was probably more an effect of time, rather than of the instruction to use a certain ACC setting. Participants generally reported a low level of job strain, both in terms of fatigue and sleeping problems.

For the latter, there was more variability between different participants. No significant differences in job strain responses were found between different campaigns.

RQ 2.5: Is the reported workload related to how often ACC has been used?
No relationship between effort and ACC use was observed.

RQ 2.6: Is the reported workload related to driving speed?
No relationship between effort and mean driving speed was observed.

RQ 2.7: Is the reported workload related to heart rate?
The poor quality of the heart rate data did not allow us to evaluate this relationship.

RQ 2.8: Does the mean driving speed differ between different campaigns?
Mean driving speed was higher in most campaigns than during the baseline period at the beginning of the study. It is unclear to what extent this was due to the different instructions regarding ACC use, or to other factors such as changing weather, day length or traffic density. There also was a clear relationship between driving speed and the proportion of time ACC was turned on (ACC was active more often at higher speeds).

RQ 2.9: Do acceleration distributions differ between campaigns?
Due to the lack of 10 Hz data, acceleration distributions could not be reliably evaluated. Instead, we analysed time gap data. Mean time gap decreased with increasing vehicle speed, but was not different for different campaigns, nor did it depend on the proportion of time the ACC system was active. As expected, a clear effect of ACC distance setting on time gap distribution was found, with higher distance settings leading to larger time gaps.

RQ 2.10: Is maximum deceleration related to ACC use?
Similarly to the acceleration data, the lack of 10 Hz data made it difficult to evaluate maximum deceleration reliably.

RQ 2.11: Does ACC use depend on the weather?
No relationship between ACC use and windscreen wiper use was observed. As we used windscreen wiper as a proxy for the weather, no relation between ACC use and weather is observed.

5 Logistics Integration and Business Case

5.1 Introduction

Logistics partners in the supply chain need a viable logistic business case for successful and scaled-up deployment. Theoretical research (Van Ark et al., 2017) shows that positive business cases are possible under the right circumstances. Verifying these scenarios by real-world experimenting and testing is the next step. Once it can be proven with real-world data that the logistics business case is positive, a significant step can be made towards deployment of truck platooning.

Therefore, the overarching research question in the Integrator project is:
What is the logistics business case of truck platooning? By answering this question we analyse how platooning integrates into regular logistics and transport business and investigate the potential for logistics cost savings, based on a platoon's fuel use and CO_2 emissions in daily logistic operations while driving in mixed public traffic. In order to assess the impact of ACC driving on the logistics business case, the following sub questions are formulated:

- RQ 3.1 What are the requirements for the operational processes for preparation, formation and arrival at final destinations of ACC convoys?
- RQ 3.2 What are the potential cost savings of ACC driving based on fuel consumption and CO_2 emissions (RQ1) and impact on the professional truck drivers (RQ2)?
- RQ 3.3 What are potential measures to improve the logistics business case?
- RQ 3.4 What are boundary conditions for implementation of ACC convoy driving (and truck platooning)?

Note that in this stage we are not researching truck platoons, but develop a baseline by assessing the impacts of ACC-convoy driving. Though, by researching sub question 3.4, we aim to give an indication or an outlook for the implementation of truck platooning.

5.2 Literature

In this chapter we evaluate the elements that constitute the logistics business case. Subsequently we list some business case considerations or factors that possibly influence the logistics business case. Lastly, we summarize the business case calculations found in the literature. It should be noted that the number of studies discussed is limited, since not that much literature seems to be available that covers the logistics business case of truck platooning or (C)ACC convoy driving.

5.2.1 Business case elements

In the Value Case on Truck Platooning (Van Ark, et al., 2017) identified the value elements of truck platooning: it includes both economic aspects (for logistics service providers) and societal benefits (see Figure 39).

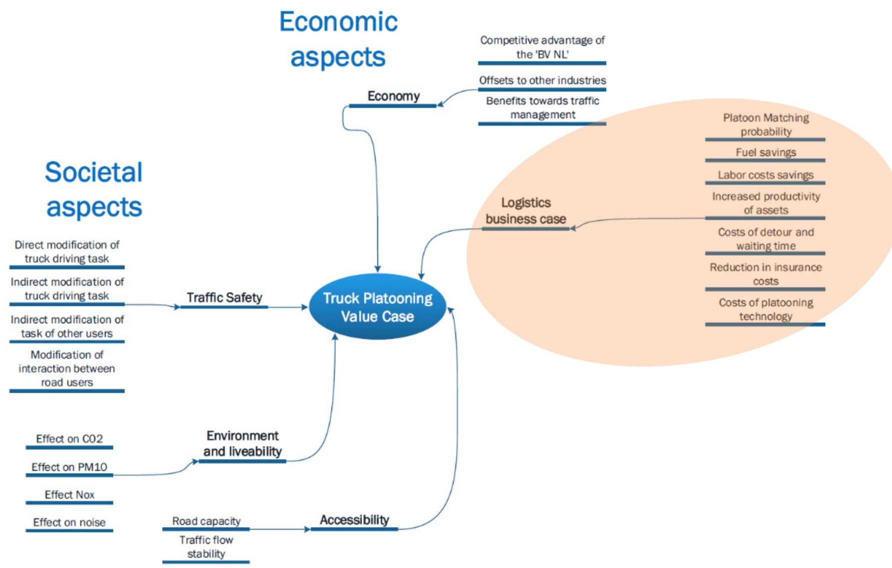


Figure 39: Value elements of truck platooning Adapted from Van Ark et al. (2017). Logistics Business case highlighted.

By conducting literature review, consulting TNO colleagues and experts from the field Van Ark et al. (2017) identified the following elements that constitute the logistics business case:

- **Platoon matching probability**
  The platoon match rate is the number of kilometres driven in platoon formation as percentage of all eligible kilometres. Benefits of platooning only accrue when trucks have actually driven in platoon formation. The platoon match rate is an indicator for this.
- **Fuel savings**
  A reduction in fuel consumption can be achieved by truck platooning because of a reduction in aerodynamic drag and air resistance.
- **Labour cost savings**
  This depends on the operational capability (amongst others the level of automation) and the legislation. The higher the level of automation, the more potentially can be saved on labour cost if legislation allows for less driver interaction.
- **Costs of detour and waiting time**
  For platoon formation it might be the case that the trucks have to make a detour or that one of the trucks has to wait for the other platooning partner. Van Ark et al. (2017) focus on a corridor with a relative high freight traffic density. They calculate that the leading truck would lose around 30 seconds in a heavy traffic scenario. Consequently they assume that such a delay is negligible and thus they do not take these costs into account in the final calculation of the logistics business case.
- **Reduction in insurance costs**
  Four factors will impact insurance costs of truck platooning/ automated driving: accident reduction, shift of liability, increased hours of service and enforcement (Bishop, 2015). Van Ark et al. (2017) assume that insurance costs do not decrease until a 50% adoption is reached.

- **Costs of platooning technology**
  In 2017 there was no official commercial price list available for platooning technology. (Van Ark et al., 2017). Based on literature review Van Ark et al. (2017) estimated a cost per vehicle of 12.000 EUR, assuming large-scale deployment.

In 4.2 we describe in more detail which factors will be included in the set-up of the logistics business case. In short we focus on: *fuel savings, labour cost savings, costs of detour and waiting time*. And for improving the logistics business case we also take matching probability into account. Thus we exclude increased productivity of assets, reduction in insurance costs and costs of platooning technology from our study as these cannot be derived directly from the data that will be gathered.

5.2.2 Business case considerations

The Research project "Heavy Truck Cooperative Adaptive Cruise Control: Evaluation, Testing, and Stakeholder Engagement for Near Term Deployment," led by Auburn University, performed research and evaluation to assess the commercial viability of truck platooning (Bevly et al., 2015). By conducting a survey among industry contacts of the American Transportation Research Institute (ATRI) such as motor carriers, company drivers, owner-operators and trucking association executives they compiled a list of issues and considerations concerning the business case of "Driver Assistive Truck Platooning" (DATP)[11].

Below the ones that are probably also relevant in the Netherlands are listed:

- **Industry sector**
  DATP is probably most advantageous when travel speeds are higher, truck trips are longer and the likelihood of encountering trucks with C-ACC technology is high. The following types of routes are considered to satisfy these provisions:
  - Pre-determined routes or corridors between large freight generators (business parks, manufacturing centers, warehouses, retail establishments).
  - Line-haul routes that both utilize hub and spoke pick-ups and deliveries in urban areas and rely on the line-haul trips that connect the consolidation terminals in different urban areas.
- **Commodity types**
  Most freight would be equally suitable for DATP. Some anecdotal evidence exists that heavier commodities would benefit slightly more compared to light commodities with respect to fuel savings.
- **Truck trip length**
  It is hypothesized that the longer a truck is a truck platoon, the greater the benefit. Therefore, it is expected that longer trip lengths generate a higher Return On Investment (ROI).
- **Truck driver involvement**
  Anecdotal evidence suggests that technology acceptance improves with familiarity and training.

[11] This label was chosen for Cooperative Adaptive Cruise Control (C-ACC) in order to support stakeholder engagement with the trucking industry. "In DATP, two or more trucks are exchanging data, with one or more trucks closely following the leader. The technology basis includes radar (for longitudinal sensing), V2V communications (for low latency exchange of vehicle performance parameters between vehicles), satellite positioning (sufficient to discriminate in-lane communications from out-of-lane communications), actuation (for vehicle longitudinal control), and human-machine interfaces (with distinct modes for leading or following)." (Bevly et al., 2015; p.11).

5.2.3 *Business case calculations*

Van Ark et al. (2017) made logistics business case calculations as part of their value case assessment of truck platooning on the Dutch freight corridor Rotterdam – Venlo (using the A15 / A16 / A58 / A67 motorways).

A distinction is made between varying levels of automation of the truck driver's tasks. At Initial Operating Capability (IOC) the leading vehicle of the platoon is manually driven and the following vehicle uses Cooperative Adaptive Cruise Control (CACC) for longitudinal control. In case of Full Operating Capability (FOC), the driver's tasks are fully automated and the following vehicles could be driven without driver on motorway sections. Mid-term Operating Capability (MOC) is somewhat in between: drivers in the following vehicle are still present and may get their hands, feet and/ or eyes of their work for a limited or specified amount of time.

Figure 40 shows the calculations for a natural deployment scenario. In this scenario the timelines for deployment are derived from official automotive roadmaps (ACEA and ERTRAC). It can be seen that the logistics business case becomes only positive in case of Full Operating Capability, thus when no driver is present in the following vehicle. Labour savings take the largest share of cost savings in this (theoretical) business case calculation.

Value Case Truck Platooning	Natural Deployment scenario			
	2020	2023	2029	2030
Operating Capability	IOC	MOC	MOC	FOC
Value case result	**Total [€/yr]**	**Total [€/yr]**	**Total [€/yr]**	**Total [€/yr]**
L1: Technology costs	-25.000	-371.000	-6.735.000	-10.970.000
L2: Fuel savings	-	1.000	3.616.000	7.429.000
L3: Labor savings	-	1.000	1.961.000	37.830.000
L4: Asset savings	-	-	865.000	1.483.000
L5: Insurance savings	-	-	50.000	1.261.000
Total-Logistic case	**-25.000**	**-369.000**	**-243.000**	**37.033.000**

Figure 40: Logistics Business case (Van Ark et al., 2017).

It is, however, quite uncertain whether this Full Operating Capability driverless platoons will be realized, based on insights of recent research projects (ENSEMBLE, EDDI) and Daimler's announcement to re-evaluate its platooning activities (Lopez, Supply Chain Dive, 2019). Therefore, based on these new insights, in our business case calculations we will not take labour cost savings (as a result of driverless platoons) into account.

Since the publication of the conceptual paper of Van Ark et al. (2017), several other publications appeared with respect to the business case of truck platooning or ACC convoy driving, these are summarized in Table 14. Some of these were published while this project was being started, so by progressive understanding this also feeds our research. The overall trend is that fuel cost savings are quite marginal, especially compared to potential labour cost savings in case of full operating capability or driverless platooning.

Table 14: Overview studies business case.

Study	Source	Main conclusion
Value Case Truck Platooning (2017) (Van Ark, et al., 2017)	Conceptual report. Corridor approach	Positive business case for driverless truck platooning. Fuel savings alone are not enough for positive business case.
Daimler (2019) (Lopez, Supply Chain Dive, 2019)	News article	The business case for fuel savings resulting from truck platooning is limited. Therefore future R&D efforts will be more directed towards SAE L3/L4 trucks.
EDDI (April 2019)	Final presentation, based on field tests with MAN.	In the field test, a fuel saving of 3-4 % can be achieved for the following vehicle with the given conditions (gap distance 15 m.).
Sweden4Platooning (2020)	Report (partly) based on real life tests with Volvo and Scania.	Fuel savings of 1,6-7,4% are presented at a gap distance of 1,2 s. Due to confidentiality the real numbers are not presented. The authors conclude that there is a very large potential of improving the business case in the scenario of fully autonomous trucks or when drivers are allowed to perform other tasks when platooning.
Interreg – IAT (February 2020)	Workshop Logistics Business case	Net fuel benefit of platooning due to shorter following distance will be relatively small compared to the fuel benefits resulting from ACC.

5.2.4 *Boundary conditions*

Boundary conditions often listed for a viable business case is the adoption rate of the technology and thus the number of vehicles outfitted with interoperable (multi-brand) platooning technology. The match rate – the number of kilometres driven as platoon as ratio of annual kilometres driven – heavily relies on this and in turn has a major impact on the logistics business case (Van Ark, et al., 2017).

Next to that, the Netherlands can be considered a transit country and therefore the viability of implementation of truck platooning in the Netherlands hinges upon the connectivity to our neighbouring countries. Therefore we provide a concise overview of legislative issues to take into account in Appendix E.

Lastly, with respect to cross-border platooning, the findings of the Dutch-German project Interregional Automated Transport (Interreg- IAT) are worthwhile to highlight. In this project a field test with cross-border platooning on Dutch-German corridors was executed (70.000 kilometres driven). One of the issues that was encountered during border crossing was the roaming gap. The V2V communication in the trucks is constantly seeking for the best communication network, which can lead to delays or even to complete discontinuation of the data connection (Transport en Logistiek, 2020).

5.3 Methodology

In section 2.4.4 we describe the data sources that we use (See Table 2) for answering the logistics research questions. Subsequently in section 2.8.3 we describe the steps we use for analysis (See Figure 14).

Based on the literature review we refine the RQs in the following way:

RQ 3.1* What are the requirements for the operational processes for:
   a. Preparation,
   b. Formation and
   c. Arrival at final destinations of ACC convoys?

RQ 3.2* What are the potential cost savings of ACC driving based on
   a. *Fuel savings,*
   b. *Labour cost savings*
   c. *Costs of detour and waiting time*?[12]

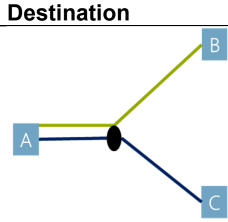
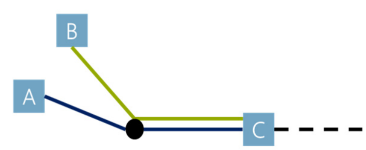
RQ 3.3* What are potential measures to improve the logistics business case?
   a. What are the qualitative measures for increasing the number of convoys (matching probability)?

RQ 3.4* What are boundary conditions for implementation of ACC convoy driving (and truck platooning)?
   a. From a logistics operations (industry sector, commodity types) perspective?
   b. From a planner and driver perspective?
   c. From a transport management perspective (match rate, legislation)?

5.3.1 Planners meeting

For the driving campaigns that involve ACC-convoy driving (C1&C2), convoys are scheduled, i.e.: actively planned by the transport companies. To ensure the same starting point for all partners, a meeting with the planners and the transport managers is set up. Furthermore, by this meeting we aim to involve the planners in the (social) innovation process, as the Experience Week Connected Transport 2018 has shown that this is also an important stakeholder group .
Three different convoy configurations were presented and discussed during the meeting, see Table 15.

Table 15: Possible convoy configurations.

I. Same Origin and Destination	**II. Same Origin different Destination**	**III. Different origin same Destination**
		
Possible Consequences		
• Requires overlapping routes • Might require waiting at origin (f.e. deep sea terminals Port of Rotterdam). • Challenging to stick together during the whole trip.	• Might require waiting at origin (f.e. deep sea terminals Port of Rotterdam). • Might be easier to sustain as it is not required to stick together during the whole trip.	• Challenging to find one another physically (f.e. at a truck stop). • Waiting time at meeting place can be unreliable.

[12] Thus, we exclude increased productivity of assets, reduction in insurance costs and costs of platooning technology from our study as these cannot be derived directly from the data that will be gathered.

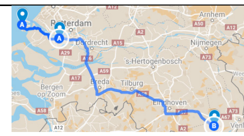
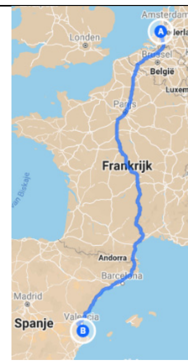
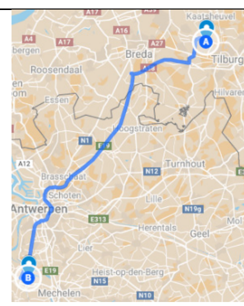
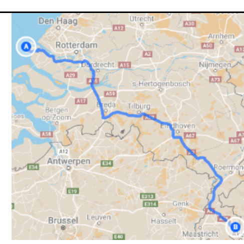
The following agreements were made during this session:

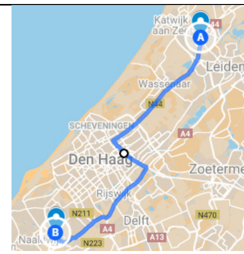
- For a period of 1 driving campaign (2 weeks), the aim is to plan at least 1 ACC-convoy with the instrumented vehicles per day.
- The aim is to drive at least 50 kilometres in one ACC-convoy trip.

5.3.2 *Introduction to the use cases*

Six different transporters, either specialized in container or flower logistics, participate in het Integrator Connected Truck Trials. Together these constitute five different use cases as summarized in Table 16.

