Safe Roadtrains for Efficient Transports

Public report

Project within Platooning
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Table of Contents

1. Summary

The project Safe road trains for efficient transport, SERET, has carried out research on platooning with heavy vehicles. Platooning means that two or more vehicles drive with reduced distance to minimize drag and thereby minimizing fuel consumption and emissions. A reduced distance also increases the capacity of the road. Safety is enhanced as the vehicle communicates their maneuvering over radio to control longitudinal and lateral position.

The project has carried out research and development in a number of areas. Use cases and safety analysis have been made, a human machine interface has been developed and evaluated as well as algorithms for longitudinal and lateral control. Focus group interviews with drivers have been conducted to collect their needs and requirements, as well as evaluations of user interfaces in a truck simulator. Extensive computer simulations have been made of drag. Detailed simulation of fuel consumption has been made for different distances, control algorithms and different types of power trains such as conventional diesel trucks and electrical hybrids.

Special attention has been devoted to the radio communication between the vehicles, as Vehicle to Vehicle communication (V2V) is essential for safe and energy efficient platooning.

Finally a system solution has been implemented in three vehicles and extensive validation has been made on track as well as on public road. The vehicles participated, amongst other, in the European Truck Platooning Challenge 2016 driving between Gothenburg and Rotterdam.

2. Sammanfattning på svenska

Projektet Safe road trains for efficient transport, SERET, syftade till att forska runt kolonnkörning, i dagligt tal kallat Platooning, av tunga fordon. Platooning innebär att man kör två eller flera fordon med reducerat avstånd för att minska luftmotståndet och därmed bränsleförbrukning och utsläpp. Med reducerade avstånd så ökar också vägkapaciteten. Med radiokontakt mellan fordonen och reglerfunktioner för longitudinell och lateral styrning så kompenseras olycksrisken som följer av kortare avstånd.

Inom projektet så har forskning och utveckling skett på en rad områden. Användningsfall och säkerhetsanalys har gjorts, användargränsnitt för föraren utvecklats och utvärderats liksom regleralgoritmer för fordonens laterala och longitudinella styrning.

Fokusgruppintervjuer med förare har genomförts för att ta reda behov och krav, samt utvärdering av förargränssnitt (HMI) i lastbilssimulator.

Omfattande datorsimuleringar av luftmotstånd och bränsleförbrukning har gjorts för olika avstånd mellan fordonen och olika optimeringsalgoritmer. Simuleringar med platooning med olika fordonstyper såsom konventionella dieseldrivna och elhybrider har också utförts.

Speciellt fokus har i projektet lagts på radiokommunikationen mellan fordonen då så kallade Vehicle to Vehicle (V2V) är central för platooning med hög säkerhet och minska energiförbrukningen. Slutligen har en systemlösning implementeras i tre fordon och omfattande verifiering har gjorts på såväl bana såsom på väg. Fordonen deltog bland annat i European Truck Platooning Challange 2016 från Göteborg till Rotterdam.

3. Background

A Platoon is a unit of several trucks driving together in close headway distances (1,0-0,5 seconds) to reduce air resistance. The main purpose of platooning is to reduce the fuel consumption and to decrease the emissions. Other potential benefits with platooning are improved safety and increased transport efficiency.

The trucks are automatically controlled with longitudinal and lateral control. Sensors such as radars, GPS and cameras are used to measure distances, keep track of lane markings and position. The trucks share information between each other using radio communication (V2V).

Platooning can be executed at different levels. One level of platooning is to use the Adaptive Cruise Control (ACC) as in today’s vehicles. Another level is to complement the ACC function is with information like speed, acceleration, position from the vehicle(s) in front using V2V, which makes it possible to drive safely with shorter distances and also to save more energy (fuel). This mode is based on Cooperative Adaptive Cruise Control (CACC), and requires radio communication between the vehicles and radar sensors to measure and control the distance to the vehicle in front. CACC handle the longitudinal control of the platooning trucks while the driver still controls the lateral position.

The next step, to control the vehicle also laterally, needs additional sensors and algorithms. One concept for this is that the following trucks are using sensors to identify and follow the lane in which the vehicle in front is driving and another way to do this is to follow the first truck in its tracks using the geographical positions that are transferred over the V2V radio interface or using sensors to track the rearmost part of the vehicle head. The first concept is suitable for longer distances between the trucks while the second might be appropriate in situations when the distance between the trucks are so short that the following trucks sensors has hard to follow lanes as the lane markings are hidden by the vehicle in front. It is possible to combine those two algorithms making it possible to handle situation with bad lane marking. In this project only lateral control following lane markings has been implemented and demonstrated.

Platooning means fuel saving due to reduced drag. The savings increases with increased speed and shorter distance between the trucks. Obviously the savings are higher on flat and straight roads were the speed can be high and constant than on hilly roads were the speed is lower and changes up and down hills. It can be shown that varying the speed and gap of individual vehicles over hilly terrain can reduce energy consumption compared to driving at constant speed.

How much fuel that can be saved depends on, as stated above, how close behind each other the vehicles can drive safely and comfortably? With very short distances the driver in the following truck will only have a limited view forward which puts additional requirements on redundant systems and on the roads that platooning can be performed. The CACC and CACC+ (CACC plus lateral control) platooning modes are based on that each truck controls its position using the input from the truck(s) in front but without being controlled from the leading truck nor controlling the trucks in front or behind. There are other scenarios that have been covered in the project. One way to increase fuel saving is to optimize speed for each vehicle based on road conditions and vehicle characteristics and thereby get an individual optimized profile for each truck.