Table 16: Use cases.

	ACC Convoy driving use case	Example map of route	Involved partners
1	Container transport multifleet: Port of Rotterdam – Venlo		De Rijke & Overbeek DHL Global Forwarding
2	International conditioned transport single fleet: The Netherlands -Spain		Getru
3	Full truck load transport single-fleet: GVT Tilburg – GVT Willebroek (BE)		GVT group of logistics
4	Container transport single-fleet: Port of Rotterdam – Hinterland		Starmans

5	Flower transport single fleet: Auction Rijnsburg – Auction Naaldwijk		Koninklijke Van der Slot transport

5.4 Results

As presented in Table 3 there were two times 2 weeks of convoy driving: one with ACC mode 3 (~50 m. with 80 km/h) and one with ACC mode 1 (~33 m. with 80 km/h). During these weeks in total 41 convoys and were driven (29 convoys use case 1 ~ 4500 kilometres; 12 convoys use case 3 ~ 677 kilometres).
Below, we list the general observations for each use case.

	General observations
1. Container transport multi-fleet: Port of Rotterdam – Venlo	Since this use case entailed multi-fleet convoy driving, data sharing among the transporters and shipper was required. Also agreements between the drivers were made with respect to the meeting place (Shell tank station next to the A15 motorway).
2. International convoys	It was intended to create a convoy that would cross several countries (Spain, France, Belgium, The Netherlands). However, it turned out that one of the instrumented vehicles needed to be double manned (two drivers) instead of single manned. This was enforced as vehicles need to drive a specific amount of kilometres before the end of term of the leasing contract. This had implications for the driving and resting times of this vehicle. As the other vehicle was still single manned, the driving and resting times were out of sync and thus it was not possible anymore to plan convoys with these two vehicles.
3. Full truck load transport single-fleet: Hub Tilburg – Hub Willebroek (BE)	Since the trucks had to execute various trips or assignments during the day, planners were tended to plan the first trip as a convoy in order to improve the possibility that the convoy could be realized without any waiting time. This resulted in very early morning shifts for the truck drivers (earlier than they were used to).
4. Container transport single-fleet: Port of Rotterdam – Hinterland	Convoy driving is something that the involved persons had to get used to (drivers, planners, the rest of the organisation. Normally, there are also certain activities that certain vehicles can or cannot do. In that sense, planning convoys is the same: it is an extra requirement for the instrumented vehicles.

5. Flower transport single fleet: Auction Rijnsburg – Auction Naaldwijk	As flower transport involves fresh products, timing is crucial. It was only possible to form convoys if the volume equalled exactly 2 FTL's. If this was not the case, no convoy could be formed (despite the route being the same). Waiting time before departure was not allowed.

5.4.1 *Changes in operational processes*

We distinguish three phases in the operational process: convoy preparation and planning, convoy formation and convoy arrival (see Figure 41). We elaborate on these below.

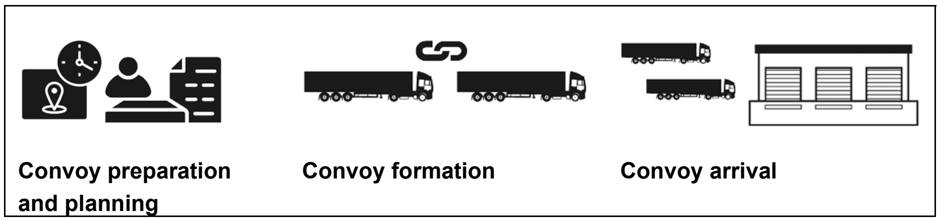


Figure 41: Operational process (schematic representation).

- Convoy preparation and planning
  - Planner instruction. Planners were instructed to plan the convoys. In general, since this was a dedicated project with 1 or 2 trucks per partner, 1 person was involved in planning the convoys. See for more information on the planners' perceptions below.
  - Overlapping routes. As highlighted in Table 15 overlapping routes are required for planning a convoy.
  - Timing. Also, transports needed to have a similar timing, or a timing that was flexible so that transports could be synchronized.
    We observed several coping strategies here:
    a. First thing in the morning. In order to guarantee the same starting time of the trucks involved in the convoy and minimize the risk of waiting, the convoys were planned as the first transport of the day.
    b. Decouple pick-up at port terminal and next day transport. Due to high variability in handling times at the container terminals of the Port of Rotterdam, some transporters decided to schedule container pick-up at the end of the day, park overnight and schedule the convoy the next day to minimize the risk of delays for convoy formation. So in order to be able to form convoys, an inefficiency was built in the process.
    c. No waiting time allowed. If vehicles were not fully loaded at the same time, no waiting time was allowed and the trucks drove the same route separately.
    d. Driving and resting times. Especially for international transport it turned out that the possibility to have synchronized driving and resting times is a crucial prerequisite for forming convoys.
  - Data sharing for multi-fleet convoys. The transport assignments for the multi-fleet convoy were given by a shipper. This eased the process of aligning two transports with the same destination and the same time slot.

Still, the transporters had to agree on the departure time, meeting place, share number plates of the involved trucks and share contact details of the involved truck drivers.

- Convoy formation
  - Meeting place.
    a. All single fleet convoys had the same origin and destination (type I in Table 15). So the meeting place was the point of departure (usually their home base).
    b. The multi fleet convoy had different origins and the same destination (type III in Table 15). Therefore the different transport companies had to agree on a meeting place. This was usually a tank station next to the A15 motorway, close to their home bases and on-route of their final destination. On the day itself the drivers arranged the meet-up and kept in touch via telephone and/ or WhatsApp.
  - Convoy continuation.
    a. Some of the drivers reported that a difference in engine power could affect the ease of sticking together as a convoy. For example, when the leading vehicle had a more powerful engine (or lower payload), in case of acceleration, the following vehicle sometimes could experience difficulties of keeping up. Once the drivers experienced this, the leading driver took it into account when accelerating.
    b. Cut-ins by other traffic. One of the main issues the truck drivers highlighted were cut-ins by other traffic; mostly passenger cars who would drive between the leading and following vehicle (for a limited amount of time). It should be noted that this is not something unique for ACC convoy driving only. Also in case of solo driving, the truck drivers report that other road users – especially personal cars – tend to join or leave the highway just in front of their truck, which might cause a startle response and irritation – and of course requires braking either by the driver or by the ACC.
- Convoy arrival
  - The drivers did not report any special events when their convoy arrived at the final destination.
  - The maximum waiting time reported at the final destination equals 5 minutes.

Reflections of key players involved

- Truck drivers
  - Most truck drivers who participated in the project were enthusiastic and eager to participate in a project like this. Their employers also selected them based on their enthusiasm. The drivers indicated that the day at the test track was very helpful to get to know the project, each other, and drive with various ACC-settings. Some concerns were raised with respect to the future of their profession. Together with their management we tried to reassure them as much as possible.
- Transport planners
  - For the transport planners a special meeting was organized just before the driving campaigns with planned convoys would start. Due to the workload not every planner could attend this meeting. The instructions were shared by their managers. They indicated that most planners consider planning convoys as an extra burden. It is something on top of their usual workload. And sometimes it also felt counterintuitive for the planners to plan the convoys; normally trucks leave once they are loaded.

And no extra step is required to check whether a convoy can be formed with the other, instrumented vehicle.

- Transport management
  - Information and ideas were exchanged between the partners, which was considered to be very positive. Furthermore, the transporters are always keen to find out new ways to reduce fuel consumption, improve safety employee satisfaction. Hence the transporters also participate in or closely follow the developments of related projects such as Connected Transport Corridors and the living lab CATALYST.
  - The transporters acknowledge that planning the convoys did not always turn out according to plan. Looking towards the future they think that planning convoys is only necessary in the transition phase. Ultimately, they envision every truck on the road equipped with the right technology to form convoys or platoons ‘on-the-fly’; with limited involvement of planners and no alterations to their operational processes.

5.4.2 Logistics business case elements

Logistics business case – based on fuel savings (CH4, Table 25) and impact with respect to human interaction (CH5), the potential cost savings for LSPs will be determined under different circumstances using various scenarios.

Operational processes

Even though some planners considered planning the convoys as a burden, no specific extra planning time was reported. With respect to the waiting times for the drivers, the drivers were asked to fill out the survey after each trip. Unfortunately, waiting times for the convoy driving campaigns were reported irregularly and not consistently for every convoyed trip. Waiting times before convoy driving ranged from 0-10 minutes. If waiting times were reported, this mostly equalled 2 minutes. Equally, waiting times before unloading at final destination were reported infrequently. Most reports were made by the drivers of one transporter only and in these instances always equalled five minutes.

Based on interviews with the transporters, revenues per hour driven range from €65,- to €75,- EUR, depending on the subsector. Thus, based on these transport management reports costs of waiting equal: €1.08-€1.25 per minute as it is assumed these minutes reflect the lost revenues[13].

Fuel consumption

Resulting from the analysis in Chapter 3 - Fuel consumption and emissions, it can be stated that on average the use of ACC reduces fuel consumption. Also based on convoy data (29 convoys, 4.500 kilometres), we can provide the example below in Table 17 of a convoy that drives from Rotterdam to the hinterland (158 kilometres).

From the fuel consumption analysis it follows that when driving in ACC 3 and following another vehicle, fuel savings of 4.3 % can be realized, for ACC 1 this is on average 5.6%. These percentages are based on average fuel rates throughout a trip and do not account for variations. Given the preconditions as described, this leads to the following fuel consumption and related costs – based on the average fuel price in 2020 of €1.14/L (Evofenedex, 2020):

[13] In Sweden4Platooning costs of waiting include: Driver + insurance, taxes, mobile phone + depreciation + capital costs. This compared with fuel savings.

Table 17: Illustrative example of fuel consumption and costs on a trajectory from Rotterdam to the hinterland. Note that this is highly illustrative since this example is based on average fuel consumption and does not take into account the variations in one trip.

	Average corrected fuel consumption (L/100 km)					
	Total	Convoy ACC 1	Convoy ACC 3		Convoy ACC 1	Convoy ACC 3
Trailing truck	22	20.8	21.05		-5.6%	-4.3%
Suppose the trucks drive 158 km. from Rotterdam to Venlo. Fuel costs (and savings) would look like the following, given a fuel price of €1.14/L.					Average Fuel savings.	
Trailing truck	€ 39.63	€ 37.46	€ 37.92		€2.17	€1.71

When looking at these savings of €1.71 - €2.17 one can conclude that on a 158 kilometre trip (taking about 2 hours driving at a speed of 80 km/h), hardly any waiting times for convoy formation can be allowed as the costs of 1 minute waiting (€1.08-€1.25) consumes already a large share of the benefits. In the Sweden4Platooning report it is assumed that fuel savings are balanced among the platooning partners and then it can be viable. Lastly, as trucks usually drive in ACC3, the net savings will not be as large as one could expect when comparing ACC off versus convoy driving, as in reality trucks already materialized part of these savings by switching on ACC in solo.

Human interaction

Resulting from the analysis in Chapter 5, it can be stated that self-reported effort was higher in the campaign without ACC. The ACC mode seems to be less important for experienced effort. Unfortunately the Fitbits produced no reliable results for the heart rate monitoring. Combining this with an overall good acceptance and trust of (A)CC, at this point we are not able to include any monetary values for this aspect in the business case.

5.4.3 *Improving logistics business case elements*

For each use case it is explored to what extent there is potential for forming single fleet convoys. First of all, potential corridors are discussed with the transporters. Second, based on the HI and FC analysis it is investigated whether the trucks could have switched on ACC during the driving campaigns, while they did not. Lastly, the planned versus the realized convoys where compared to see whether there were more planned than realized convoys.
Table 18 presents these findings. The last columns indicate to what extent improvement is possible (green: full potential realized; orange: potential with some barriers to overcome; red: no further potential).

It can be seen that for three out of five use cases, the transporters see potential for forming single fleet convoys given certain conditions. For international transport (use case 2) it is important to: 1). Synchronize the driving and resting times by having the same amount of drivers in each truck of the convoy and 2). Take account for the delivery windows of the receivers and if possible make agreements on those. For the last two use cases that we discuss here, the transporters do not see the potential for forming convoys within their own fleet at a regular base. It might be that occasionally two trucks have the same destination (use case 1) or that occasionally two trucks are loaded at the same time (use case 5). However, this is not foreseen in a standard planning.

Table 18: Potential for increasing the number of convoys (green: full potential realized; orange: potential with some barriers to overcome; red: no further potential).

	Indication of potential		
Potential corridors	1. Container transport single fleet	Within the own fleets of the transporters in this use case it is very hard to form single fleet convoys. Hardly ever do trucks (un)load at the same address on a daily basis. Many customers spread their orders during the week.	red
	2. International transport single fleet	Each Friday about 15 trucks leave to Spain. It could be possible to make 2-3 convoys on a weekly basis. An important condition is that agreements with the final receiver are made about arrival times. For some clients (for example supermarket distribution centers in Southern France, there is only a 30 minute delivery window). Another important condition here is that the driving and resting times are synchronized (so only trucks with the same number of drivers can drive together as a convoy).	orange
	3. Full truck load transport single-fleet	The trucks in this fleet mainly drive short distances in the Benelux region. It is possible that about 60 vehicles are driving at the A50 motorway throughout the day. However, synchronizing the timing of these is challenging, especially when the vehicles have multiple stops throughout the day.	orange
	4. Container transport single-fleet	At the moment on the trajectories Rotterdam-Venlo/Kerkrade trucks are loaded every 30 minutes. About 20 trucks each day. Depending on the economic calculation fuel savings versus waiting time, it could be possible to form more convoys here.	orange
	5. Flower transport single fleet	Potential trajectories are between the Flower Auctions of Aalsmeer, Rijnsburg and Naaldwijk. However, it is very hard to synchronize the times of departure of the trucks. Depending on the season, trucks leave from the Auction Aalsmeer and the Auction Rijnsburg every 30 minutes. No waiting time is allowed. So for single fleet convoy driving there is hardly any potential here.	red

Potential kilometres		From it results that 32.732 kilometres are driven with ACC switched on and with leading a vehicle at a distance closer than 75m. (ACC 1 ~6.456 km. and ACC 3~26.276 km). Also 13.995 kilometres are driven at a distance closer than 75m, but without ACC switched on. Therefore, the percentage of kilometres driven in ACC relative to the maximum potential kilometres accounts for 70% (32.732/46.727), still leaving a 30% unexploited potential. However, it should be noted that of these 13.995 kilometres, 3.300 kilometres were in driving campaign A2 where drivers were instructed to switch of ACC as much as possible.	
Planned versus realized convoys		During the convoy periods, all planned convoys were executed. It should be noted however that not for every use case it was feasible to plan 1 convoy per day during the specific driving campaigns.	

Lastly, it is often debated to what extent the following distance contributes to the business case. A recent report of Rijkswaterstaat (Dicke-Ogenia et al., 2020) shows that the gap distance of trucks on the Dutch highways equals approximately 1.3 seconds. This is on average shorter than the gap distance based on ACC mode 3 (~50 meters at 80 km/h) or ACC mode 1 (~33 meters at 80 km/h). Therefore it is questionable to what extent ACC driving leads to an additional fuel saving caused by aerodynamic drag compared to normal everyday traffic. Though, it should not be neglected that the fuel consumption results reflect that the IQR, thus the *variability of fuel consumption results decreases* when ACC is switched on.

5.4.4 Boundary conditions and requirement for implementation

Here we make a distinction between: single-fleet convoy driving, multi-fleet convoy driving and truck platooning.

- Single fleet convoy driving
    - Involve planners: despite the planners meeting that we set up, planners were involved and committed to a limited extent. Consequently, the amount of planned convoys depended quite heavily on the top-down instructions of management.
    - Enough volume on the same corridor and at the same time is required for ensuring that two trucks can form a convoy together.
    - Insight on maximum waiting time allowed to still reap the benefits. In the use cases in our study we see that depending on the type of transport, there is more or less sensitivity for time windows at the delivery address. In that sense, our findings corroborate with (Bevly et al. (2015) as they also suggest that benefits of truck platooning might depend on the industry sector. We observe a difference between fresh products (use case 5) and international transport (use case 2).
    - Synchronize driving and resting times for international transport. When drivers have different driving and resting schedules it is not feasible to form a convoy.

    - Unloading capacity at receiver side and time windows at receiver side are required. Shippers might possibly have a role here by making agreements with the receivers and transporters.
- Multi fleet convoy driving. Basically happening already on-the-fly when drivers switch on ACC and follow some vehicle. The lead vehicle might not always be aware of this in contrast to planned convoys where drivers intend to stick together.
    - By planned single/multi fleet convoy driving you can ensure that a vehicle is followed in ACC, and you can maximize the fuel saving benefits compared to following random vehicles 'on-the-fly', where gap distances are likely to vary along the trip.
- Truck platooning: Transporters consider 'multi-fleet convoys or platoons as the most realistic future scenario. An important precondition is that trucks are equipped with the needed technology by default so that matching can take place 'on the fly' rather than planned or scheduled.

5.5 Conclusions

Logistics integration – RQ3.1* What are the requirements for the operational processes for preparation, formation and arrival at final destinations of ACC convoys?

1. Convoy preparation. **Synchronized timing** of the vehicles is crucial and makes planning a challenge. This is illustrated by the relatively few planned convoys (only in 3 out of 5 use cases).
2. Convoy formation. In case of different origins, a **meeting place** (like a tank station) contributes to the success of the convoy formation. Clear agreements on waiting times should be made.
3. Convoy continuation. **Differences in engine power** affect the ease of sticking together as a convoy. Especially if the leading vehicle has more power sticking together becomes more challenging.
4. Convoy continuation. **Cut-ins by other traffic** were one of the main issues drivers highlighted. Though this is also a source of nuisance without convoy driving.
5. Convoy arrival. Usually **no significant additional waiting times** were reported at final destination. In the use cases handling the arrival of two vehicles at the same time was not an issue.

Logistics business case – RQ3.2* What are the potential cost savings of ACC driving based on *fuel savings, labour cost savings and costs of detour and waiting time*?

1. On average costs of waiting: €1,08-€1,25/ minute (based on €65-€75 revenues per hour).
2. Fuel savings of driving in a convoy account on average approximately for 4.3-5.6%. Savings will not be very large if there will be actual platooning, based on what we now know for solo driving and convoy driving.

Improving business case – RQ 3.3* What are the qualitative measures for increasing the number of convoys (matching probability)?

1. Potential to improve for single fleet convoys is very limited. Only in three out of five use cases the transporters see possibilities for forming single fleet convoys under the condition that: driving and resting times are

synchronized for international transport and enough volume is present on the same time for the same corridor so that departure can be synchronized.
2. Better planner involvement could improve synchronization and thus increase the amount of planned convoys.
3. Among these use cases there is still 30% of unexploited potential to switch ACC on. In these instances trucks were within following distance (<75 m.) of a predecessor, but did not use ACC.
4. In all use cases all planned convoys were also realized.
5. Fuel savings are only marginal compared to earlier studies. This can (partially) be explained by the fact that during the baseline where no instructions were given, drivers were highly likely to drive with ACC on (mode 3). Hence, by forming a convoy and driving on a close distance, the benefits of better aerodynamic drag differ only marginally from the 'normal traffic' baseline.
6. By planned single/multi fleet convoy driving you can ensure that a vehicle is followed in ACC, and you can maximize the fuel saving benefits compared to following random vehicles 'on-the-fly', where gap distances are likely to vary along the trip.

Boundary conditions – RQ3.4* What are boundary conditions for implementation of ACC convoy driving (and truck platooning)?

1. Logistics operations perspective: See point 1 on improving business case.
2. Planner and driver perspective: See point 2 on improving business case.
3. Transport management perspective: In the long run, the transporters envision standard availability of technology on trucks for multi-fleet on-the-fly platooning. They expect that single fleet platooning will be possible to a limited extent only as the ACC convoy driving use cases illustrate.

6 The impacts of ACC driving – conclusions and outlook

6.1 Fuel Consumption

- Driving with ACC on is more fuel efficient than driving with ACC off and no leading vehicle. Drafting with a headway of 50 m led to an average reduction of 4.3%, while with a headway of 33 m the average reduction was 5.6%. ACC driving is more fuel efficient than when ACC is switched off in the control condition, or at distances not associated with the relevant ACC mode.
- Pressure measurements suggest that a short headway (shorter than the settings of the different ACC modes) would reduce air drag further. It is estimated that if the headway can be reduced to 10 metres, in combination with an ACC mode, the fuel consumption reduction could be about 9% (2 litres per 100 km) as compared to not following another vehicle. Note that when comparing this to a headway of 33 metres (ACC 1), the fuel consumption reduction could be about 4%.
- Because of the direct relationship between fuel and CO_2, these percentage reductions may also be applied to CO_2.

6.2 Human interaction

- Self-rated effort decreased over time with some significant differences between ACC instruction conditions. Effort was significantly higher when participants were instructed not to use ACC. No relationship between effort and driving parameters, such as driving speed and ACC use was observed.
- The observed ACC use reflected the effect of ACC use instructions participants were given in the different campaigns. On motorways, ACC was turned on approximately 75% of the time. When the ACC system was active, it was mostly in Distance mode, indicating that the truck was following another vehicle. The most frequent time gap to the lead vehicle when driving with ACC off was about 1.3 s, which was similar to the one with ACC at the shortest distance setting (ACC1). However, with ACC1 the distribution of time gaps was much narrower with fewer low time gap values but also fewer longer time gaps.
- There was a clear relationship between driving speed and the proportion of time ACC was turned on. Mean time gap decreased with increasing vehicle speed, but was not different for different conditions, nor did it depend on the proportion of time the ACC system was active.
- The Fitbit devices used in this study did not produce reliable heart rate measurements. Consequently, heart rate could not be used to evaluate workload or stress responses.
- Participants indicated a high degree of acceptance of and trust in the ACC system without significant differences between the different conditions.
- Participants generally reported a low level of job strain, both in terms of fatigue and sleeping problems. No significant differences in job strain responses were found between different conditions
- In general, participants were already used to driving with ACC. Some of them reported to find driving without ACC strenuous. Also, having the ACC distance set to the shortest distance was experienced by some drivers as uncomfortable.

6.3 Logistics integration and business case

It is found that fuel savings are quite marginal, compared to what was expected at the time of writing the research proposal for this project (August 2018) based on earlier studies (e.g.Van Ark et al., 2017) and. This can (partially) be explained by the fact that during the baseline where no instructions were given, drivers were highly likely to drive with ACC on (mode 3). Hence, by forming a convoy and driving on a close distance, the benefits of better aerodynamic drag differ only marginally from the ‘normal traffic’ baseline.

Furthermore, in the meantime various developments in the sector were already shifting towards more moderate estimations of the (fuel) savings as a result of truck platooning:

1. Daimler reassessed its view with respect to truck platooning in the beginning of 2019 (Lopez, 2019). Various on-road tests in the United States showed that only marginal effects for fuel savings were achieved, in contrast with higher expectations. Daimler continues its development of trucks with a high level of automation (SAE level 4).
2. The European research project ENSEMBLE reassess its course with respect to the following distance of the multi-brand platooning technology that they develop (beginning of 2020). They recognize the theoretical fuel savings of 4-10% for the following vehicle with today’s trucks with or without platooning technology (with following distance 1,5s, speed 80 km/h). However, ENSEMBLE expects a negligible effect on fuel consumption when implemented in real life due to the following distances already driven (including risky tailgating).
3. The EDDI project (by MAN and DB) found The EDDI project (MAN, DB Schenker) shows the results of real-world platooning at a gap distance of 0.7s. or 15m. (at a speed of 80 km/h). The fuel savings are 1.3% for the leading truck and 3-4% for the following truck. These are considerably lower than the expected fuel savings reported in earlier studies and can be explained by the fact that real-world conditions are more diverse than tests on a test track (Brandt, 2019).

With respect to the integration of convoy driving or truck platooning, the transporters that participated in this project are unanimous: when the truck platooning technology is part of the standard technology on a truck, it will really set of in the sector. Most transporters do not have enough volume at the same moment in order to form single fleet convoys. For forming multi-fleet convoys it is now only possible with the help of a shipper (as use case 1 showed us). Therefore, the transporters envision future convoy driving and truck platooning as taking place ‘on-the-fly’ or spontaneously with vehicles that drive the same routes as theirs.

To summarize and provide an outlook with respect to the business case of ACC and truck platooning we can say that in the past years fuel savings were expected to contribute to a large share of the business case. However, based on recent insights and the findings in this study we should lower our expectations on this aspect for now. Yet, there are still fuel savings reported (4-6%). Van Ark et al. (2017) report in the value case of truck platooning other potential elements that lead to positive value (a.o. safety, traffic flow, reduced role of the driver).

Once we consider ACC driving as a step towards further automating the driver task, future value can be expected when less drivers are needed to operate a set of trucks as Van Ark et al. (2017) show.

Moreover the safety argument is finding its way in the sector. More and more, ACC and the further evolved systems such as C-ACC and truck platooning are seen as a potential safety measure rather than a sustainability measure. Further research is required to support this newly evolving safety vision.

6.4 Recommendations for C-ACC trials

As set out in section 1.3, the project consists of two stages:

Stage 1: *ACC Truck Trials* *[this report]*
Driving trucks – in solo and convoy formation – equipped with Adaptive Cruise Control (ACC), executed in 2019/2020.
Internal project reference: Integrator Connected Truck Trials
Stage 2: C-ACC *Truck Platooning Trial*
Driving trucks – in solo and convoy formation – equipped with Cooperative-Adaptive Cruise Control (C-ACC), to be executed in 2021
Internal project reference: Ursa Major neo Truck Platooning Trial

As the second stage will be executed in 2021, we shortly highlight aspects for setting up the trial that are recommendable, based on the experiences we gained in the ACC Truck Trials. These are in addition to the aspects mentioned in section 2.10 Adaptions to the original research set-up.

Instrumentation and measurement plan
- Fuel consumption - The SEMS measurement system worked well, make sure instrumenting (and getting it out) is budgeted for;
- Human interaction – Fitbits did not produce reliable heart rate data;
- Human interaction – The app we used for collecting the survey after each trip (drivers rated their trip) worked well. Make sure drivers submit their answers.
- Measurement plan - Make sure to follow GDPR protocols if the next trial also collects (semi) personal data. Set up a detailed measurement plan in advance.

Involvement and commitment
- Logistics integration - Top management commitment was important for planner involvement. Ideally do on-site visit to involve planners. Planner briefing in Ridderkerk was not entirely sufficient for planner involvement;
- Test track day: use a day to calibrate equipment and check whether sensors provide the required data
- Truck driver involvement: the test-track day and buddy system worked nicely to keep truck drivers involved.

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8 Signature

The Hague, 22 March 2021

TNO

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Projectleader

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A Additional information Fuel consumption

8.1.1 *Impact of planned convoys on corrected fuel consumption*

Table 19: Fuel consumption, corrected for payload and dynamics, in L/100km, *while in convoy vs solo,* at high speeds during ACC off for following distances >170 m; and ACC Off, 3, and 1, for following distances less than 75 m. Std. dev, median, and IQR of the corrected fuel consumption are noted. Distance and time per ACC mode are also shown.

Name	ACC		FC_{corr} [L/100km]	Std dev	Median Fuel	IQR Fuel	Dist. [km]	Time [h]
Truck 1a	Off > 170 m	Solo	28.5	11.0	27.4	10.3	2167	25.8
Truck 1a	Off < 75 m	Solo	25.9	10.8	25.2	9.4	4603	55.3
Truck 1a	Off < 75 m	Convoy	23.1	7.5	22.3	6.0	54	0.7
Truck 1a	3	Solo	24.9	7.0	24.3	6.5	2330	28.4
Truck 1a	3	Convoy	22.5	5.2	21.9	4.8	1411	17.5
Truck 1a	1	Solo	25.3	7.0	24.7	6.9	5297	63.9
Truck 1a	1	Convoy	22.4	5.5	22.2	4.5	1154	14.2
Truck 1b	Off > 170 m	Solo	22.1	11.6	21.0	10.4	1374	16.6
Truck 1b	Off < 75 m	Solo	19.2	10.4	18.7	9.0	2202	26.3
Truck 1b	Off < 75 m	Convoy	19.4	6.1	18.5	5.9	74	0.9
Truck 1b	3	Solo	18.7	8.9	18.2	7.7	11584	140.5
Truck 1b	3	Convoy	18.7	5.0	18.3	4.7	1121	13.6
Truck 1b	1	Solo	17.2	6.8	17.1	5.4	697	8.4
Truck 1b	1	Convoy	17.5	4.7	16.9	4.6	653	7.8

8.1.2 *Examination of uncorrected fuel consumption*

An initial examination of the correlation between fuel consumption and ACC modes and convoying was performed. However, without accounting for the payload and driving dynamics, the observed effects can be biased by operating conditions with a heavy payload, or conditions on specific routes with specific payloads. If the influencing parameters payload and dynamics are not accounted for, the uncertainty, or variations in the results, are several times larger than the observed effects. In practice there are many factors which influence the actual fuel consumption. An extended discussion on this is given by (Vonk, van Mensch, & Verbeek, 2013) in the ‘Truck van de Toekomst’, where several fuel consumption reduction options are compared.

For completeness, we present the correlation between the uncorrected fuel consumption and ACC modes and convoying in the section below

8.1.2.1 *Impact of ACC state on fuel consumption*

Considering the measured fuel consumption data directly, minor differences in fuel consumption can be observed, likely affected by the large underlying variation.

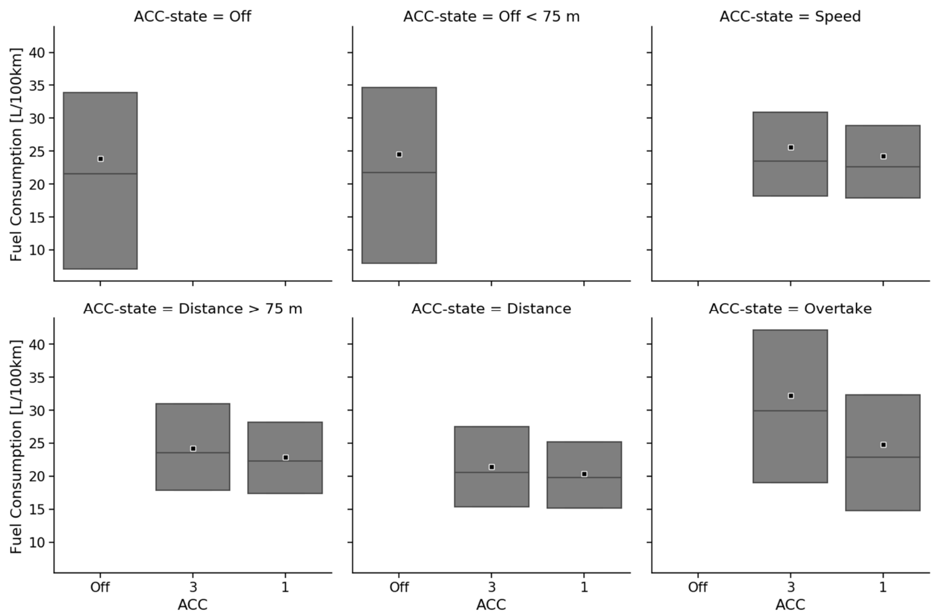

Figure 42: Mean, median and interquartile range of the instantaneous fuel consumption as dependent on the ACC mode (Off, 3, or 1) for the different states of ACC operation. The means are shown by the white-outlined black square. Note that whiskers are excluded to allow for a better comparison of the mean instantaneous fuel consumption, due to the nature of the measurements instantaneous fuel consumption ranges between 0 and 100 L/100 km.

The mean, median and interquartile ranges (IQR[14]) of the instantaneous fuel consumption during different states of operation, for all vehicles is shown in Figure 42.

The different ACC states discussed here are as follows:

- Off: system turned off
- Speed: normal cruise control mode
- Distance: vehicle detected in front of the truck; minimum distance maintained
- Overtake: system target speed overridden by user

The interquartile range is larger when driving with ACC off, both at distances larger than 75 m, and those less than 75 m (see Table 20 for values). While the ACC is on (Distance, Distance > 75 m, Speed, and Overtake), the mean fuel consumption is lower for ACC 1 as compared to ACC 3. It could be assumed that driving in the Speed state would have similar fuel efficiency as driving in the Distance state at large following distances (> 75 m), but there is a benefit with respect to driving in the Distance state > 75 m.

[14] The interquartile range (IQR) is the range of the middle 50% of the scores in a distribution. It is computed as follows: IQR = 75th percentile - 25th percentile

Table 20: The mean of the fuel consumption during different states of operation, for all vehicles. The time spent in that combination of state and modes is also shown. The median and interquartile ranges (IQR) are given for the instantaneous fuel consumption. Fuel consumption (FC) is given in L/100 km, while time is shown in hours.

ACC-state	ACC	Distance [km]	Time [h]	Average Fuel [L/100km]	Median Fuel [L/100km]	IQR Fuel [L/100km]
Off	Off	24 672	284	26.2	24.3	27.5
Speed	3	22 157	263	28.5	27.1	15.0
	1	5 169	60	27.0	25.9	15.3
Distance > 75 m	3	20 403	243	25.8	25.8	13.9
	1	3 456	40	24.6	24.6	11.9
Off < 75 m	Off	13 995	166	25.2	22.7	27.6
Distance	3	26 276	317	24.0	24.2	15.8
	1	6 456	77	23.4	23.1	11.9
Overtake	3	19 389	230	32.2	30.2	23.2
	1	1 765	20	25.3	23.9	18.8

8.1.2.2 *Impact of drafting on fuel consumption*

That following at longer distances can still offer slight differences in fuel consumption can also be seen when considering following distances (and following times) at high speeds. The following time is determined by dividing the following distance as recorded by the CAN bus by the speed of the vehicle at that moment. Per time/distance interval, the average is taken and plotted in Figure 43 and Figure 44, where a differentiation is made between whether ACC was on or not. A linear regression is performed on the data, which is shown as the blue straight line. As expected, this regression line has a slightly positive gradient: there are fuel savings to be made as following distance decreases from 150 m to 25 m. The number of seconds in each time/distance interval is shown as an orange line in the background.

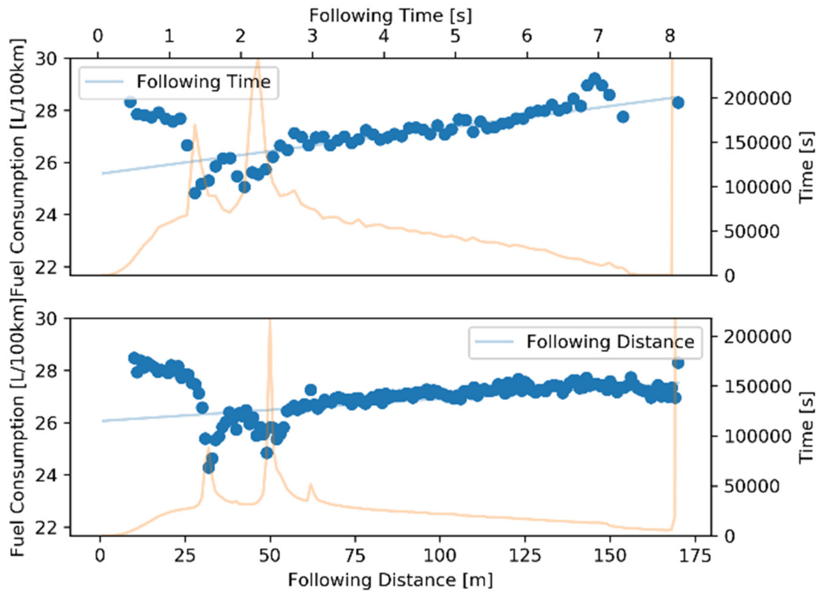

Figure 43: Fuel consumption per following distance and time in cases where ACC is *on* .The fuel consumption per distance or time increment is shown by the blue dots, while a linear regression of all data is shown in light blue. The number of seconds spent at that increment is shown by the orange line.