Another concept is that the leading truck (or a back office function) decides the speed and distances for all platoon members and thereby controls actively the platoon. The advantage is that the platoon can be kept together in denser traffic or in heavy traffic as the complete platoon can slow down as soon as a truck at the back of the platoon starts lagging.

Driving in platoon involves a number of use cases, such as joining the platoon, increase and decrease the distances between the trucks at entries and exits as well as handling situation were other vehicles cut in between two platooning trucks, and dissolving the platoon because trucks leave the platoon or when road conditions or traffic conditions makes platooning inappropriate. There are also other use cases, such as match making to find a partner to platoon with and arrange the platoon order in an optimal order.

There are use cases that are not possible to make with the CACC+ approach such a full automated lane change as this requires sensors to detect traffic from behind and at the side of the column of trucks. However many see platooning as a first step into automated driving assuming that it would be possible on dedicated roads to have the second truck, in a platoon of two vehicles, drive without driver.

Platooning requires high level of functional safety, e.g. a faulty sensor should not cause accidents, hard braking must not occur on false positives from the vehicle in front. Platooning also means new roles and responsibilities for the drivers. For example, the driver leading a platoon may need to be attentive to situations that could affect the platoon, and the drivers in the following trucks may need abilities to compensate the limited field of view due to the close distance to the truck in front.

Legal aspects such as regulations around drive and rest times have not been in the scope of this project, nor have business models or back office support systems. However the general conclusion is that platooning can be even more profitable than just the saving in fuel if the drivers in following trucks can be removed entirely or at least get some more daily drive time. It is also a common belief that there is a need for back office systems to make match making so that the distance trucks are platooning can be maximized.

4. Purpose, research questions and method

Purpose

The purpose of the project was to continue development of knowledge through research and development so that at the end of the project, knowledge has been gained for:

- Means to achieve necessary improvements of performance, system stability and robustness – especially for different weather conditions and varying topography
- Validation of simulated fuel consumption improvements for different vehicle combinations and conditions
- Strategies for designing the human/machine interaction, both in normal and abnormal/critical situations
- Effects on drivers acceptance, behavior and trust to the system, especially during long usage
- The platoon's interaction with other traffic
- Harmonization and verification of specifications of the main functionality.
- Methods to minimize the wear of the road by the vehicles

Research questions

- How is safety guaranteed within the platoon?
- What level of autonomous driving (in the leader and follower vehicle) is wanted?
- What data is needed to exchange between vehicles to create and maintain a platoon?
- How is string stabilization achieved?
- What type of sensors and sensor technologies are needed for lateral and longitudinal control?
- What type of sensory modalities (vision, hearing, feel) can be used to provide information to the driver?
- How can the system be compatible between the driver and the system with respect to driver and system intentions and driver and system actions?

Method

The project was divided into seven Work Packages:

1. WP1 Project Management
2. WP2 Use-Cases and functional safety
3. WP3 Human Machine interaction
4. WP4 V2V communication and sensors
5. WP5 Platooning application
6. WP6 Verification
7. WP7 Dissemination and publication of research results

WP1 – Project management has been responsible for work methods, financial reporting and to ensure that the objectives are meet.

WP2 – Define use cases for driving in platoon and to analyze functional safety matters for platooning.

WP3 – Based on the use-cases (wp2) different for human machine interaction (HMI) concepts were developed and evaluated. The research in this work package has also investigated user/driver needs and requirements from Lead-vehicle drivers and from Follow-vehicle drivers in platoons.

WP4 – This work package has investigated how communication can be established between the platooning vehicles and the needed reliability and update frequency.

WP5 – This work package has focused on the control of the vehicle and the platoon including string stability and development of algorithms for lateral and longitudinal control. The work has also investigated what information needs to be exchanged between the vehicles and how can string stability be ensured and what kind of measurements is needed for lateral and longitudinal control.

WP6 – This work package has handled the verification of the developed concepts and solutions, including building of the systems, verification of the technical solutions and algorithms as well as logging fuel consumption etc.

WP7 – Dissemination, publishing and demonstrations of activities and results from the project.

For HMI, vehicle-to-vehicle communication and vehicle control, simulation and tests in real vehicles was used for development and validation. HMI simulations were performed in vehicle simulators located at Volvo and questionnaires together with discussions were used to evaluate different concepts. Interviews were also held with drivers using the platooning system.

Vehicle-to-vehicle communication and vehicle control was mostly validated together to get a complete system validation. The vehicle control is very much dependent on the vehicle-to-vehicle communication, but it was also interesting to validate different disconnection scenarios, where the vehicle-to-vehicle communication became unavailable during platooning.

Simulations were also done to get measurements on fuel consumption for variety of different scenarios, some of them difficult to do in test vehicles.

5. Objective

The objective has been to investigate/study, develop and verify algorithms and models for vehicle longitudinal and lateral control to maintain functional safety and string stability along with development of HMI-concepts and V2V functionality. The project has also carried out extensive simulations of drag and fuel consumption and described alternative algorithms to optimize fuel savings.

6. Results and deliverables

The project has been successful and fulfilled its objectives and essential knowledge and practical experience of platooning has been achieved.