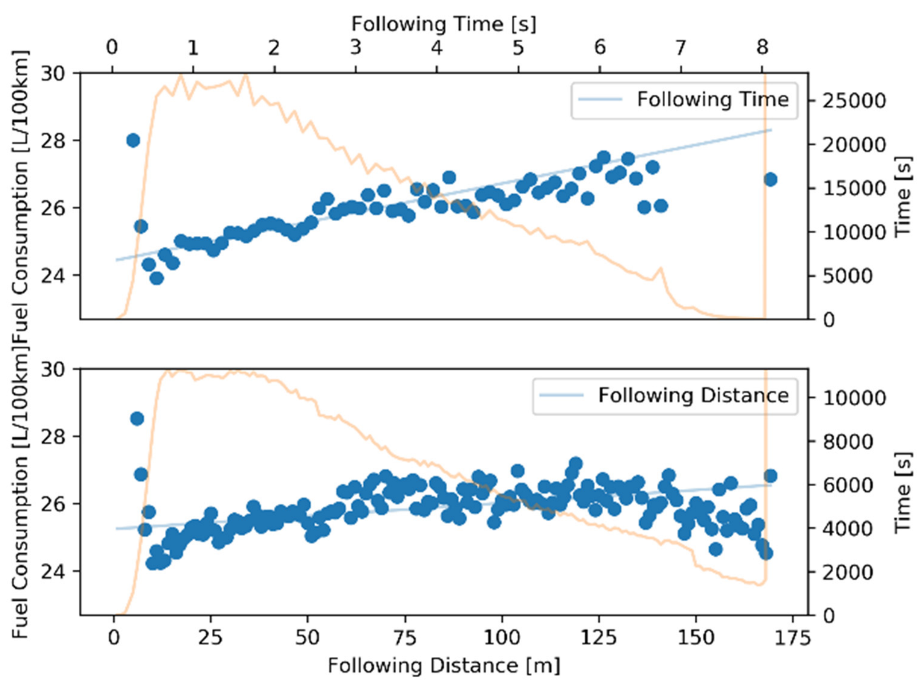

Figure 44: Fuel consumption per following distance and time in cases where ACC is *off* .The average fuel consumption per distance or time increment is shown by the blue dots, while a linear regression of all data is shown in light blue. The number of seconds spent at that increment is shown by the orange line.

For the case where ACC is on, a dip is seen in the fuel consumption at following distances around 33 m and 50 m, coupled with a sharp peak in time driven at that following distance. These distances correspond to ACC settings 1 and 3 resp., with the average fuel consumption at 33 m being lower than that at 50 m. At following distances less than 33 m, there is a deviation from the trend: fuel consumption increases dramatically before flattening out. This is different behaviour than that observed if ACC is off. In that case, fuel consumption decreases fairly linearly until around 10 m following distance. It should be noted that there is an order of magnitude difference in the scale of time driven at each following distance between driving with ACC off and with it on.

8.1.2.3 Impact of drafting on fuel consumption, in combination with ACC mode

We continue by investigating the impact of drafting on fuel consumption in combination with ACC mode. The furthest ACC setting (ACC 5) has a following distance of 75 m, so this is taken as the cut-off distance from where driving with different ACC modes would likely have an effect: in Table 20 this was referred to as Distance and Off < 75 m. During normal driving at high speeds, around 30% of kilometres are driven at following distances shorter than 75 m.

For each truck the mean, median and IQR of the instantaneous fuel consumption are noted along with the distance driven in each setting/mode in Figure 45 (data can also be found in Table 24). The only consistent observation across all vehicles is that the IQR when ACC is off is the largest. Truck 2b appears to be an outlier, in that the median fuel consumption with ACC Off < 75 m is unusually low, and in ACC 1 it is unusually high.

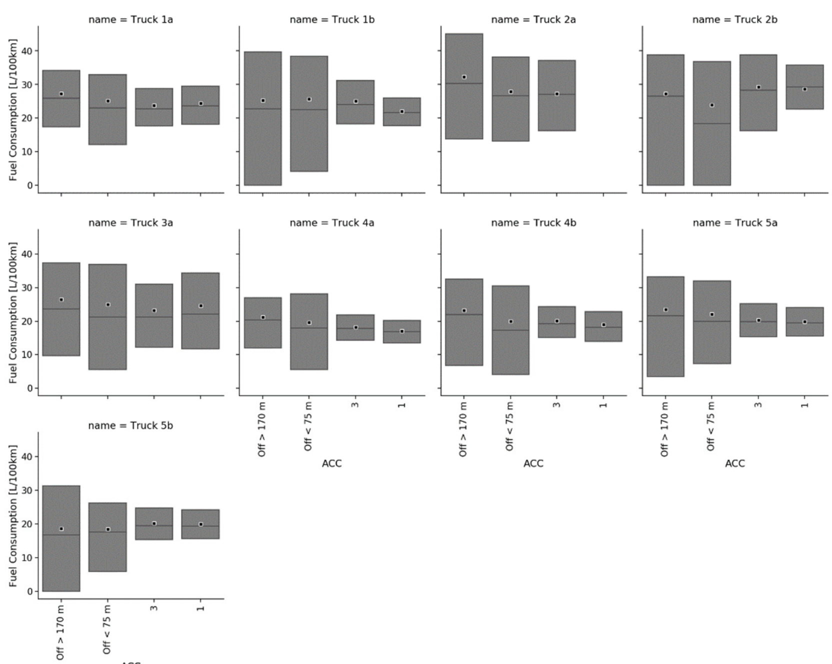

Figure 45: The mean, median and interquartile ranges of the instantaneous fuel consumption during different states of operation. ACC Off is shown for following distances larger than 170 m, as well as shorter than 75 m. ACC 1 and 3 are shown where following distances are less than 75 m. Note that whiskers are excluded to allow for a better comparison of the mean fuel consumption, due to the nature of the measurements instantaneous fuel consumption ranges between 0 and 100 L/100 km.

Percentage reduction in fuel consumption
Reductions in fuel consumption are shown in Figure 46 as well as Table 25 in Section 8.1.2.5. The reduction is calculated by

$$Reduction\ [\%] = \frac{Fuel\ consumption_{baseline} - Fuel\ consumption_{test}}{Fuel\ consumption_{baseline}} \times 100,$$

where $Fuel\ consumption$ is the average fuel consumption as calculated by dividing the total fuel/CO_2 by the total number of kilometres.

For this work the reductions while drafting with ACC 3 (50 m) compared to no leading vehicle was on average (7 ± 20)%.[15] This reduction is similar to those published by (Veldhuizen, Van Raemdonck, & van der Krieke, 2019): (10.0 ± 0.9)% for following distances of 50 m as compared to a baseline following distance of 950 m. For drafting with ACC 1 (33 m) as compared to no leading vehicle, the average reduction was (9 ± 30)%. We do note here however, that when comparing ACC 3 to driving with ACC off with following distances less than 75 m, the reduction is only on average (3 ± 10)%.

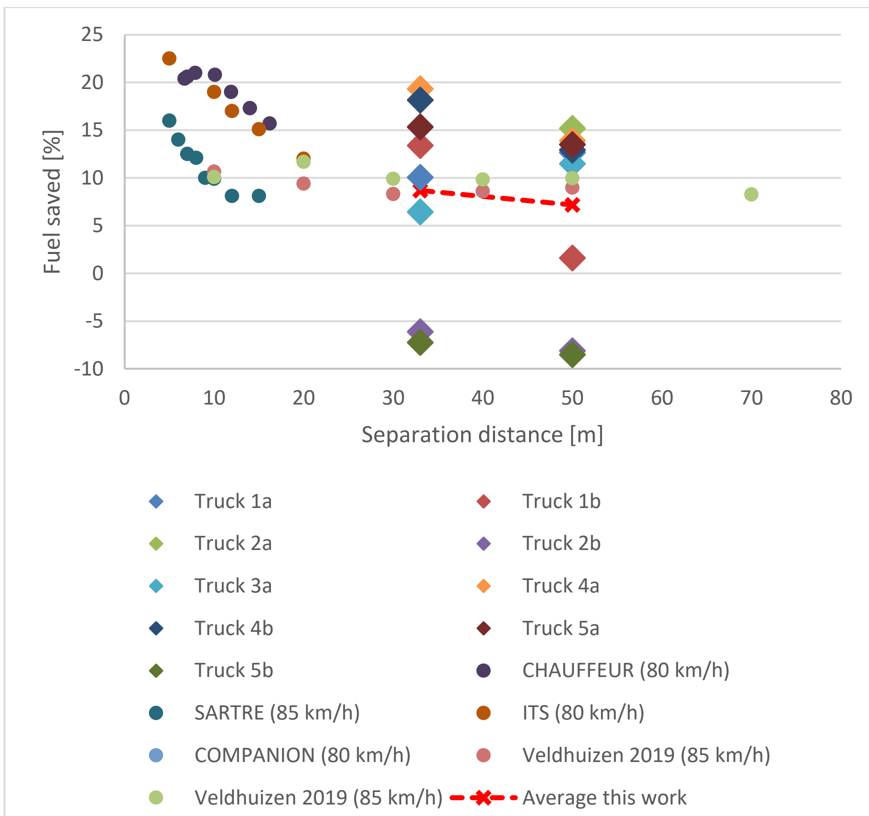

Figure 46: Fuel savings achieved during the real-world monitoring in this project, as compared to other platooning results obtained from literature (Veldhuizen, Van Raemdonck, & van der Krieke, 2019).

[15] 3σ (3 times the standard deviation) is used here as an indication of uncertainty, although it should be noted that the fuel consumption reduction is not distributed normally

8.1.2.4 *Impact of planned convoys on fuel consumption*

The difference in fuel consumption is examined between driving alone and in a planned convoy (see also Table 21 and Table 26 in Section 8.1.2.5). In this way one can investigate whether specifically planning a convoy saves fuel, or whether drafting is enough.

Table 21: Percentage reduction in fuel consumption while driving in different ACC modes *in convoy*, as compared to driving solo with no leading vehicle, or the same mode while not in a planned convoy.

Name	ACC mode	Baseline	
		Off > 170 m	**ACC**
Truck 1a	Off < 75 m	20	10
	3	16	3
	1	14	4
Truck 1b	Off < 75 m	20	20
	3	10	9
	1	20	3
Truck 4a	Off < 75 m	-3	-10
	3	14	-0.1
	1	8	-15
Truck 4b	Off < 75 m	8	-6
	3	9	-5
	1	10	-5

Trucks 1a and 1b drove 29 trips in planned convoy, with a combined distance of 4500 km. Truck 1a was lead vehicle for 23 % of the convoys driven with Truck 1b. On average, across all ACC modes, a reduction of (8 ± 20)% is seen for Trucks 1a and 1b while following a vehicle in an arranged convoy as compared to solo driving.

For Truck 4a and 4b the convoying time was noted by hand (as opposed to Truck 1a and 1b which could be matched by GPS coordinates). Matching by hand leads to more uncertainty as to the precise moments of convoying. 12 convoys were recorded, with a combined distance of around 700 km. Furthermore, Truck 4a and 4b were not outfitted with sensors, but the CAN bus was logged for the relevant signals. Truck 4a and 4b equally shared leading and following positions, but there does not appear to be a consistent trend with Trucks 1a and 1b: convoying appears to be less fuel efficient than driving solo in ACC 1 and 3. On average (7 ± 10)% more fuel was used.

8.1.2.5 Data tables

Table 22: Total distance travelled, total fuel consumption, and average fuel consumption, per vehicle over the measurement period 10/09/2019 – 29/02/2020. This distance is calculated by integrating the speed of the vehicle over time. The total fuel is calculated via integrating either the CAN bus fuel rate (OBD in the table), or the CO_2 mass flow as determined by mass flow sensor in the exhaust (Sensor in the table).

Name	Distance [km]	Total Fuel, OBD [L]	Total Fuel, Sensor [L]	Sensor – OBD	Average Fuel, OBD [L/100km]	Average Fuel, Sensor [L/100km]
Truck 1a	30930.1	9049.8	9151.7	1.1%	29.3	29.6
Truck 1b	51847.8	14724.5	14895.3	1.1%	28.4	28.7
Truck 2a	13367.8	5025.5	5075.7	1.0%	37.6	38.0
Truck 2b	56558.5	19843.8	20026.3	0.9%	35.1	35.4
Truck 3a	39378.4	10818.4	10930.3	1.0%	27.5	27.8

Table 23: Total distance travelled, total time travelled on, total fuel consumption, and average fuel consumption, per road type over the measurement period 10/09/2019 – 29/02/2020. The distance and time are also shown as percentages of the total (indicated by %).

Road	Distance [km]	Distance [%]	Time [h]	Time [%]	Average Speed [km/h]	Total Fuel [L]	Average Fuel [L/100km]
Motorway	76962	40%	983	27%	78	21149	27.5
Rural	5112	3%	123	3%	42	1901	37.2
Unknown	108310	56%	2424	67%	45	36242	33.5
Urban	1699	1%	88	2%	19	788	46.3
Total	192083		3618			60079	

Table 24: Fuel consumption in L/100km at high speeds during ACC Off, 3, and 1, for following distances less than 75 m, as well as for ACC Off with following distance > 170 m. Average fuel is determined from the total fuel and distance , while std. dev, median, and IQR are noted as determined for the instantaneous fuel consumption. Distance, time and average speed per ACC mode are also shown. Note that Truck 4a – 5b are shown separately as in those cases fuel consumption is measured by OBD instead of by sensor

Name	ACC	Av. Fuel	Std dev	Median Fuel	IQR Fuel	Distance [km]	Time [h]	Av. Speed [km/h]
Truck 1a	Off > 170 m	27.1	19.3	25.9	16.7	2139	25	84
Truck 1a	Off < 75 m	25.0	19.4	23.0	20.7	4543	55	83
Truck 1a	3	23.7	13.0	22.8	11.2	2328	28	82
Truck 1a	1	24.4	12.9	23.7	11.4	5259	63	83
Truck 1b	Off > 170 m	25.3	24.6	22.7	39.6	1374	17	83
Truck 1b	Off < 75 m	25.5	23.0	22.6	34.4	2125	25	84
Truck 1b	3	24.9	14.2	24.0	12.8	11574	140	82
Truck 1b	1	21.9	11.0	21.6	8.3	696	8	83
Truck 2a	Off > 170 m	32.0	24.7	30.3	31.2	827	10	83
Truck 2a	Off < 75 m	27.8	20.7	26.6	25.1	1849	22	83

Truck 2a	3	27.1	16.8	27.1	20.9	398	5	83
Truck 2b	Off > 170 m	27.0	24.7	26.5	38.8	1187	14	83
Truck 2b	Off < 75 m	23.5	26.3	18.3	36.8	671	8	82
Truck 2b	3	29.2	19.6	28.2	22.5	21413	258	83
Truck 2b	1	28.7	14.0	29.2	13.2	105	1	83
Truck 3a	Off > 170 m	26.1	21.7	23.6	27.8	11037	124	89
Truck 3a	Off < 75 m	24.6	22.1	21.3	31.4	4807	55	87
Truck 3a	3	23.1	17.2	21.2	19.0	2225	25	87
Truck 3a	1	24.4	18.9	22.1	22.7	1413	16	88

Name	ACC	Av. Fuel	Std dev	Median Fuel	IQR Fuel	Distance [km]	Time [h]	Av. Speed [km/h]
Truck 4a	Off > 170 m	21.2	16.0	20.4	15.2	2325	29	81
Truck 4a	Off < 75 m	19.6	16.5	18.0	22.5	2944	36	81
Truck 4a	3	18.2	9.0	17.9	7.5	9768	118	83
Truck 4a	1	17.1	8.7	16.8	6.8	752	9	83
Truck 4b	Off > 170 m	23.1	18.7	22.0	25.9	1807	21	85
Truck 4b	Off < 75 m	19.9	17.8	17.4	26.6	4655	55	84
Truck 4b	3	20.1	10.7	19.2	9.3	2557	30	85
Truck 4b	1	18.9	10.1	18.2	8.9	7402	87	85
Truck 5a	Off > 170 m	23.5	19.8	21.6	29.9	1591	19	82
Truck 5a	Off < 75 m	22.1	17.8	20.0	24.8	1590	20	81
Truck 5a	3	20.3	10.3	19.9	9.9	4132	50	82
Truck 5a	1	19.9	9.4	19.5	8.4	1287	16	83
Truck 5b	Off > 170 m	18.6	18.9	16.7	31.3	1465	18	80
Truck 5b	Off < 75 m	18.5	14.7	17.6	20.3	1439	18	81
Truck 5b	3	20.1	10.8	19.5	9.3	6971	84	83
Truck 5b	1	19.9	10.3	19.3	8.7	1643	20	82

Table 25: Percentage reduction in fuel consumption while driving in different ACC modes, as compared to three different baseline situations.

Name	ACC mode	Baseline		
		Off > 170 m	**Off < 75 m**	**ACC 3**
Truck 1a	Off < 75 m	8		
Truck 1a	3	13	5	
Truck 1a	1	10	2	-3
Truck 1b	Off < 75 m	-1		
Truck 1b	3	2	2	
Truck 1b	1	10	10	12
Truck 2a	Off < 75 m	10		
Truck 2a	3	20	2	
Truck 2b	Off < 75 m	10		

Truck 2b	3	-8	-20	
Truck 2b	1	-6	-20	2
Truck 3a	Off < 75 m	5		
Truck 3a	3	10	6	
Truck 3a	1	6	1	-6
Truck 4a	Off < 75 m	7		
Truck 4a	3	14	7	
Truck 4a	1	20	13	6
Truck 4b	Off < 75 m	10		
Truck 4b	3	13	-1	
Truck 4b	1	20	5	6
Truck 5a	Off < 75 m	6		
Truck 5a	3	10	8	
Truck 5a	1	20	10	2
Truck 5b	Off < 75 m	0.2		
Truck 5b	3	-9	-9	
Truck 5b	1	-7	-7	1.2
Average	Off < 75 m	7		
	3	7	3[16]	
	1	9	5[17]	3

Table 26: Fuel consumption in L/100km, *while in convoy,* at high speeds during ACC Off, 3, and 1, for following distances less than 75 m. Average fuel is determined from the total fuel and distance , while std. dev, median, and IQR are noted as determined for the instantaneous fuel consumption. Distance, time and average speed per ACC mode are also shown.

Name	ACC	Av. Fuel	Std dev	Median Fuel	IQR Fuel	Distance [km]	Time [h]	Av. Speed [km/h]
Truck 1a	Off < 75 m	21.4	18.6	19.1	19.8	54	0.7	82
Truck 1a	3	22.9	10.5	22.6	8.2	1411	17.5	81
Truck 1a	1	23.4	10.3	23.4	7.8	1154	14.2	81
Truck 1b	Off < 75 m	21.2	20.1	16.7	27.7	74	0.9	83
Truck 1b	3	22.6	9.4	22.5	7.6	1121	13.6	82
Truck 1b	1	21.4	8.9	21.2	6.9	653	7.8	84
Truck 4a	Off < 75 m	21.7	20.4	19.5	39.0	35	0.4	84
Truck 4a	3	18.2	10.6	17.7	8.5	207	2.5	82
Truck 4a	1	19.6	10.9	19.3	11.3	33	0.4	84
Truck 4b	Off < 75 m	21.2	18.1	17.0	28.0	33	0.4	83
Truck 4b	3	21.1	9.4	21.2	6.8	72	0.9	84
Truck 4b	1	19.8	9.9	20.0	8.4	199	2.4	84

[16] The results with respect to Off < 75 shown here are excluding the outlying behaviour of Truck 2b, as Truck 2b has unusually low consumption during Off < 75 (as mentioned earlier).
[17] As above.

8.1.2.6 Distribution fuel consumption at high speeds

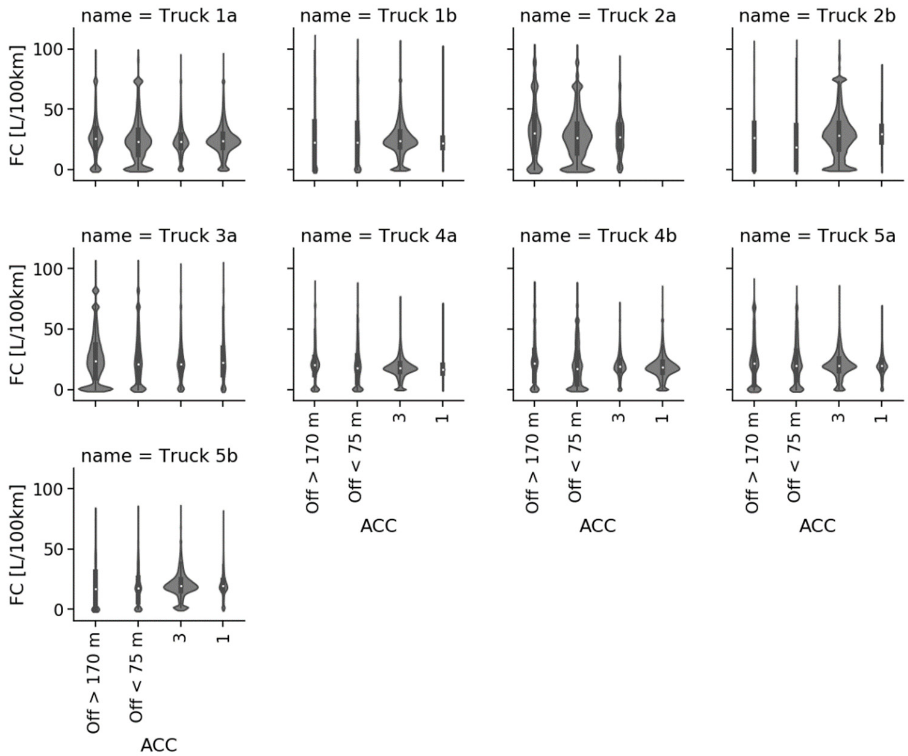

Figure 47: The distribution of the instantaneous fuel consumption during different states of operation at high speeds, shown as a violin plot. In a violin plot a box plot is shown on top of the probability density, where the relative width per truck depends on the amount of time (smoothed by a kernel density estimator). ACC Off is shown for following distances larger than 170 m, as well as shorter than 75 m. ACC 1 and 3 are shown where following distances are less than 75 m. Note that in most cases there is a significant amount of time where no fuel is consumed, while there are also high outliers > 50 L/100 km.

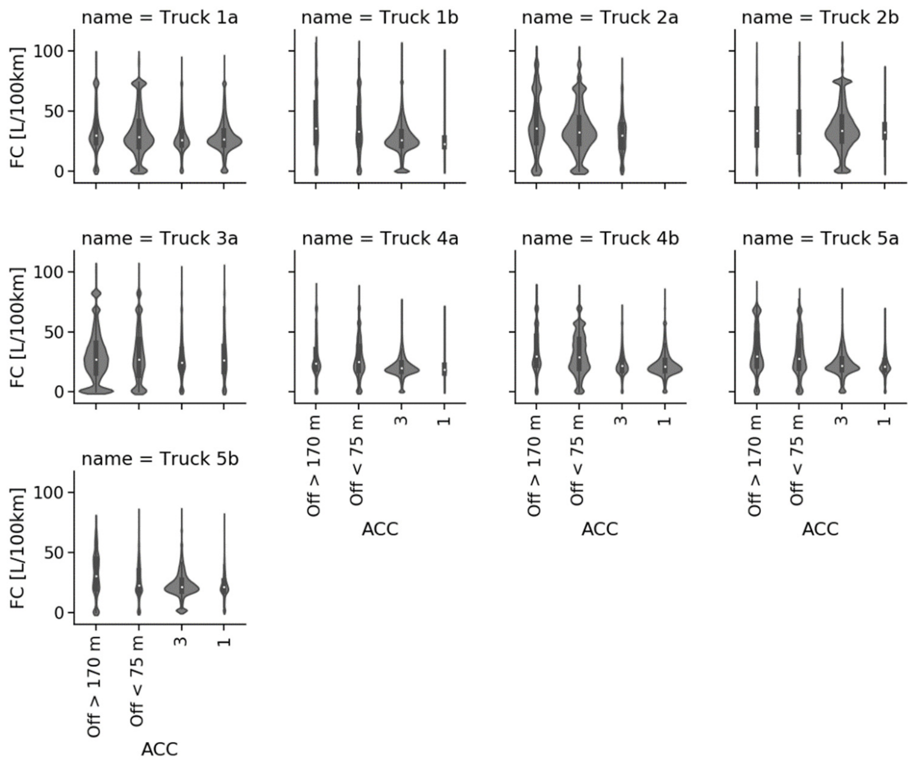

Figure 48: The distribution of the instantaneous fuel consumption during different states of operation at high speeds, *where acceleration is positive*, shown as a violin plot. There are situations where a fuel consumption of around 0 can be measured, even when not decelerating. These situations could, for example, include coasting down a hill while gaining speed. More investigation is needed to reach definite conclusions.
In a violin plot a box plot is shown on top of the probability density, where the relative width per truck depends on the amount of time (smoothed by a kernel density estimator). ACC Off is shown for following distances larger than 170 m, as well as shorter than 75 m. ACC 1 and 3 are shown where following distances are less than 75 m.

8.1.3 Further investigation into truck operation

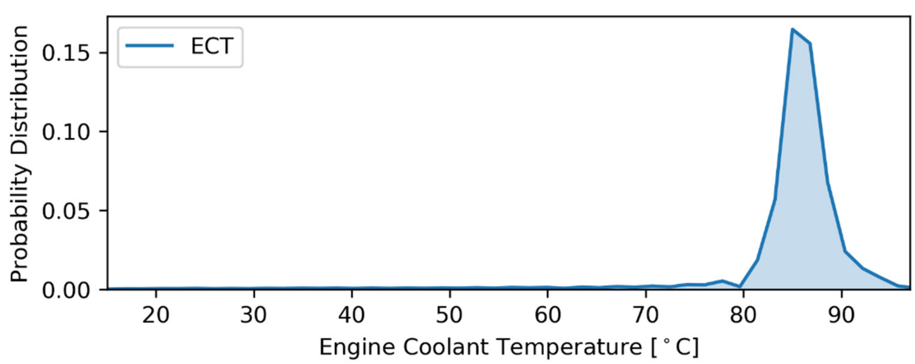

Figure 49: Distribution of engine coolant temperature for all vehicles. Most of the time this is between 80 and 90°C.

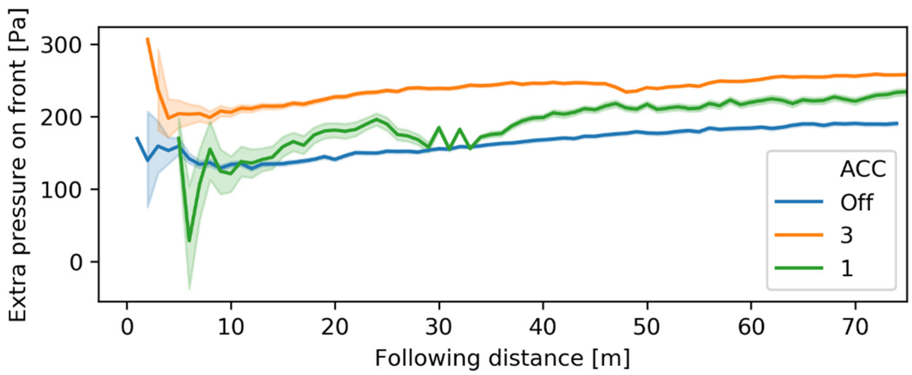

Figure 50: The extra pressure on the front of the truck (aggregated for the vehicles which have pressure sensors) while travelling at high speed per ACC mode, as a function of following distance. The shaded bands show the 95% confidence interval. Driving with ACC Off subjects the front of the truck to the least amount of pressure, and there is a decrease from 75 m to around 10 m following distance. At distances shorter than 10 m, the pressure increases. For ACC 1 and 3 the following distances are around 33 and 50 m respectively, and pressure increases are observed at distances slightly shorter than this. At shorter distances the bandwidth of the confidence interval also increases for all ACC modes. It is assumed that this would be due to cut-ins, but this has not been investigated further.

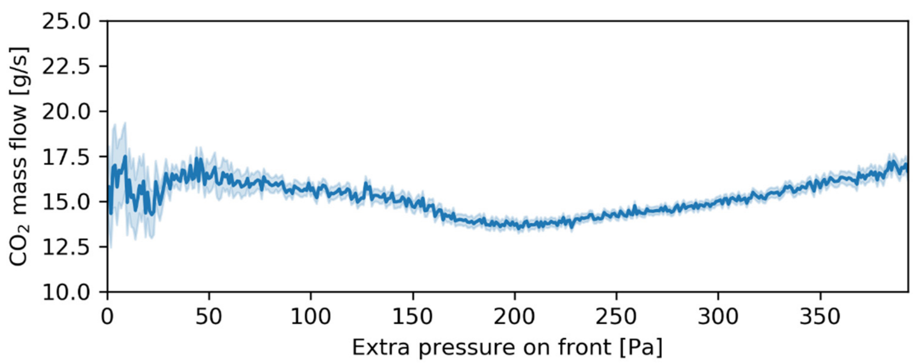

Figure 51: The CO_2 mass flow as a function of pressure on the front of the vehicle, for all five vehicles while travelling at high speeds. The shaded bands show the 95% confidence interval. There appears to be a slight minimum around 200 Pa.

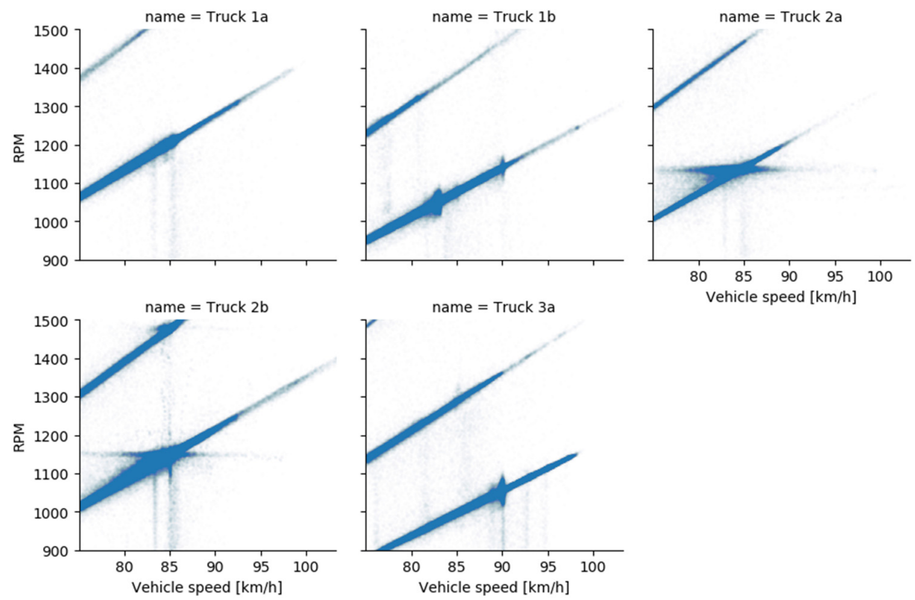

Figure 52: The dependency of RPM on vehicle speed for = Trucks 1a – 3a. The two bands seen in each panel are due to the two different gears driven in at those speeds. The differences between the vehicles are likely due to driving conditions as well as the loads of the vehicles.

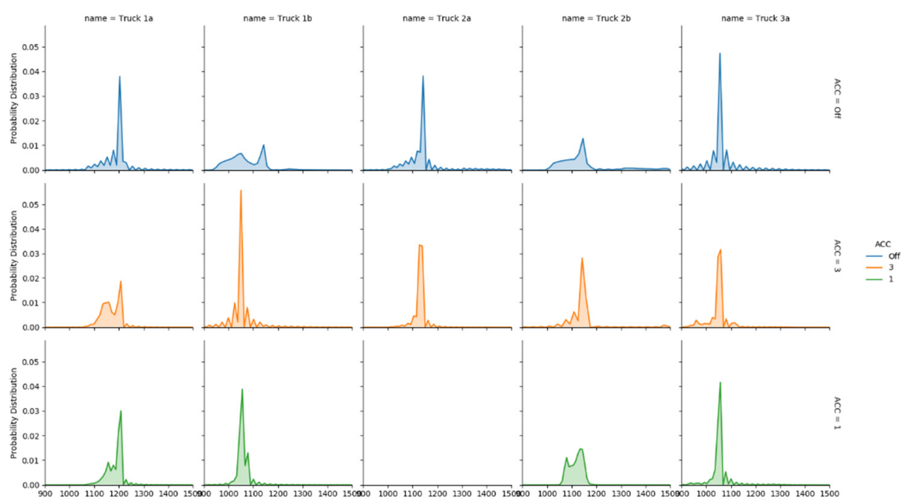

Figure 53: Frequency distribution of the RPMs of Trucks 1a – 3a, where each column is a separate vehicle and each row is different ACC mode. There are slight differences during different ACC mode, but more work is needed to reach definite conclusions.

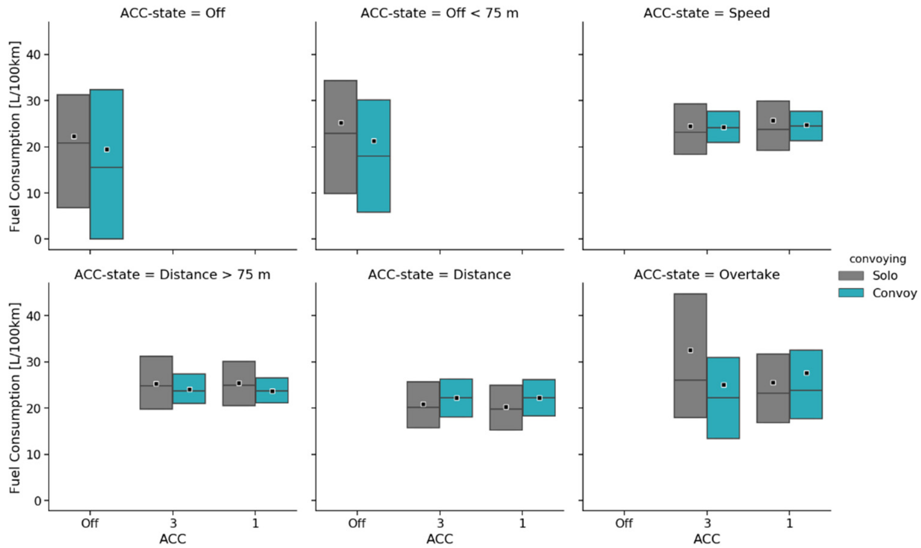

Figure 54: The mean, median and interquartile ranges of the instantaneous, uncorrected, fuel consumption during different states of operation, for solo and convoy driving, for Trucks 1a, 1b, 4a and 4b. The leading vehicle of the convoy, if it doesn't have a vehicle in front of it would be in the Speed state, though Distance > 75 should be comparable. The average fuel consumption in these states is lower when in a planned convoy than while driving solo.