- Improvements of performance, system stability and robustness have been addressed during the development and extensive testing.
- Fuel savings has been simulated and verified. The simulation has included optimization of speed profile over hilly roads.
- Calculation of air drag for truck in platooning for different gaps has been carried out.
- The interaction between driver and vehicle has been studied; driving in simulator as well on road has been done to evaluate various concepts.
- Driver behavior including how surrounding traffic behaves has been studied and experienced during, amongst other, the European Truck Platoon Challenge.
- Drivers need for critical information has been investigated using a HMI that displays the status of the platoon and cameras/monitor that shows the road before the leading truck.

The following areas are further summarized in this chapter

- Human Machine Interface (HMI), summary from study in simulator and description of implemented functionality as well as evaluation of driving.
- Longitudinal and Lateral Control, implementation and performance, challenges, fuel saving and drivers comfort.
- Vehicle to Vehicle communication (V2V), protocol and considerations such as update frequency.
- Platooning Application and Demonstrators, short description of the functionality and hardware that was implemented in the test Vehicles.
- Functional Safety, a general overview and a deep dive in one use case covering false positive braking message over V2V.
- Energy optimization using a genetic algorithm, an alternative optimization method to find a speed reference over hilly terrain.

6.1 HMI

Platooning infers a different concept of driving. It demands other requirements for safe driving and new solutions for the interactions between the drivers, the vehicles and the platooning system. In this context, the Human Machine Interaction (HMI) in terms of input and output, i.e. information to the driver about the platooning system and the driver's interactions with the platooning system, are critical for safe and effective platooning.

AB Volvo participated in the EU Truck Platooning Challenge with three trucks driving as a platoon from Göteborg (Sweden) to Rotterdam (The Netherlands) in March 2016. This event provided valuable experiences and gained knowledge about driving in a platoon.

Interviews with platoon drivers

Two drivers from the Platooning challenge were interviewed. The purpose was to get first-hand information about their experiences of driving in a platoon. The following areas were discussed:

- General experiences from driving in a platoon
- Experiences from specific situations, such as enter/exit motorway, changing lanes, overtake other vehicles, intruders between the trucks, driving through traffic lights and roundabouts
- How to display platooning related messages to the drivers
- Information to indicate the different modes and the transitions (platooning, manual driving)
- Information when changing the tasks from driving as FV-driver to driving as LV-driver
- Communication between the drivers in the platoon
- Other specific problems experienced by the drivers while driving in platoon.

The interviews proved important information about driving in a platoon, for example:

- The information to the drivers must be meaningful, i.e. clear message (what), consequences and if/what/how/ the driver should act; *what should I do if…?*
- Information about other vehicles cutting into the platoon is important for the drivers to better understand what is happening in the platoon
- The system should inform the drivers what systems are active/not active, and inform the drivers what they should do in specific situations
- The design of the HMI is important for the drivers' understanding of the system and of the truck's behavior
- Information to the drivers about the Lead Vehicle's route and destination is useful
- Video streaming from the Lead Vehicle was perceived as a useful
- The internal radio communication was important to inform each other about intruding vehicles, upcoming situations, e.g. vehicles entering the highway, obstacles in front, roundabouts etc. The radio was important to "keep the platoon together"
- Other vehicles that cut in between the platooning trucks increased the distances between the trucks
- Cars could suddenly cut between the trucks in order to reach an exit in time.
- To keep the platoon together and at the same time merge with the traffic on the highway was perceived as difficult in short entries to highways, as often was the case in Germany
- Roundabouts and traffic lights were difficult to pass without being disconnected to the other trucks
- Objects standing at the side of the road could cause critical situations. The Lead vehicle could see the objects, but not the following trucks. In cases like these, the video streaming could be useful

Simulator study

The interviews provided important experiences and knowledge for the development of an HMI-concept which was implemented in GTT/ATR truck simulator. Twelve truck drivers participated in the study. The main purposes of the simulator study were; (i) to evaluate the test drivers' understanding, acceptance and satisfaction of the HMI-concept and; (ii) to gather input for further development of HMI-concepts.

Figure 6-1 Truck simulator in front of a 130 degree screen

Figure 6-2 Cameras mounted in the cab to monitor the driver

The driving scenarios were the following:

- Enter highway
- Create platoon
- Drive in Platoon (as Follow vehicle)
- Other vehicle cut in → increase gap
- Intruder leaves → decrease gap
- Change lanes due to slow vehicle in front
- Steer away from obstacle partly obstructing the lane
- Approaching roundabout
- Lead vehicle leaves platoon (exit lane)
- Next follow vehicle takes over as new Lead vehicle

Methods

While the participants were driving in the truck simulator a Think-aloud protocol was used to capture the drivers' direct thoughts, questions, reactions and impressions of the HMI-concept while driving, which is valuable input in order to understand the drivers' first impressions, which in turn indicate HMI-concept's clarity, or lack of clarity to convey its intended messages.

After the drivers had finished the route they filled in three questionnaires:

Questionnaire	Description	Scale
Understanding of messages and symbols	Measures how clear and understandable the HMI is. Eight statements about the HMI (texts, symbols, colors etc.) to which the respondent agrees or disagrees on a 5-grade scale.	5-grade Likert scale
Acceptance (satisfaction & usefulness)	Measures the users' acceptance in terms of satisfaction and usefulness. Nine pairs of antonyms at each end of a 5-grade scale. Five items represent *Usefulness* and four items represent *Satisfaction*.	5-grade Likert scale
System Usability Scale (SUS)	Measures the usability. Eight statements capturing the dimensions of usability to which the respondent agrees or disagrees on a 5-grade scale.	5-grade sematic diff. scale

After the questionnaires were completed the drivers were asked to comment on the HMI-concept. The follow-up questions were complemented with screenshots of the messages and symbols in the cluster and the SID in order to facilitate the discussions about the HMI-concept. The purpose was to gather further comments (positive and negative) about the HMI-concept, as well as to gather information about areas of improvements.

Results

The interviews provided important first-hand information from real driving in platoon revealing needs and requirements for further development of interaction concepts for platooning.

The results from the questionnaires and the follow-up discussions with the drivers showed that the HMI-concept in this study was perceived as useful, clear and received good acceptance in terms of usability and satisfaction. Some specific issues were highlighted by the drivers:

- The video streaming function was good (supported the driver to “be in-the-loop”).
- The intruder-indicators provided valuable information (good to know what is happening in the platoon that can affect it).
- The information about the other trucks in the platoon (destination etc.) was very good.
- Direct radio/audio communication with the other drivers in the platoon is good and important (experiences from the Truck Platooning Challenge).

The results from the simulator study also provided important input for further development of platooning HMI-concepts.

The identified problem areas from this study were mainly about to make the messages to the drivers more clear in terms of what the drivers should do, i.e. how to act accordingly to the situation, when the driver needs to take lateral and longitudinal control, and when the drivers needs to be prepared to take control when the system cannot handle the situation.

6.2 Longitudinal and lateral control

Longitudinal control

In the project, an ”egoistic” longitudinal control was implemented, meaning that each truck controls itself based on what the trucks ahead are doing and without trying to do a total optimization on the entire platoon. This was done due to the big potential for fuel savings while keeping the system complexity relatively low. Since the lead truck is not controlled by the platooning function at all, it requires that it is driven with a slightly lower top speed than the follower trucks to be able to keep the platoon together. If the load differs significantly between the trucks and the lighter truck is in the lead, this can also lead to that a bigger gap is created between the trucks in the platoon if the lead truck is not actively controlled so that the platoon is kept together.

However, since each truck is only responsible for its own function and safety, complexity can be kept on a lower level than if the entire platoon shall be controlled together as one unit. State changes between different function states are unambiguous, and vehicles leaving the platoon can do so without affecting vehicles further ahead in the platoon.

The longitudinal control was tuned to achieve a balance of the three, often conflicting, requirements of safety, driver comfort and fuel savings. Fuel savings require, in general, a short following distance to the truck ahead, while ensuring safety sets requirements on both following distance and system latency. Driver comfort is hard to measure, but is often limited by jerks, strong accelerations, relative speed and similar metrics. As an example of this complexity, to save fuel the distance is needed to be kept short, and to be able to maintain safety in that situation a very quick and decisive action is required if the vehicle ahead is starting to decelerate, for example. However, driver comfort is severely reduced if the vehicle acts forcefully to changes in speed of the vehicle ahead, and it is not how drivers normally drive, so to keep the driver comfort high, slower movements are preferable. In the end, it becomes a compromise between the three requirements.

For longitudinal control, the main input signals are the speed and acceleration of the preceding target vehicles in the platoon. The distance to the closest target is also used to make sure that a sufficient gap is always kept to the vehicle immediately in front. However, speed and acceleration are typically also received and used from vehicles further ahead in the vehicle string, to reduce the delay and to improve string stability.

The demonstrator vehicles used the longitudinal control both on test tracks as well as on public roads. The performance is further described in Chapter 7.1: Performance.

Lateral control

Lateral control can be done in many different ways and with completely different goals. The implementation in this project was done in an exploratory way to see what worked well and was acceptable by drivers, and what created the most robust vehicle control. Similarly to longitudinal control, drivers are sensitive to accelerations laterally, and it can be argued even more so laterally since there is less support to the sides on seats in vehicles so lateral accelerations can lead to that the drivers are being “thrown around”. Furthermore, where the distance to other vehicles longitudinally is at least 5-10 meters, laterally it can be distances as small as a few decimeters to the lane markings. This means that also small faults in the lateral control can lead to the vehicle drifting out of lane, causing dangerous situations.

The solution could very well be to create a strict lateral control, making sure that the vehicle at all times is centered in the lane. However, a strict control often means an active control output which in this case can lead to a very active steering wheel, doing small corrections in a fast pace. This is typically experienced as a nervous, unreliable system if a driver is in the driver seat. Even though the vehicle itself is keeping itself perfectly centered in lane, the driver’s main impression is that the steering wheel has a very intense correction pattern. However, if the steering wheel is calmed down and instead the vehicle drifts slowly in the lane, it can be seen as a better and more confident system, even though the vehicle is not kept perfectly in lane.

As for longitudinal control, there is a balance needed between responsiveness of the system and driver comfort. A too fast and responsive system will reduce driver comfort, but at the same time the margins are small if the vehicle shall stay in its own lane.

For input to the lateral control, lane marking data was used from both the ego vehicle as well as from vehicles further ahead in the vehicle string. The point of this is that when the vehicle distances are reduced, the effectiveness of the sensors of the ego vehicle is reduced at the same time, since they are partially blocked by the preceding vehicle. The lead vehicle typically has a more unobstructed view, however, so data can be taken from that vehicle and sent using V2V. This gives vehicles further back in the vehicle string lane marking data that can be used for the lateral control.