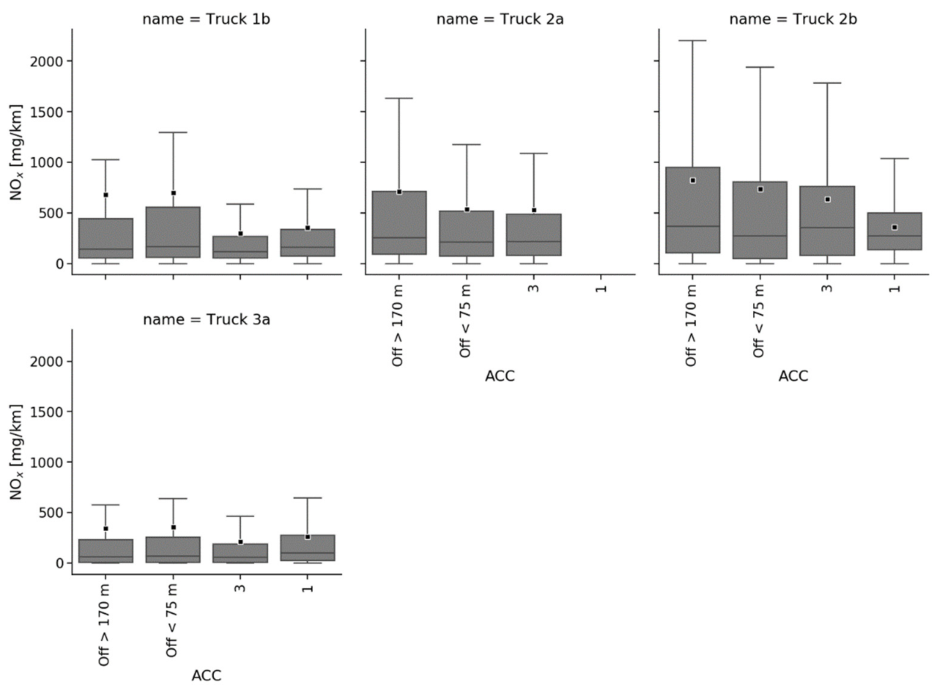

Figure 55: The mean, median and interquartile ranges of the instantaneous NO_x emissions during different states of operation. ACC Off is shown for following distances larger than 170 m, as well as shorter than 75 m. ACC 1 and 3 are shown where following distances are less than 75 m. Due to high outliers, the average emissions are higher than the median. On average, engaging ACC correlates with lower NO_x emissions.

B Surveys Human Interaction

This Appendix shows the surveys as filled in by the participants. At the start of the driving campaigns, after every campaign and when the driving campaigns stopped the participants filled in a survey.

8.1.4 Survey at the start of the driving campaigns

Naam:
Datum:

U gaat deelnemen aan verschillende meetperiodes om te onderzoeken hoe de ervaringen van vrachtwagenchauffeurs zijn met rijden terwijl ACC (Adaptive Cruise Control) actief is. We zijn benieuwd naar uw ervaringen en verwachtingen vooraf aan deze meetperiodes. We vragen u daarom de volgende vragen te beantwoorden.

Algemene vragen

1. Bent u een man of een vrouw? (aankruisen wat van toepassing is)

- ☐ Man
- ☐ Vrouw

2. Wat is uw leeftijd?

…… jaar

3. Hoe lang bezit u uw rijbewijs al?

…… jaar

4. Hoe lang bezit u uw vrachtwagen rijbewijs al?

…… jaar

5. Hoeveel kilometer rijdt u gemiddeld per week?

…… km

6. In hoeverre bent u naar eigen inschatting persoonlijk <u>geïnteresseerd</u> in de nieuwste technologische ontwikkelingen in de autosector. Bent u …?

- ☐ heel erg geïnteresseerd
- ☐ erg geïnteresseerd
- ☐ gemiddeld geïnteresseerd
- ☐ minder geïnteresseerd
- ☐ niet geïnteresseerd

7. In hoeverre bent u naar eigen inschatting persoonlijk geïnformeerd in de nieuwste technologische ontwikkelingen in de autosector. Bent u …?

- ☐ zeer goed geïnformeerd
- ☐ goed geïnformeerd
- ☐ gemiddeld geïnformeerd
- ☐ minder goed geïnformeerd
- ☐ niet geïnformeerd

De volgende vragen gaan over de auto die u normaliter privé rijdt.

8. Welke systemen heeft/had deze auto?

a) Systemen/bediensystemen.

☐ **Achteruitkijkcamera** *(toont op het centrale display de omgeving achter uw auto op camerabeeld)*
☐ **Ingebouwd Navigatiesysteem**
☐ **Park-Distance-Control** *(geluidswaarschuwing bij dreigende aanrijding met obstakels tijdens parkeren)*
☐ **Head-up-Display** *(Informatie wordt direct in het zicht van de bestuurder getoond, dus zichtbaar op de voorruit of via een uittrekbaar display zodat u niet omlaag hoeft te kijken)*
☐ **Multifunctioneel stuur** *(Toetsen op het stuur, om belangrijke functies vanuit het stuur uit te kunnen voeren, bijv. telefoon, spraakcommandos, audiofuncties of cruise control).*
☐ *geen van deze systemen*

b) Driver Assistance

☐ **Automatische parkeer assistent** *(parkeerassistent waabij het voertuig automatisch word ingeparkeerd door bij te sturen en/of gas en remmen)*
☐ **Cruise control** *(houdt de auto op een bepaalde ingestelde snelheid)*
☐ **Active cruise control** *(houdt zowel de auto op een bepaalde snelheid als een aangegeven afstand tot de voorligger)*
☐ **Lane departure warning** *(Geeft bij het verlaten van de rijstrook zonder richtingaanwijzer een waarschuwing door middel van vibraties aan het stuur of een geluid)*
☐ **Lane keeping assistant** *(Systeem dat door stuurondersteuning actief meehelpt om in de rijstrook te blijven.)*
☐ **Nachtzichtsysteem** *(camera gebaseerd hulpsysteem dat door middel van infrarood-technologie s 'nachts bij het herkennen van mensen en dieren helpt.)*
☐ **Lane change assist** *(Systeem dat tijdens het van rijstrook wisselen actief naar de andere rijstrook stuurt.)*
☐ *geen van deze systemen*

9. Hoe vaak gebruikt u de volgende functies? Wilt u deze vraag ALLEEN beantwoorden als deze functie daadwerkelijk op uw eigen auto zit/zat?

	(bijna) elke rit	*De meeste ritten*	*Sommige ritten*	*Zelden*	*(Bijna) nooit*
Ingebouwd Navigatiesysteem	☐1	☐2	☐3	☐4	☐5
Automatische parkeer assistent	☐1	☐2	☐3	☐4	☐5
Cruise control	☐1	☐2	☐3	☐4	☐5
Actieve cruise control	☐1	☐2	☐3	☐4	☐5
Lane keeping assistant	☐1	☐2	☐3	☐4	☐5
Lane change assist	☐1	☐2	☐3	☐4	☐5
☐ Niet van toepassing					

De volgende vragen gaan over de truck die u normaliter rijdt.

10. Welke systemen heeft/had deze truck?

a) Systemen/bediensystemen.

☐ **Achteruitkijkcamera** *(toont op het centrale display de omgeving achter uw truck op camerabeeld)*
☐ **Ingebouwd Navigatiesysteem**
☐ **Head-up-Display** *(Informatie wordt direct in het zicht van de bestuurder getoond, dus zichtbaar op de voorruit of via een uittrekbaar display zodat u niet omlaag hoeft te kijken)*
☐ **Multifunctioneel stuur** *(Toetsen op het stuur, om belangrijke functies vanuit het stuur uit te kunnen voeren, bijv. telefoon, spraakcommandos, audiofuncties of cruise control).*
☐ *geen van deze systemen*

b) Driver Assistance

☐ **Cruise control** *(houdt de truck op een bepaalde ingestelde snelheid)*
☐ **Active cruise control** *(houdt zowel de truck op een bepaalde snelheid als een aangegeven afstand tot de voorligger)*
☐ **Lane departure warning** *(Geeft bij het verlaten van de rijstrook zonder richtingaanwijzer een waarschuwing door middel van vibraties aan het stuur of een geluid)*
☐ **Lane keeping assistant** *(Systeem dat door stuurondersteuning actief meehelpt om in de rijstrook te blijven.)*
☐ **Nachtzichtsysteem** *(camera gebaseerd hulpsysteem dat door middel van infrarood-technologie s 'nachts bij het herkennen van mensen en dieren helpt.)*
☐ **Lane change assist** *(Systeem dat tijdens het van rijstrook wisselen actief naar de andere rijstrook stuurt.)*
☐ *geen van deze systemen*

11. Hoe vaak gebruikt u volgende functies? Wilt u deze vraag ALLEEN beantwoorden als deze functie daadwerkelijk op uw eigen truck zit/zat?

	(Bijna) elke rit	*De meeste ritten*	*Sommige ritten*	*Zelden*	*(Bijna) nooit*
Ingebouwd Navigatiesysteem	☐1	☐2	☐3	☐4	☐5
Cruise control	☐1	☐2	☐3	☐4	☐5
Actieve cruise control	☐1	☐2	☐3	☐4	☐5
Lane keeping assistant	☐1	☐2	☐3	☐4	☐5
Lane change assist	☐1	☐2	☐3	☐4	☐5
☐ Niet van toepassing					

Vragen over Adaptive Cruise Control in de truck

12. Bij de volgende vragen gaat het om uw inschatting vooraf aan de meetperiodes over ACC.

	Helemaal van toepassing				*Helemaal niet van toepassing*
Rijden met ACC maakt rijden veel relaxter.	☐1	☐2	☐3	☐4	☐5
Rijden met ACC is voor mij te onveilig.	☐1	☐2	☐3	☐4	☐5
Rijden met ACC geeft mij de mogelijkheid om naast het rijden nog andere dingen te doen.	☐1	☐2	☐3	☐4	☐5
Ik vertrouw niet op de technologie.	☐1	☐2	☐3	☐4	☐5
Ik zou het rijden met ACC alleen in files gebruiken.	☐1	☐2	☐3	☐4	☐5
Ik ben bang, dat de techniek opeens uit valt of niet meer beschikbaar is.	☐1	☐2	☐3	☐4	☐5
Ik wil zelf rijden, bij rijden met ACC raak ik mijn rijplezier kwijt.	☐1	☐2	☐3	☐4	☐5
Rijden met ACC voorkomt ongelukken en maakt rijden veiliger.	☐1	☐2	☐3	☐4	☐5

13. In de volgende stellingen wordt gevraagd naar uw gevoel of indruk vooraf over rijden met ACC. Wilt u inschatten in hoeverre deze uitspraken op u van toepassing zijn.

	Helemaal van toepassing				*Helemaal niet van toepassing*
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

14. Wat is uw inschatting vooraf over rijden met ACC, vooraf aan deze meetperiode?

<u>Graag de kruisjes op de 5-punt schaal neerzetten!</u>

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
Veilig ☐1	☐2	☐3	☐4	Onveilig ☐5

15. De volgende vraag gaat over de voordelen en nadelen die u verwacht met het rijden met een truck waar ACC actief is.

Het voordeel van rijden met ACC lijkt me (kruis eventueel meerdere voordelen aan):

☐dat ik energie-zuinig rijdt.
☐dat de doorstroming van het verkeer beter wordt.
☐dat het veiliger wordt op de weg.
☐dat ik altijd met constante snelheid rijd.
☐dat ik minder op hoef te letten
☐dat ik minder risico loop om te botsen
☐Anders, namelijk: …………………………………………………………………………….
☐Geen mening.

Het nadeel van rijden met ACC lijkt me (kruis eventueel meerdere nadelen aan):

☐dat ik zelf geen controle meer heb over de truck

□dat het minder veilig wordt op de weg
□dat ik niet snel kan rijden
□dat de volgafstand anders wordt dan ik wil
□dat een ander het gat tussen mij en de voorligger opvult en mijn truck plotseling sterk reageert
□dat ik niet mijn eigen snelheid bepaal.
□dat in en uitvoegen lastiger wordt.
□dat truck rijden niet meer leuk is.
□dat er op onnodige momenten geremd wordt.
□dat mijn aandacht voor het verkeer zal verslappen
□dat er op een gevaarlijk moment geremd wordt.
□dat ik moet vertrouwen op de rijstijl van de persoon die voor mij rijd.
□Anders, namelijk: …………………………………………………………………………….
□Geen mening.

16. De volgende vragen gaan over de situaties waar u verwacht ACC te activeren. Kunt u hieronder aangeven in welke situaties u ACC verwacht te gaan gebruiken?

	100% van toepassing	*Grotendeels van toepassing*	*Deels van toepassing*	*Eerder niet van toepassing*	*Helemaal niet van toepassing*
Ik verwacht ACC te gebruiken op de snelweg	□1	□2	□3	□4	□5
Ik verwacht ACC te gebruiken op de provinciale weg	□1	□2	□3	□4	□5
Ik verwacht ACC te gebruiken in de stad	□1	□2	□3	□4	□5
Ik verwacht ACC te gebruiken in de buurt van een kruispunt	□1	□2	□3	□4	□5
Ik verwacht ACC te gebruiken in tunnels	□1	□2	□3	□4	□5
Ik verwacht ACC te gebruiken op de oprit van een snelweg	□1	□2	□3	□4	□5
Ik verwacht ACC te gebruiken op de afrit van een snelweg	□1	□2	□3	□4	□5
Ik verwacht ACC te gebruiken als het regent	□1	□2	□3	□4	□5
Ik verwacht ACC te gebruiken als het erg zonnig weer is en ik word verblind door de zon.	□1	□2	□3	□4	□5
Ik verwacht ACC te gebruiken als ik achter een bekende bestuurder rijd.	□1	□2	□3	□4	□5
Ik verwacht ACC te gebruiken als ik achter een onbekende bestuurder rijd.	□1	□2	□3	□4	□5

Vraag over Cruise Control in de truck

17. Bij de volgende vragen gaat het om uw inschatting vooraf aan de meetperiodes over CC (Cruise Control).

	Helemaal van toepassing				*Helemaal niet van toepassing*
Rijden met CC maakt rijden veel relaxter.	☐1	☐2	☐3	☐4	☐5
Rijden met CC is voor mij te onveilig.	☐1	☐2	☐3	☐4	☐5
Rijden met CC geeft mij de mogelijkheid om naast het rijden nog andere dingen te doen.	☐1	☐2	☐3	☐4	☐5
Ik vertrouw niet op de technologie.	☐1	☐2	☐3	☐4	☐5
Ik zou het rijden met CC alleen in files gebruiken.	☐1	☐2	☐3	☐4	☐5
Ik ben bang, dat de techniek opeens uit valt of niet meer beschikbaar is.	☐1	☐2	☐3	☐4	☐5
Ik wil zelf rijden, bij rijden met CC raak ik mijn rijplezier kwijt.	☐1	☐2	☐3	☐4	☐5
Rijden met CC voorkomt ongelukken en maakt rijden veiliger.	☐1	☐2	☐3	☐4	☐5

Vragen over stress in de truck

18. Bij de volgende vragen gaat het over de werkdruk die u normaal ervaart als vrachtwagenchauffeur.

	Helemaal van toepassing				*Helemaal niet van toepassing*
Na enkele dagen met veel laden en lossen, kan ik mijn werk niet meer goed doen door vermoeidheid.	☐1	☐2	☐3	☐4	☐5
Na een lange werkdag heb ik nog genoeg energie om dingen te doen.	☐1	☐2	☐3	☐4	☐5
Tijdens een werkdag heb ik extra pauzes nodig.	☐1	☐2	☐3	☐4	☐5
Na enkele dagen met veel laden en lossen, voel ik me fysiek uitgeput.	☐1	☐2	☐3	☐4	☐5
Wanneer ik de hele dag heb gereden, is het moeilijk voor mij om te ontspannen.	☐1	☐2	☐3	☐4	☐5
Na het werk ontspan ik gemakkelijk.	☐1	☐2	☐3	☐4	☐5
Ik slaap goed.	☐1	☐2	☐3	☐4	☐5

Ik val meestal gemakkelijk in slaap.	☐1	☐2	☐3	☐4	☐5
Ik slaap onrustig.	☐1	☐2	☐3	☐4	☐5
Wanneer ik s' nachts wakker word, vind ik het moeilijk om weer in slaap te vallen.	☐1	☐2	☐3	☐4	☐5

19. De volgende vragen gaan over de situaties wanneer u rijdt in de truck. Kunt u hieronder aangeven in welke situaties u meer stress ervaart?

	100% van toepassing	*Grotendeels van toepassing*	*Deels van toepassing*	*Eerder niet van toepassing*	*Helemaal niet van toepassing*
Ik ervaar meer stress op de snelweg, dan in de stad.	☐1	☐2	☐3	☐4	☐5
Ik ervaar meer stress op de provinciale weg, dan op de snelweg.	☐1	☐2	☐3	☐4	☐5
Ik ervaar meer stress in de stad, dan op een provinciale weg.	☐1	☐2	☐3	☐4	☐5
Ik ervaar meer stress in de buurt van een kruispunt	☐1	☐2	☐3	☐4	☐5
Ik ervaar meer stress in tunnels	☐1	☐2	☐3	☐4	☐5
Ik ervaar meer stress op de oprit van een snelweg	☐1	☐2	☐3	☐4	☐5
Ik ervaar meer stress op de afrit van een snelweg	☐1	☐2	☐3	☐4	☐5
Ik ervaar meer stress als het regent	☐1	☐2	☐3	☐4	☐5
Ik ervaar meer stress als het erg zonnig weer is en ik word verblind door de zon.	☐1	☐2	☐3	☐4	☐5
Ik ervaar meer stress als ik achter een onbekende bestuurder rijd.	☐1	☐2	☐3	☐4	☐5
Ik ervaar meer stress als er een voertuig voor mij rijd.	☐1	☐2	☐3	☐4	☐5
Ik ervaar meer stress als ik rijd met semi-automatische systemen (bijvoorbeeld ACC, CC, lane keeping etc.).	☐1	☐2	☐3	☐4	☐5

Dit is het einde van deze vragenlijst. Bedankt voor het invullen.

8.1.5 Survey after every driving campaign

Naam: **Datum:**

U heeft de afgelopen weken deelgenomen aan een meetperiode met ACC (Adaptive Cruise Control). We zijn benieuwd naar uw ervaringen tijdens deze meetperiode. We vragen u daarom de volgende vragen te beantwoorden.