The lateral control was never enabled on public roads, but only on test tracks. Further work should be done to evaluate how well the lateral control works on normal highways, as well as evaluating how drivers experience the lateral control.

6.3 V2V

Early in the project analysis on what data and what frequencies are needed for the communication between vehicles engaging in CACC/platooning were done based on previous experience.

The majority of the signals identified were found to be already present in Cooperative Awareness Message (CAM), as defined by ETSI EN 302 637-2 V1.3.2, and the decision was to change the CAM message by adding optional extension container(s) with CACC/platooning supporting signals. The intention was that with a slightly changed standard CAM, basic CACC would be enabled while still backwards compatible for traditional use.

Apart from extending the CAM with a few new basic fields needed in general for safety and particularly for CACC, the extended CAM adds an optional PlatooningContainer including more advanced control-signals as well as a container including signals supporting automatic lateral control. Furthermore it was decided that as soon as a vehicle engages in platooning, the PlatooningContainer becomes mandatory and CAMs shall be transmitted with a fix frequency of 10 Hz, still on the same control channel as before. If 10 Hz would be enough then the extra bandwidth required on the control channel would be marginal (and the solution wouldn't require extra message exchange or a second radio channel).

The extra signals added to the PlatooningContainer are:

platoonId: The identity of the platoon
platoonPosition: Own position in the platoon
predictedAcceleration: Own predicted acceleration
gapDistance: Own gap to the vehicle in front
enginePower: Own available Engine power
vehicleMass: Own vehicle mass
brakeCapacity: Own current brake capacity
vehicleWarnings: A set of warning flags.
roadInclination: Own perceived inclination of the road.

The optional lateralCtrlContainer adds the following signals:

distToLeftLaneMark: Distance to left lane marking
distToRightLaneMark: Distance to right lane marking
predictedCurvature: The predicted curvature
curvatureRate: The rate at which actual curvature changes
roadHeadingAngle: The heading of the road

These modified CAMs will be broadcasted from all members of the platoon. If for some reason (noise, blocked signal path, congestion...) the packet error rate is increasing during operation, the vehicles are expected to take precautions, like increasing gap distances or even dissolving the platoon.

Kapsch developed support for encoding and decoding of the extended CAM using previously developed V2X stack as basis.

An application routing data between the stack and the vehicle interface (CAN) was also developed.

The modified stack and the application were then deployed on Kapsch V2X evaluation kit, the EVK-3300, and integrated in the truck.

6.4 Platooning applications - demonstrators

For demonstration and development purposes, three demonstrator vehicles were equipped with equipment for platooning. All three vehicles were Volvo FH 4x2 2014 equipped from factory with Volvo Dynamic Steering, Volvo's production ACC and Volvo I-shift dual clutch, see Figure 6-3. For this project, extra equipment was added in the form of a dSpace MicroAutoboxII for rapid prototyping, a Kapsch EVK for V2V communication and V2V antennas. For driver HMI an Android tablet was used which communicated with the MicroAutoboxII using UDP over Wifi provided by a D-link router.

See *Figure 6-5* for a schematic picture over the installation and Figure 6-4 for a photo of the actual installation in one of the three trucks.

Vehicle control software was running in the MicroAutoboxII, communicating via CAN with the vehicle for controlling engine, brake and steering. CAN was also used for communication between the MicroAutoboxII and the Kapsch EVK.

Figure 6-3 The three demonstrator vehicles during testing.

Figure 6-4 The physical installation of the prototype equipment in one of the demonstrator trucks.

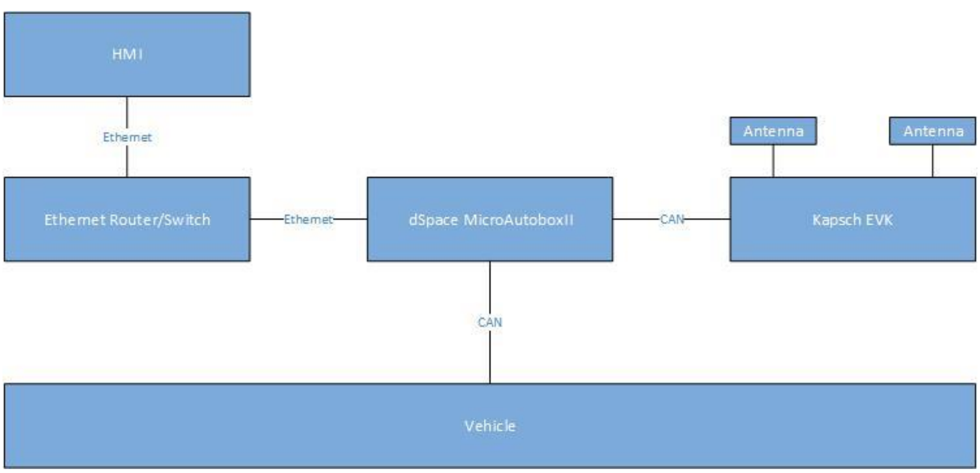

Figure 6-5 Schematic picture of the demonstrator installation

6.5 Functional Safety

A major direction for enhancing the EE system safety is to ensure that the system functions are safe to use in all situations, even when the system on a whole or some sub-system does not function properly. This is a very important dependability aspect.
There are many different kinds of in-vehicle functionality for commercial heavy vehicles that in some form or another are critical since they have an impact on a vehicle´s overall safety issues.

In an ideal world, all EE systems are developed without flaws and operate without mal-functioning. Our world, however, is not ideal in this regard. A fault is an abnormal condition that can cause an element or an item to fail.

Faults can come from many sources, such as faults introduced during development, faults introduced by hardware component aging or breaking, and faults introduced by disturbances from the environment. These faults may affect the in-vehicle functionality.
A failure is an inability of an element to perform a function as required. Not all faults lead to a failure, however, every failure results from one or more faults. An error is a discrepancy between a computed, observed or measured value or condition, and the true, specified or theoretically correct value or condition. A component failure may be a fault within an EE system that contains that component. Thus, the sequence of fault, error, and failure may repeat itself within a hierarchically structure. Errors can propagate from one component to another, ultimately resulting in an EE system-level failure. To prevent this, the error propagation needs to be analyzed and solutions for detecting and handling errors need to be developed and implemented.

Fault tolerance is the ability of the EE system to maintain full functionality in the presence of faults. It is determined by the number of errors which can occur without the occurrence of a failure. Taking care of problems while they are still errors can help prevent it from going into failure.

The fault tolerant design should keep most of the minor errors from propagating into failures. To manage faulty situations, it is common to organize the error handling at the system level. If properly designed, the EE system can respond to “glitches” by detecting errors and correcting them, intelligently.

For safety critical EE systems, it is best to design in fault tolerance. A fail-safe EE system means that it will not endanger lives or property if it fails. In many cases for in-vehicle functionality, some kind of fail-safe state is defined. A fail-safe state is one that, in the event of a specific type of failure, responds in a way that will cause no harm, or at least a minimum of harm, to other devices or to personnel.

An EE system being fail-safe doesn´t mean that failure is impossible or improbable, but rather that it is designed to prevent or mitigate unsafe consequences if it “fails”.

This study, in the SERET work package 2, investigated different functional safety aspects for a vehicle train.

Focus, in the study, was on the hazardous event of unintended deceleration, higher than 6.4 m/s2 and velocity reduction > 40 km/h when driving on highway with a car within a short distance behind the truck, for a path from the V2X radio, via the ECU, to the actuating brake. The corresponding hazard analysis indicates very high safety integrity level, ASIL D for the Safety Goal according to ISO 26262.

Use-case	Three vehicles are driving in platoon*
Pre-condition	The leader vehicle is manually steered and controlled automatically (CC or ACC). The two follower vehicles are automatically controlled laterally and longitudinally based on radar data and V2V data from lane position camera from the leader vehicle and relative position between the leader vehicle and the subject vehicle. Subject vehicle has position 2 or 3 in platoon.
Main flow	Leader vehicle brakes. Subject vehicle brakes simultaneously.
Alternative flow	Leader vehicle steers to keep lane position. Subject vehicle keeps same trajectory as leader vehicle by automated lateral control.

CACC and Platooning use Vehicle-To-Vehicle (V2V) communication, to complement the information received by the on-board sensors (radar and camera) in order to reduce the vehicle following distance while maintaining (or even increase) safety. V2V communication using the 802.11p standard (C-ITS in Europe, DSRC in the United States) is expected to be rolled out in the coming years.

There are no guarantees that (all) messages sent out by a Platooning vehicle train member will be picked up by (all) other Platooning members. Issues that may affect reception are obstacles, radio noise and radio channel congestion.

V2V is more accurate and has less delay than data received by on-board sensors, and also allows the system to use information from vehicles that cannot be seen by the on-board sensors. The main motivation for reducing the time gap is fuel savings. Fuel consumption testing has been performed showing that short distances between vehicles reduce the air drag and less fuel is used. The effect is higher on the follower trucks but also the leader truck is expected to have limited savings.

Fault tree analysis (Unwanted hard braking applied- V2V)