Vragen over Adaptive Cruise Control in de truck

1. **Bij de volgende vragen gaat het om uw ervaring met ACC in de afgelopen meetperiode.**

	Helemaal van toepassing				*Helemaal niet van toepassing*
Rijden met ACC maakt rijden veel relaxter.	☐1	☐2	☐3	☐4	☐5
Rijden met ACC is voor mij te onveilig.	☐1	☐2	☐3	☐4	☐5
Rijden met ACC geeft mij de mogelijkheid om naast het rijden nog andere dingen te doen.	☐1	☐2	☐3	☐4	☐5
Ik vertrouw niet op de technologie.	☐1	☐2	☐3	☐4	☐5
Ik zou het rijden met ACC alleen in files gebruiken.	☐1	☐2	☐3	☐4	☐5
Ik ben bang, dat de techniek opeens uit valt of niet meer beschikbaar is.	☐1	☐2	☐3	☐4	☐5
Ik wil zelf rijden, bij rijden met ACC raak ik mijn rijplezier kwijt.	☐1	☐2	☐3	☐4	☐5
Rijden met ACC voorkomt ongelukken en maakt rijden veiliger.	☐1	☐2	☐3	☐4	☐5

2. **In de volgende stellingen wordt gevraagd naar uw gevoel of indruk over rijden met ACC, na de afgelopen meetperiode. Wilt u aangeven in hoeverre deze uitspraken op u van toepassing zijn.**

	Helemaal van toepassing				*Helemaal niet van toepassing*
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

3. **Wat is uw beoordeling over rijden met ACC, na de afgelopen meetperiode?**
   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	Slaapverwekken d ☐5
Veilig ☐1	☐2	☐3	☐4	Onveilig ☐5

4. **De volgende vraag gaat over de voordelen en nadelen die u hebt ervaren tijdens de afgelopen meetperiode met het rijden met een truck waar ACC actief is.**

Het voordeel van rijden met ACC dat ik heb ervaren in de afgelopen meetperiode is (kruis eventueel meerdere voordelen aan):

☐dat ik energie-zuinig rijdt.
☐dat de doorstroming van het verkeer beter wordt.
☐dat het veiliger wordt op de weg.
☐dat ik altijd met constante snelheid rijd.
☐dat ik minder op hoef te letten
☐dat ik minder risico loop om te botsen
☐Anders, namelijk: ………………………………………………………………………….
☐Geen mening.

Het nadeel van rijden met ACC dat ik heb ervaren in de meetperiodes is (kruis eventueel meerdere nadelen aan):

☐dat ik zelf geen controle meer heb over de truck
☐dat het minder veilig wordt op de weg

☐dat ik niet snel kan rijden
☐dat de volgafstand anders wordt dan ik wil
☐dat een ander het gat tussen mij en de voorligger opvult en mijn truck plotseling sterk reageert
☐dat ik niet mijn eigen snelheid bepaal.
☐dat in en uitvoegen lastiger wordt.
☐dat truck rijden niet meer leuk is.
☐dat er op onnodige momenten geremd wordt.
☐dat mijn aandacht voor het verkeer zal verslappen
☐dat er op een gevaarlijk moment geremd wordt.
☐dat ik moet vertrouwen op de rijstijl van de persoon die voor mij rijd
☐Anders, namelijk: …………………………………………………………………………….
☐Geen mening.

5. De volgende vragen gaan over de situaties wanneer u rijdt met ACC. Kunt u hieronder aangeven in welke situaties u ACC heeft gebruikt?

	100% van toepassing	*Grotendeels van toepassing*	*Deels van toepassing*	*Eerder niet van toepassing*	*Helemaal niet van toepassing*
Ik gebruik ACC op de snelweg	☐1	☐2	☐3	☐4	☐5
Ik gebruik ACC op de provinciale weg	☐1	☐2	☐3	☐4	☐5
Ik gebruik ACC in de stad	☐1	☐2	☐3	☐4	☐5
Ik gebruik ACC in de buurt van een kruispunt	☐1	☐2	☐3	☐4	☐5
Ik gebruik ACC in tunnels	☐1	☐2	☐3	☐4	☐5
Ik gebruik ACC op de oprit van een snelweg	☐1	☐2	☐3	☐4	☐5
Ik gebruik ACC op de afrit van een snelweg	☐1	☐2	☐3	☐4	☐5
Ik gebruik ACC als het regent	☐1	☐2	☐3	☐4	☐5
Ik gebruik ACC als het erg zonnig weer is en ik word verblind door de zon.	☐1	☐2	☐3	☐4	☐5
Ik gebruik ACC als ik achter een bekende bestuurder rijd.	☐1	☐2	☐3	☐4	☐5
Ik gebruik ACC als ik achter een onbekende bestuurder rijd.	☐1	☐2	☐3	☐4	☐5

Vragen over Cruise Control in de truck

6. Bij de volgende vragen gaat het om uw ervaring met CC (cruise control) in de afgelopen meetperiode.

	Helemaal van toepassing				*Helemaal niet van toepassing*
Rijden met CC maakt rijden veel relaxter.	☐1	☐2	☐3	☐4	☐5
Rijden met CC is voor mij te onveilig.	☐1	☐2	☐3	☐4	☐5
Rijden met CC geeft mij de mogelijkheid om naast het rijden nog andere dingen te doen.	☐1	☐2	☐3	☐4	☐5

Ik vertrouw niet op de technologie.	☐1	☐2	☐3	☐4	☐5
Ik zou het rijden met CC alleen in files gebruiken.	☐1	☐2	☐3	☐4	☐5
Ik ben bang, dat de techniek opeens uit valt of niet meer beschikbaar is.	☐1	☐2	☐3	☐4	☐5
Ik wil zelf rijden, bij rijden met CC raak ik mijn rijplezier kwijt.	☐1	☐2	☐3	☐4	☐5
Rijden met CC voorkomt ongelukken en maakt rijden veiliger.	☐1	☐2	☐3	☐4	☐5

Vragen over stress in de truck

7. Bij de volgende vragen gaat het over de werkdruk die u ervaart hebt tijdens de afgelopen meetperiode.

	Helemaal van toepassing				*Helemaal niet van toepassing*
Na enkele dagen met veel laden en lossen, kan ik mijn werk niet meer goed doen door vermoeidheid.	☐1	☐2	☐3	☐4	☐5
Na een lange werkdag heb ik nog genoeg energie om dingen te doen.	☐1	☐2	☐3	☐4	☐5
Tijdens een werkdag heb ik extra pauzes nodig.	☐1	☐2	☐3	☐4	☐5
Na enkele dagen met veel laden en lossen, voel ik me fysiek uitgeput.	☐1	☐2	☐3	☐4	☐5
Wanneer ik de hele dag heb gereden, is het moeilijk voor mij om te ontspannen.	☐1	☐2	☐3	☐4	☐5
Na het werk ontspan ik gemakkelijk.	☐1	☐2	☐3	☐4	☐5
Ik slaap goed.	☐1	☐2	☐3	☐4	☐5
Ik val meestal gemakkelijk in slaap.	☐1	☐2	☐3	☐4	☐5
Ik slaap onrustig.	☐1	☐2	☐3	☐4	☐5
Wanneer ik s' nachts wakker word, vind ik het moeilijk om weer in slaap te vallen.	☐1	☐2	☐3	☐4	☐5

8. De volgende vragen gaan over de situaties wanneer u rijdt in de truck. Kunt u hieronder aangeven in welke situaties u meer stress ervaart dan wanneer u in een normale situatie truck rijdt?

	100% van toepassing	*Grotendeels van toepassing*	*Deels van toepassing*	*Eerder niet van toepassing*	*Helemaal niet van toepassing*		
Ik ervaar meer stress op de snelweg, dan in de stad.	☐1	☐2	☐3	☐4	☐5		
Ik ervaar meer stress op de provinciale weg, dan op de snelweg.	☐1	☐2	☐3	☐4	☐5		
Ik ervaar meer stress in de stad, dan op een provinciale weg.	☐1	☐2	☐3	☐4	☐5		
Ik ervaar meer stress in de buurt van een kruispunt	☐1	☐2	☐3	☐4	☐5		
Ik ervaar meer stress in tunnels	☐1	☐2	☐3	☐4	☐5		
Ik ervaar meer stress op de oprit van een snelweg	☐1	☐2	☐3	☐4	☐5		
Ik ervaar meer stress op de afrit van een snelweg	☐1	☐2	☐3	☐4	☐5		
Ik ervaar meer stress als het regent	☐1	☐2	☐3	☐4	☐5		
Ik ervaar meer stress als het erg zonnig weer is en ik word verblind door de zon.	☐1	☐2	☐3	☐4	☐5		
Ik ervaar meer stress als ik achter een onbekende bestuurder rijd.	☐1	☐2	☐3	☐4	☐5		
Ik ervaar meer stress als er een voertuig voor mij rijd.	☐1	☐2	☐3	☐4	☐5		
Ik ervaar meer stress als ik rijd met systemen (bijvoorbeeld ACC, CC, l	☐1	☐2	☐3	☐4	☐5	☐3	☐4
Ik ervaar meer stress als ik rijd met ACC actief.	☐1	☐2	☐3	☐4	☐5		
Ik ervaar meer stress als ik rijd met CC actief.	☐1	☐2	☐3	☐4	☐5		

Dit is het einde van deze vragenlijst. Bedankt voor het invullen.

8.1.6 Survey at the end of all driving campaigns

Naam: Datum:

U heeft de afgelopen maanden deelgenomen aan de verschillende meetperiodes. We zijn benieuwd naar uw ervaringen met rijden in vrachtwagens terwijl ACC (Adaptive Cruise Control) actief is. We vragen u daarom de volgende vragen te beantwoorden.

Vragen over Adaptive Cruise Control in de truck

1. Bij de volgende vragen gaat het om uw ervaring in de proef met ACC.

	Helemaal van toepassing				*Helemaal niet van toepassing*
Rijden met ACC maakt rijden veel relaxter.	☐1	☐2	☐3	☐4	☐5
Rijden met ACC is voor mij te onveilig.	☐1	☐2	☐3	☐4	☐5
Rijden met ACC geeft mij de mogelijkheid om naast het rijden nog andere dingen te doen.	☐1	☐2	☐3	☐4	☐5
Ik vertrouw niet op de technologie.	☐1	☐2	☐3	☐4	☐5
Ik zou het rijden met ACC alleen in files gebruiken.	☐1	☐2	☐3	☐4	☐5
Ik ben bang, dat de techniek opeens uit valt of niet meer beschikbaar is.	☐1	☐2	☐3	☐4	☐5
Ik wil zelf rijden, bij rijden met ACC raak ik mijn rijplezier kwijt.	☐1	☐2	☐3	☐4	☐5
Rijden met ACC voorkomt ongelukken en maakt rijden veiliger.	☐1	☐2	☐3	☐4	☐5

2. In de volgende stellingen wordt gevraagd naar uw gevoel of indruk over rijden met ACC. Wilt u aangeven in hoeverre deze uitspraken op u van toepassing zijn.

	Helemaal van toepassing				*Helemaal niet van toepassing*
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

3. Wat is uw beoordeling over rijden met ACC?

<u>Graag de kruisjes op de 5-punt schaal neerzetten!</u>

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
Veilig □1	□2	□3	□4	Onveilig □5

4. De volgende vraag gaat over de voordelen en nadelen die u hebt ervaren tijdens de proef met ACC.

Het voordeel van rijden met ACC dat ik heb ervaren in de meetperiodes is (kruis eventueel meerdere voordelen aan):

□dat ik energie-zuinig rijdt.
□dat de doorstroming van het verkeer beter wordt.
□dat het veiliger wordt op de weg.
□dat ik altijd met constante snelheid rijd.
□dat ik minder op hoef te letten
□dat ik minder risico loop om te botsen
□Anders, namelijk: ……………………………………………………………………………….
□Geen mening.

Het nadeel van rijden met ACC dat ik heb ervaren in de meetperiodes is (kruis eventueel meerdere nadelen aan):

□dat ik zelf geen controle meer heb over de truck
□dat het minder veilig wordt op de weg
□dat ik niet snel kan rijden
□dat de volgafstand anders wordt dan ik wil
□dat een ander het gat tussen mij en de voorligger opvult en mijn truck plotseling sterk reageert

☐dat het systeem remt terwijl er geen verkeer is.
☐dat het systeem te vroeg remt
☐dat het systeem te laat remt
☐dat ik niet mijn eigen snelheid bepaal.
☐dat in en uitvoegen lastiger wordt.
☐dat truck rijden niet meer leuk is.
☐dat er op onnodige momenten geremd wordt.
☐dat mijn aandacht voor het verkeer zal verslappen
☐dat er op een gevaarlijk moment geremd wordt.
☐dat ik moet vertrouwen op de rijstijl van de persoon die voor mij rijd.
☐Anders, namelijk: ……………………………………………………………………….
☐Geen mening.

5. In hoeverre zijn de volgende uitspraken over rijden met ACC voor u van toepassing?

	100% van toepassing	*Grotendeels van toepassing*	*Deels van toepassing*	*Eerder niet van toepassing*	*Helemaal niet van toepassing*
Rijden met ACC leidt tot een afname van de concentratie.	☐1	☐2	☐3	☐4	☐5
Rijden met ACC leidt tot relaxter rijden.	☐1	☐2	☐3	☐4	☐5
Van rijden met ACC word je sneller vermoeid.	☐1	☐2	☐3	☐4	☐5
Bij rijden met ACC ga je je sneller vervelen.	☐1	☐2	☐3	☐4	☐5
Rijden met ACC is meer belastend omdat je toezicht over het systeem moet houden.	☐1	☐2	☐3	☐4	☐5

6. Rijden met ACC kan u mogelijk zo ondersteunen dat u activiteiten gaat uitvoeren, naast het besturen van de truck. Wilt u aangeven wat voor u van toepassing is?

Graag kruisjes zetten (meerdere keuzes mogelijk)	*Op (bijna) elke rit*	*Op de meeste ritten*	*Op sommige ritten*	*Zelden*
☐ Wanneer de ACC actief is voer ik activiteiten uit, naast het besturen van de truck.	☐1	☐2	☐3	☐4
☐ Wanneer de ACC actief is kijk ik vaker weg van het verkeer.	☐1	☐2	☐3	☐4
☐ Wanneer de ACC actief is geef ik volledige de controle aan het systeem.	☐1	☐2	☐3	☐4
☐Anders, namelijk:____________________	☐1	☐2	☐3	☐4
☐ Ik voer geen activiteiten uit, naast het besturen van de truck.				

7. Kunt u hieronder aangeven welke activiteiten (naast het besturen van de truck) u heeft uitgevoerd tijdens het rijden met ACC en op welk type weg? Als u geen activiteiten uitvoerde mag u deze vraag overslaan.

Activiteiten die u dankzij rijden met ACC vaker uitvoert… *(meerdere keuzes mogelijk)*	**Type weg…** *(meerdere keuzes mogelijk)*		
	Stad	*Provinciale Weg*	*Autosnelweg*
☐ Bellen met de telefoon aan het oor	☐1	☐2	☐3
☐ Bellen met een headset of handsfree telefoon	☐1	☐2	☐3
☐ Op het mobieltje berichten schrijven of apps gebruiken	☐1	☐2	☐3
☐ Naar muziek luisteren	☐1	☐2	☐3
☐ Gebruik maken van overige truck-applicaties (bijv. wisselen van CDs)	☐1	☐2	☐3
☐ Eten en drinken	☐1	☐2	☐3
☐ Anders:…………………………………………	☐1	☐2	☐3
☐ Ik heb geen activiteiten uitgevoerd, naast het besturen van de truck.			

8. De volgende vragen gaan over de situaties wanneer u rijdt met ACC. Kunt u hieronder aangeven in welke situaties u ACC heeft gebruikt?

	100% van toepassing	*Grotendeels van toepassing*	*Deels van toepassing*	*Eerder niet van toepassing*	*Helemaal niet van toepassing*
Ik gebruik ACC op de snelweg	☐1	☐2	☐3	☐4	☐5
Ik gebruik ACC op de provinciale weg	☐1	☐2	☐3	☐4	☐5
Ik gebruik ACC in de stad	☐1	☐2	☐3	☐4	☐5
Ik gebruik ACC in de buurt van een kruispunt	☐1	☐2	☐3	☐4	☐5
Ik gebruik ACC in tunnels	☐1	☐2	☐3	☐4	☐5
Ik gebruik ACC op de oprit van een snelweg	☐1	☐2	☐3	☐4	☐5
Ik gebruik ACC op de afrit van een snelweg	☐1	☐2	☐3	☐4	☐5
Ik gebruik ACC als het regent	☐1	☐2	☐3	☐4	☐5
Ik gebruik ACC als het erg zonnig weer is en ik word verblind door de zon.	☐1	☐2	☐3	☐4	☐5
Ik gebruik ACC als ik achter een bekende bestuurder rijd.	☐1	☐2	☐3	☐4	☐5
Ik gebruik ACC als ik achter een onbekende bestuurder rijd.	☐1	☐2	☐3	☐4	☐5

Vragen over Cruise Control in de truck

9. Bij de volgende vragen gaat het om uw ervaring in de proef met CC (Cruise Control).

	Helemaal van toepassing				*Helemaal niet van toepassing*
Rijden met CC maakt rijden veel relaxter.	☐1	☐2	☐3	☐4	☐5
Rijden met CC is voor mij te onveilig.	☐1	☐2	☐3	☐4	☐5
Rijden met CC geeft mij de mogelijkheid om naast het rijden nog andere dingen te doen.	☐1	☐2	☐3	☐4	☐5
Ik vertrouw niet op de technologie.	☐1	☐2	☐3	☐4	☐5
Ik zou het rijden met CC alleen in files gebruiken.	☐1	☐2	☐3	☐4	☐5
Ik ben bang, dat de techniek opeens uit valt of niet meer beschikbaar is.	☐1	☐2	☐3	☐4	☐5
Ik wil zelf rijden, bij rijden met CC raak ik mijn rijplezier kwijt.	☐1	☐2	☐3	☐4	☐5
Rijden met CC voorkomt ongelukken en maakt rijden veiliger.	☐1	☐2	☐3	☐4	☐5

Vragen over stress in de truck

10. Bij de volgende vragen gaat het over de werkdruk die u ervaart hebt tijdens deze meetproef.

	Helemaal van toepassing				*Helemaal niet van toepassing*
Na enkele dagen met veel laden en lossen, kan ik mijn werk niet meer goed doen door vermoeidheid.	☐1	☐2	☐3	☐4	☐5
Na een lange werkdag heb ik nog genoeg energie om dingen te doen.	☐1	☐2	☐3	☐4	☐5
Tijdens een werkdag heb ik extra pauzes nodig.	☐1	☐2	☐3	☐4	☐5
Na enkele dagen met veel laden en lossen, voel ik me fysiek uitgeput.	☐1	☐2	☐3	☐4	☐5
Wanneer ik de hele dag heb gereden, is het moeilijk voor mij om te ontspannen.	☐1	☐2	☐3	☐4	☐5
Na het werk ontspan ik gemakkelijk.	☐1	☐2	☐3	☐4	☐5
Ik slaap goed.	☐1	☐2	☐3	☐4	☐5

Ik val meestal gemakkelijk in slaap.	☐1	☐2	☐3	☐4	☐5
Ik slaap onrustig.	☐1	☐2	☐3	☐4	☐5
Wanneer ik s' nachts wakker word, vind ik het moeilijk om weer in slaap te vallen.	☐1	☐2	☐3	☐4	☐5

11. De volgende vragen gaan over de situaties wanneer u rijdt in de truck. Kunt u hieronder aangeven in welke situaties u meer stress ervaart dan wanneer u normaal truck rijdt?

	100% van toepassing	*Grotendeels van toepassing*	*Deels van toepassing*	*Eerder niet van toepassing*	*Helemaal niet van toepassing*
Ik ervaar meer stress op de snelweg, dan in de stad.	☐1	☐2	☐3	☐4	☐5
Ik ervaar meer stress op de provinciale weg, dan op de snelweg.	☐1	☐2	☐3	☐4	☐5
Ik ervaar meer stress in de stad, dan op een provinciale weg.	☐1	☐2	☐3	☐4	☐5
Ik ervaar meer stress in de buurt van een kruispunt	☐1	☐2	☐3	☐4	☐5
Ik ervaar meer stress in tunnels	☐1	☐2	☐3	☐4	☐5
Ik ervaar meer stress op de oprit van een snelweg	☐1	☐2	☐3	☐4	☐5
Ik ervaar meer stress op de afrit van een snelweg	☐1	☐2	☐3	☐4	☐5
Ik ervaar meer stress als het regent	☐1	☐2	☐3	☐4	☐5
Ik ervaar meer stress als het erg zonnig weer is en ik word verblind door de zon.	☐1	☐2	☐3	☐4	☐5
Ik ervaar meer stress als ik achter een onbekende bestuurder rijd.	☐1	☐2	☐3	☐4	☐5
Ik ervaar meer stress als er een voertuig voor mij rijd.	☐1	☐2	☐3	☐4	☐5
Ik ervaar meer stress als ik rijd met semi-automatische systemen (bijvoorbeeld ACC, CC, lane keeping, etc.).	☐1	☐2	☐3	☐4	☐5
Ik ervaar meer stress als ik rijd met ACC actief.	☐1	☐2	☐3	☐4	☐5
Ik ervaar meer stress als ik rijd met CC actief.	☐1	☐2	☐3	☐4	☐5

Dit is het einde van deze vragenlijst. Bedankt voor het invullen.

C Results Human interaction surveys

8.1.7 Mean value and interquartile range of questions

Table 27: Mean value and interquartile range of acceptance scale dimension values, for each campaign.

Dimension	Campaign: Beginning		Campaign: Baseline1		Campaign: No ACC		Campaign: ACC3		Campaign: ACC1		Campaign: Baseline2		Campaign: ACC3 Convoy		Campaign: ACC1 Convoy		Campaign: Final	
	Med	Iqr	Med	Iqr	Med	Iqr	Med	Iqr	Med	Iqr	Med	Iqr	Med	Iqr	Med	Iqr	Med	Iqr
Usefulness	1.8333	0.3750	1.6667	0.5000	1.4167	0.6667	1.6667	0.5000	1.6667	0.5000	1.6667	0.5833	1.7500	0.1667	1.5000	0.5000	1.5000	0.5000
Satisfying	1.8750	0.2500	1.8750	0.5000	1.7500	0.5000	2.0000	0.5625	2.0000	0.5000	2.0000	0.5625	2.0000	0	1.7500	0.5000	2.0000	0.5625

Table 28: Mean value and interquartile range of trucker strain monitor dimension values, for each campaign.

Dimension	Campaign: Beginning		Campaign: Baseline1		Campaign: No ACC		Campaign: ACC3		Campaign: ACC1		Campaign: Baseline2		Campaign: ACC3 Convoy		Campaign: ACC1 Convoy		Campaign: Final	
	Med	Iqr	Med	Iqr	Med	Iqr	Med	Iqr	Med	Iqr	Med	Iqr	Med	Iqr	Med	Iqr	Med	Iqr
Work-related fatigue	0.8333	1.0000	0.8333	0.6250	1	0.9167	1.1667	0.3333	1.1667	0.3750	1.1667	0.4167	1.3333	0.2500	1.2500	0.4167	1.3333	0.6250
Sleeping problems	1.0000	1.0625	1.7500	0.9375	2	1.2500	1.5000	1.9375	1.7500	1.6875	1.5000	1.3750	1.2500	1.7500	1.3750	1.6250	0.5000	2.0625

Table 29: Mean value and interquartile range of trust dimension values, for each campaign.

Dimension	Campaign: Beginning		Campaign: Baseline1		Campaign: No ACC		Campaign: ACC3		Campaign: ACC1		Campaign: Baseline2		Campaign: ACC3 Convoy		Campaign: ACC1 Convoy		Campaign: Final	
	Med	Iqr	Med	Iqr	Med	Iqr	Med	Iqr	Med	Iqr	Med	Iqr	Med	Iqr	Med	Iqr	Med	Iqr
Usage	2.0000	0.4375	1.5000	0.5625	1.8750	0.6250	1.8750	0.5000	1.7500	0.5000	1.7500	0.3750	1.7500	0.5000	1.7500	0.3750	2.0000	0.7500
Trust	1.2727	0.6364	1.6364	0.7273	1.6364	0.9091	1.5909	0.7273	1.3636	0.4091	1.7273	0.7273	1.5455	0.5227	1.6364	0.4091	1.4545	0.7273

8.1.8 Results linear mixed models analysis with period and % ACC active fixed factors

Table 30: Linear mixed-effect model results for the analysis of acceptance scale and use of ACC over different campaigns. The following model was tested in MatLab using REML estimation: Difference in dimension ~ 1+campaign +% ACC+ (1|Participant).

Acceptance scale dimension	Term	f	df1	df2	p (F > f)
Usefullness beginning-Usefullness campaign	Intercept	0.00064007	1	19	0.98008
	Campaign	1.6347	6	19	0.19206
	% ACC highway	0.032642	1	19	0.85854
Satisfying beginning-Satisfying campaign	Intercept	0.12682	1	24	0.72486
	Campaign	0.86225	6	24	0.53627
	% ACC highway	0.080753	1	24	0.77872

Table 31: Linear mixed-effect model results for the analysis of trucker strain monitor and use of ACC over different campaigns. The following model was tested in MatLab using REML estimation: Difference in dimension ~ 1+campaign +% ACC+ (1|Participant).

Trucker strain monitor scale dimension	Term	f	df1	df2	p (F > f)
Work-related fatigue beginning-Work-related fatigue campaign	Intercept	3.5246	1	33	0.069326
	Campaign	1.3107	6	33	0.27996
	% ACC highway	2.0919	1	33	0.15751
Sleeping problems beginning- Sleeping problems campaign	Intercept	10.524	1	33	0.31242
	Campaign	0.70638	6	33	0.64666
	% ACC highway	0.27718	1	33	0.60207

Table 32: Linear mixed-effect model results for the analysis of Trust questions and use of ACC over different campaigns. The following model was tested in MatLab using REML estimation: Difference in dimension ~ 1+campaign +% ACC+ (1|Participant).

Trust scale dimension	Term	f	df1	df2	p (F > f)
Usage beginning-Usage campaign	Intercept	0.065189	1	35	0.79997
	Campaign	19.832	6	35	0.094646
	% ACC highway	0.32155	1	35	0.5743
Trust beginning-Trust campaign	Intercept	0.061113	1	32	0.80633
	Campaign	0.1068	6	32	0.99505
	% ACC highway	1.2259	1	32	0.27645

Table 33: Linear mixed-effect model results for the analysis of question ”Driving with ACC gives me the opportunity to do other things besides driving” and use of ACC over different campaigns. The following model was tested in MatLab using REML estimation: Answer to question ~ 1+campaign +% ACC+ (1|Participant).

Acceptance scale dimension	Term	f	df1	df2	p (F > f)
Driving with ACC gives me the opportunity to do other things besides driving.	Intercept	34.517	1	35	1.1276e-06
	Campaign	1.6476	6	35	0.16342
	% ACC highway	0.22223	1	35	0.64027

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Table 34: Linear mixed-effects model parameter estimates and p-values for the effect of Condition on Effort. The effect of Condition on Effort was tested with the following model: Effort ~ 1 + Condition + (1|Participant) + (1|Day:Participant), using REML estimation in MatLab.

Parameter	Estimate	SE	t	df	p (T > t)	Lower	Upper
Intercept	22.93	2.85	8.05	6.68	0.00011	16.13	29.73
Condition A2	2.07	1.30	1.59	228.4	0.1131	-0.49	4.62
Condition A3	-10.51	2.73	-3.85	741.6	0.000129	-15.87	-5.15
Condition B1	-2.29	1.17	-1.95	230.41	0.0521	-4.59	0.02
Condition B2	-2.79	1.18	-2.37	201.21	0.0186	-5.11	-0.47
Condition C1	-3.11	1.17	-2.65	246.63	0.0086	-5.42	-0.80
Condition C2	-5.16	1.23	-4.18	284.49	3.81e-05	-7.59	-2.73

Table 35: Linear mixed-effects model parameter estimates and p-values for the analysis of Effort. The effect of Condition, pACCon, Speed and pWiperOn on Effort was tested with the following model: Effort ~ 1 + Condition + pACCon + Speed + pWiperOn + (1|Participant) + (1|Day:Participant), using REML estimation in MatLab.

Parameter	Estimate	SE	t	df	p (T > t)	Lower	Upper
Intercept	21.09	3.35	6.29	7.99	0.00024	13.36	28.82
Condition A2	3.27	1.53	2.14	294.27	0.03	0.27	6.27
Condition A3	-9.87	2.45	-4.03	294.34	7.23-05	-14.69	-5.04
Condition B1	-1.99	1.41	-1.42	294.52	0.16	-4.76	0.77
Condition B2	-2.93	1.50	-1.96	296.47	0.05	-5.88	0.01
Condition C1	-2.74	1.39	-1.98	296.29	0.05	-5.47	-0.01
Condition C2	-3.82	1.50	-2.55	298.99	0.011	-6.77	-0.87
pACCon	-0.22	3.08	-0.07	298.88	0.94	-6.28	5.85
Speed	-0.08	0.07	-1.09	298.17	0.28	-0.22	0.06
pWiperOn	-2.60	2.15	-1.21	294.38	0.23	-6.82	1.62

Table 36: Linear mixed-effect model results for the analysis of mean driving speed per trip. The following model was tested in MatLab using REML estimation: SpeedMn ~ Condition * pACCon * Speed_limit + (1|Participant) + (1|Trip:Participant).

Factor	f	df1	df2	p (F > f)
Intercept	691.19	1	5.22	9.5012e-07
Condition	23.66	6	1237.2	1.3937e-26
pACCon	337.02	1	1238.2	9.1454e-67
Speed limit	4.68	1	1237.8	0.030645
Condition:pACCon	25.45	6	1237.7	1.3054e-28
Condition:Speed limit	13.65	6	1237.2	4.6983e-15
pACCon:Speed limit	0.7385	1	1237	0.39031
Condition:pACCon:Speed limit	7.02	6	1237	2.3123e-07

Table 37: Linear mixed-effect model results for the analysis of driving speed standard deviation per trip. The following model was tested in MatLab using REML estimation: SpeedSD ~ Condition * pACCon * Speed_limit + (1|Participant) + (1|Trip:Participant).

Factor	f	df1	df2	p (F > f)
Intercept	401.81	1	5.321	3.2287e-06
Condition	11.75	6	1237.3	7.5945e-13
pACCon	130.81	1	1238.7	7.2194e-29
Speed limit	1.96	1	1238.1	0.16157
Condition:pACCon	9.26	6	1238	5.9934e-10
Condition:Speed limit	8.26	6	1237.4	8.7756e-09
pACCon:Speed limit	4.83	1	1237	0.028128
Condition:pACCon:Speed limit	2.51	6	1237	0.020443

Table 38: Linear mixed-effect model results for the analysis of time headway per trip. The following model was tested in MatLab using REML estimation: log(Time headway) ~ Condition * pACCon * Speed + (1|Participant) + (1|Trip:Participant).

Factor	f	df1	df2	p (F > f)
Intercept	260.25	1	6.62	1.4651e-06
Condition	0.90	6	1163.4	0.49379
pACCon	1.90	1	1141.6	0.16801
Speed	17.28	1	1123.1	3.4782e-05
Condition:pACCon	1.08	6	1163	0.37184
Condition:Speed	1.52	6	1161.7	0.16659
pACCon:Speed	0.20	1	1164.7	0.65103
Condition:pACCon:Speed	0.63	6	1163.5	0.709

E Legal framework for platooning

The Netherlands can be considered a transit country and therefore the viability of implementation of truck platooning in the Netherlands hinges upon the connectivity to our neighbouring countries. In 2016, first experiences with cross-border truck platooning were obtained. It proved quite challenging to allow truck platoons to cross borders, as various EU nations and also provinces had their own traffic legislations to which the platoons had to abide. The European research project ENSEMBLE developed an extensive state of the art of the regulatory framework of platooning in Europe (Tobar, 2019), including recommendations from past projects (COMPANION, SARTRE, ETPC). In this section we highlight the most important findings of this report. Thereby we focus specifically on cross-border or European regulations and not necessarily on individual member states.

8.1.9 Experiences with crossing borders

In 2016, five EU member states and six European truck manufacturers participated in the European Truck Platooning Challenge which was a successful experiment with cross-border platooning.

The key learning points of this challenge were:

- National organisations are responsible for the approval of vehicle modifications and the national requirements of these bodies differ. In total 19 exemptions were needed to execute the challenge.
- ACEA agreed to set 0,5 seconds as minimum following distance during the ETPC.
- Vehicle assessment varies among countries, but most assess the vehicle, the road and the interface between the trucks and other road users.

Next to the ETPC, the Dutch-German project Interregional Automated Transport (Interreg- IAT) conducted cross-border convoy driving field tests on Dutch-German corridors in 2019. Currently, these tests are only possible by engaging in an exemption procedure for admission on the public road.

8.1.10 Regulatory framework and current legislation

The current regulatory framework is not ready to adopt platooning as it does not support admission of autonomous driving functions on the road (Tobar, 2019). This is also underscored by the Interreg-IAT study (Hartwig, 2019).

Following the Interreg-IAT study the legislative structure can be visualized as follows:

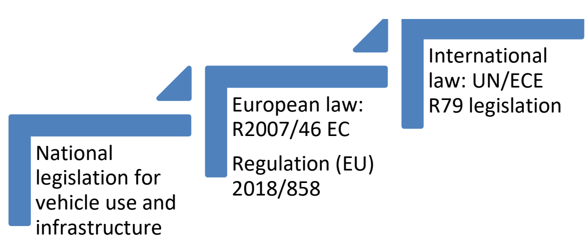

Figure 56: Regulatory framework (adapted from: (Hartwig, 2019) and (Tobar, 2019)).

- International law – UN/ ECE R79: Assistive Systems are only allowed if the driver always holds the main responsibility for driving the vehicle (Hartwig, 2019). UNECE regulatory process is integrated in EU rulemaking, so these are often mandatory in European law (Tobar, 2019).
- European law: Directive 2007/46 EC, to be repealed by Regulation (EU) 2018/858 as of September 1st 2020. This is the regulation on type approval and market surveillance of motor vehicles (Tobar, 2019). Furthermore, the directive 2010/40/EU is an instrument for the coordinated implementation of Intelligent Transport Systems (ITS) in Europe.
- National law: individual European member states have their own local bodies or ministries concerned with vehicle use and infrastructure. The different type-approval authorities and road authorities and the exemption procedures are summarized by (Tobar, 2019).

The regulatory matrix in (Tobar, 2019) lists the regulations and directives and on what aspect of truck platooning they might have impact (vehicle, use and infrastructure). With respect to experimentation, Dutch legislation provides for an experimental framework for the temporary approval of vehicles with automated driving functions where the driver is no longer in the vehicle (which is not the case in Germany (Hartwig, 2019). Furthermore, Article 39 of Regulation (EU) 2018/858 introduces the exemptions for new technologies or new concepts (Tobar, 2019).

8.1.11 *Harmonization of regulation*

Again, the state-of-the art developed by (Tobar, 2019) comes in helpful for listing current programs that evaluate harmonization of connected and automated driving regulations.

- WP.29 is the World Forum for Harmonization of Vehicle Regulations and is assisted by six specialized groups, amongst which is the Working Party on Automated/ Autonomous and Connected Vehicles (GRVA).

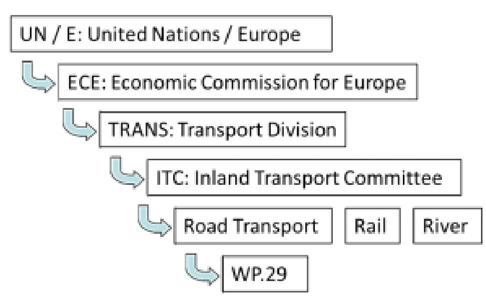

Figure 57: Hierarchical chart of the UN Transport Committee (Tobar, 2019).

- WP.1 is the Global Forum for Road Traffic Safety and recently adopted a resolution serving as a guide for countries in relation to the safe deployment of highly and fully automated vehicles in road traffic.

European Union Strategy on Automated Driving entails: encouraging the developments of key technologies and infrastructures, ensuring a safe and future-proof legal framework, addressing societal concerns especially with respect to jobs and ethical issues (Tobar, 2019).

In Q4 of 2019 the European Commission published Regulation (EU) 2019/2144, stating that a regulatory framework with harmonised rules and procedures will be needed. Article 11 includes specific requirements relating to automated vehicles and fully automated vehicles, amongst others that automated or fully autonomous vehicles shall comply with a harmonised format for the exchange of data for instance for multi-brand vehicle platooning.