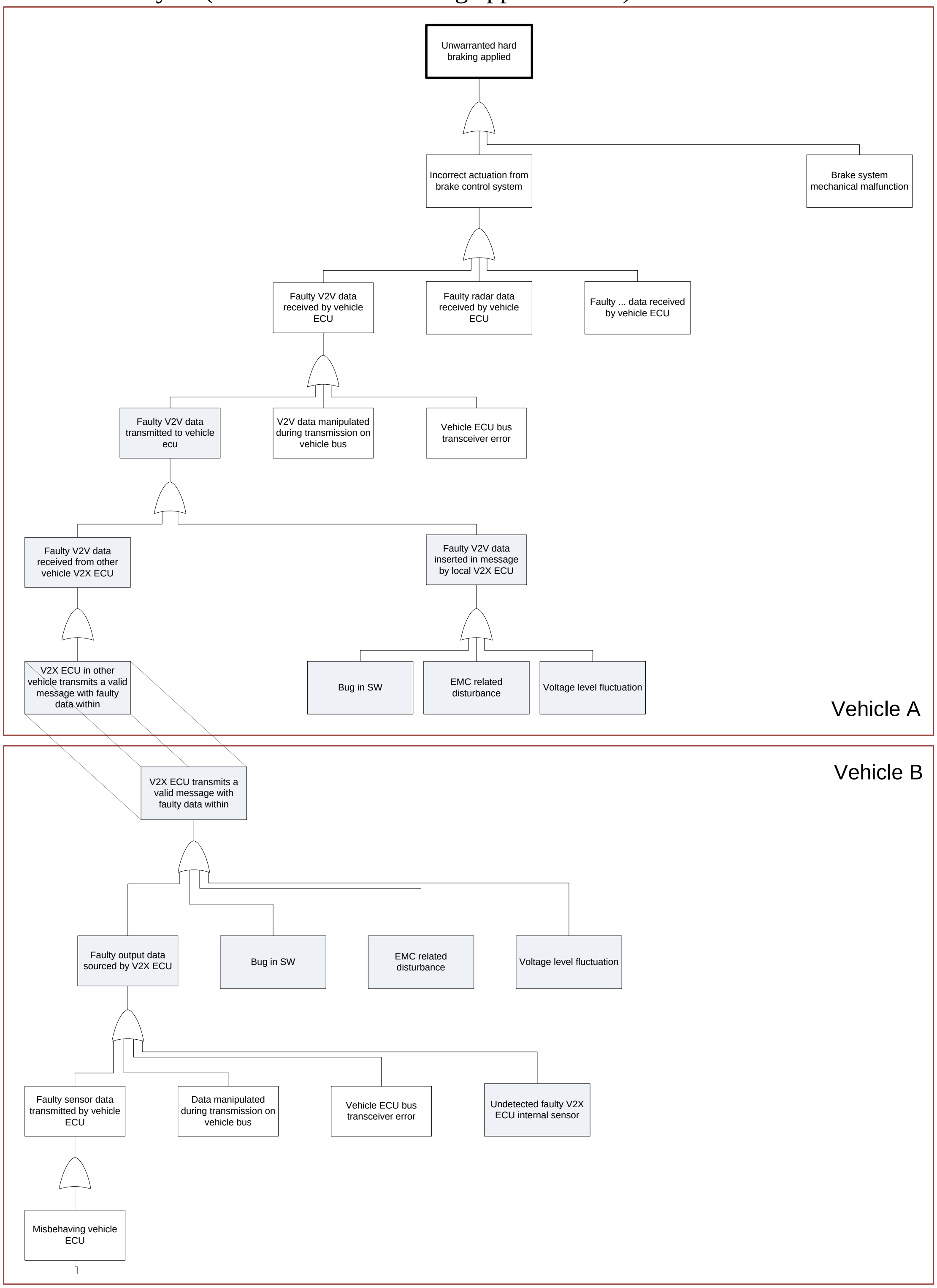

Figure 6-6 Fault tree: Unwanted hard braking applied.

The above Fault Tree Analysis for the chosen hazardous event describes how basic faults can be prevented by making brake actuation decision on correct data. Therefore focus is on avoiding data manipulation in the path from the V2X radio, via ECU, to the actuating brake. Risks (basic faults) considered are SW bugs, bus transmissions and possible bit-flips caused by EMC disturbance and voltage level fluctuations. But that only addresses the local part of the data path. The full V2X data path extends to neighbouring traffic environment, i.e. other vehicles and possibly even infrastructure.

As a consequence of this a vehicle's V2X output becomes safety critical for the receivers. Apart from the basic risks considered on the receiving side, the vehicle's sensors/ECUs providing message contents to the outgoing V2X messages becomes a risk.

The implication of this from an interoperable perspective is that some vehicles delivered from OEMs implementing high ASIL level on their V2X-solution, may become hesitant to engage some vehicles in the Platoon, vehicles from OEMs not fulfilling same high ASIL levels.

Aligning ASIL levels and third party certification against a set of mandatory requirements could be a way of building trust between Platooning vehicles from different OEMs.

6.6 Energy optimization using a genetic algorithm

One of the topics studied in the project is energy optimization. The aim is of course to minimize the amount of fuel used by reducing air drag. For a flat road, constant speed and inter vehicle gaps are given. However, when the load on the driveline is varying as a function of altitude changes of the road (topography), the kinetic energy buffer of the current and future speed could be balanced with the potential energy that follows from the altitude changes. This is a question both for a single vehicle and for a platoon: how does the optimal speed profile (the independent variable) look like? One of the optimization techniques that have been used to study this problem is genetic algorithms.

A fuel-efficient driving strategy for heavy-duty vehicles driving on highways with varying topography has been developed both for single vehicles and platoons. The method used for reducing the fuel consumption is referred to as speed profile optimization within a corridor. In this study it uses a genetic algorithm to find fuel-efficient speed profiles based on the road's topography. A speed profile refers to the speed of the vehicle as a function of its longitudinal position along the road. Using speed optimization the fuel consumption of a single vehicle was reduced by 11.5% (on average) relative to the case where the truck followed a constant speed using a standard cruise control. The results were evaluated thoroughly both in simulations and experiments on road, showing that speed optimization method is sufficiently accurate to be deployed. Furthermore, during the evaluation of a single vehicle, it was demonstrated that by allowing the speed profile to vary in a wider range (between 60 km/h and 90 km/h) compared to the case where the speed is allowed to vary in a narrower range (between 75 km/h and 86 km/h), the fuel savings obtained was doubled. During the experiments both in simulations and on road the average speed was set to 80 km/h.

For the case of platooning, the speed optimization was extended to platooning in which each truck is assigned an optimized speed profile considering first the safety of the platoon and second, the minimisation of fuel consumption of the whole platoon. The speed optimization was evaluated in simulations where the platoon's fuel consumption was reduced by respectively 15.8% and 17.4% for homogeneous and heterogeneous platoons (with different mass configurations) compared to the combination of cruise control (for the lead vehicle) and adaptive cruise control (for the follower vehicles). It was demonstrated that the expected fuel savings are not heavily dependent on the reduced air drag. In fact, 85% of the fuel savings obtained comes from truck following their "topography optimal" speed profiles. The proposed genetic algorithm based optimization method for platooning needs to be tested thoroughly in experiments on road to validate the results obtained in simulations both from the fuel efficiency and safety aspects. Moreover, it is crucial to test the requirements on the implementation and integration, especially the real-time aspects, where the speed profiles are optimized during driving. Detailed comparison to other ways of optimizing the speed profile is also a topic for future work.

7. Dissemination and publications

7.1 Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	HMI: Volvo has long and broad experiences from being partner in several research projects related to platooning and vehicle automation, e.g. HaveIt (EU), Interactive (EU), Sartre (EU), AdaptiVe (EU), and SERET has been an important project in which our knowledge and competence of HMI-strategies and concepts have been developed further.
Be passed on to other advanced technological development projects	X	HMI: Knowledge gained from SERET is transferred and made use of and further developed in other research projects: Sweden4Platooing (FFI, on-going), Ensemble (EU, planned to start 2018)
Be passed on to product development projects	X	HMI: Platooning is a transport concept of high potentials for the transport industry. The results from SERET and other research projects provide important input to product development
Introduced on the market		
Used in investigations / regulatory / licensing / political decisions		

7.2 Publications

1. Jeber M., "A moving horizon predictive controller for truck platoons", Master's thesis, Chalmers University of Technology, Gothenburg, 2015.
2. Wahnström J., "Energy optimization for platooning through utilizing the road topography", Master's thesis, Lund University, Lund, 2015.
3. Diaby M. and Sorkati A., "Optimization for energy efficient cooperative adaptive cruise control", Master's thesis, Chalmers University of Technology, Gothenburg, 2016.
4. Hovgard M. and Oscar Jonsson O., "Energy Optimization of Platooning With Hybrid Vehicles", Master thesis, Chalmers, Göteborg, 2017.
5. Hovgard M., Jonsson O., Murgovski N., Sanfridson M., Fredriksson J,"Cooperative energy management of electrified vehicles on hilly roads", Control Engineering Practice 73 (2018) 66–78, April 2018.
6. S. Torabi, M. Wahde, "Heavy-Duty vehicle platooning based on speed profile optimization", 2017.
7. Susanna Leandersson Olsson, Platooning, Safe Road trains for Efficient Transports", presentation Transportforum January 2017.

8. Conclusions and future research

With help of simulations and interviews with drivers the HMI for platooning functionality has been developed and validated. Concepts like video-streaming and radio communication to get acceptance and comfort has been found valuable as well as indication of cut-ins and display of the platooning trucks' destination.

The balance between the three, often conflicting, requirements on fuel safety, comfort and safety has been evaluated according to an "greedy" concept were each truck in the platoon controls its distance, speed and longitudinal acceleration. The "greedy" approach has been proven to be robust and less complex compared with other algorithms where the platoon is controlled centrally.

The lateral control was developed in an exploratory way as the demands for comfort and safety is critical especially as short platooning distances can create dangerous situations where the truck drifts out and other situations when the lateral movements can get the driver an uncomfortable ride as she/he is thrown around in the seat. Just as for longitudinal control the balance between safety and comfort needs to be considered as a safe maneuvering might be perceived as "nervous" by the drivers.

Based on previous experience the project developed and validated the V2V protocol used. The needed information and the frequency of updated were decided and a solution was integrated into three trucks together with necessary hardware and integration to the trucks' control systems.

A safety analysis has also been made to evaluate the robustness of the radio communication. Problems related to how the trucks can trust each other and avoid reacting on faulty messages have been evaluated. A conclusion is that the safety must be seen on a "system level" and not only on truck by truck.

Three FH tractors have been equipped and used extensively to test algorithms, V2V communication, and driver experience. The demonstrators have been valuable not only for research and development but also to show the concepts of platooning at numerous events generating media coverage and feedback. Thanks to the demonstrators the participation of the European Truck Platooning Challenge was secured given valuable feedback not only on the technology used but also about how the European legislation needs to be aligned.

Energy optimization has been a central part of the project and simulation of different approach has been evaluated to optimize the speed profile. Besides impact evaluation of control design choices, simulations of different scenarios with varying distances and combination of different drive lines such as conventional as well as hybrid has been evaluated.

For energy optimization, it can be argued if 1% unit reduction (and only for a hilly route) is a high enough energy gain compared to the drawback of addition architectural complexity for the holistic strategy. However, there is no difference in hardware needed. For future work it has been suggested to try the distributed optimization algorithm ADMM. This will preserve the holistic ambition while each vehicle calculates its own part. This will also scale well with the number of vehicles in the platoon.

Another topic for future research is legal aspects of platooning including drive and rest time regulations. If the drivers in the following trucks can use their platooning time as rest time which would considerable increase the economic benefit for platooning.

Back office systems and algorithms for e.g. finding a vehicle to platoon with (match making), has not been addressed in this project and calls for further studies. Besides match making there might also be a need for dynamic geofencing initiated by a back office as well as the possibility to receive data.

In the area of functional safety there is a need for more investigations around the complexity with the distribution of functions over two or more vehicles. For example, how is it possible to trust the source of the messages sent over the V2V interface. There is also a need for deeper safety analyses when it comes to platooning with shorter distances covering e.g. redundant sensors and V2V equipment.

In addition to the functional safety aspect, there is also a need to investigate critical "what if" situations and how to handle this safe of intended functionality from a driver - platoon system perspective.

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