# TranzPORT – Testing Real AutoNomous Zero emission vehicles to PORT

**Final report**


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TranzPORT was initiated by the board of FFI within the FFI Accelerate program.

FFI

# Content

FFI in short

FFI is a partnership between the Swedish government and automotive industry for joint funding of research, innovation and development concentrating on Climate & Environment and Safety. FFI has R&D activities worth approx. €100 million per year, of which about €40 million is governmental funding.

Currently there are five collaboration programs**:** Electronics, Software and Communication, Energy and Environment, Traffic Safety and Automated Vehicles, Sustainable Production, Efficient and Connected Transport systems.

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# 1. Summary

The TranzPORT project intended to develop a logistics system for heavy transports to stimulate a transport system for all types of heavy transports. The technology was intended to evaluate both technical and societal aspects in a global and local perspective. The project has contributed with new knowledge within the area. TranzPORT was a larger research- development- and demonstration project of autonomous, connected, and electrified vehicles for increased Swedish competitiveness, decreased fossil fuel consumption from road transportation, and increased traffic safety. Several synergy effects and new disruptive transport solutions was sought by a combination of technology areas automation, electromobility and connectivity/digital infrastructure. The project was closed prematurely but is with this report presenting what was achieved until the closure of the project.

# 2. Sammanfattning på svenska

TranzPORT projektet avsåg att utveckla ett logistiksystem för tunga transporter för att stimulera ett transportsystem för alla typer av tunga transporter. Tekniken har utvecklats med syfte att utvärdera inte enbart teknik utan också samhällsnytta både i ett globalt och ett svenskt perspektiv. Genom projektet har ny kunskap tillförts området. TranzPORT var ett större forsknings-, utvecklings- och demonstrationsprojekt av automatiserade, uppkopplade, digitaliserade och elektrifierade fordon för ökad svensk konkurrenskraft, minskad fossil energianvändning från vägtransporter och ökad trafiksäkerhet. Genom att man i projektet kombinerat tre olika teknikområden automation, elektromobilitet och digital infrastruktur/uppkoppling uppnåddes viktiga synergieffekter som kommer att bidra till nya transportlösningar med Sverige som ett föregångsland. Projektet avslutades i förtid men presenterar med denna rapport vad som åstadkommits fram till projektets avslutande.

# 3. Background

Heavy transportation in Sweden is expected to increase by 50% by 2030. Today, 65% of goods transportation is done with heavy vehicles and 2/3 of those travel on a concentrated road network. Heavy truck transportation makes up 4% of the vehicle fleet and is responsible for about 15% of $CO_2$ emissions, which in 2015 amounted to about 1.81 billion tons of $CO_2$. Connected and automated vehicles can reduce fuel consumption by up to 44%. For trucks with autonomous and connected functions, fuel consumption can be reduced by up to 18% according to a study conducted by the EIA.

The vision guiding the work is a future where autonomous, electric, and connected vehicles transport goods to a large extent, with a utilization rate that fits better with society's pulse, such as quiet transportation at night and 24/7 availability. The project will in the long run contribute to increased availability in and around cities in the form of business access to capacity-strong, sustainable, and reliable transportation solutions. In addition, availability will also increase when it comes to aspects such as better utilization of infrastructure, increased system thinking and more efficient use of data from different sources.

Also outside of Volvo, intensive research and development is ongoing in the areas of electrification, automation, and vehicle connectivity. At CES 2018, it was noted that there have never been more trends challenging how we will live in the future. The combination of new technologies can fundamentally change mobility and transportation in society.

AB Volvo is constantly working on research and development to address the sustainability challenges in society. The company's stated ambition is to act as a technology leader and be at the forefront of important technological shifts that contribute to a sustainable society. The TranzPORT project has been an opportunity for AB Volvo and other parties, both private and public, to work together to build knowledge and a unique concept for future sustainable transportation solutions. This has been done by taking the existing level of knowledge (a level that has been reached, among other things, thanks to the FFI program) and European collaborations within the ramp programs FP7 & H2020) and based on this, building new knowledge about the disruptive technology areas that are revolutionizing the transportation industry; automation, electromobility and connectivity.

# 4. Purpose, research questions and method

The purpose of the project was to develop an autonomous, electric, and connected transportation solution that could be highly efficient in terms of energy use at the vehicle and system level.

The project was implemented as a pilot that started from an existing transportation flow where containers are transported from a logistics terminal in Arendal, Gothenburg to Gothenburg port. The transportation need consisted of containers loaded on a trailer and transported on a route of a total of 4 km, see Figure 1.

Figure 1 Aerial photo of the route between the logistics terminal and Gothenburg port

The project also aimed to answer and create knowledge in important areas such as energy efficiency, environment and health, accessibility, robustness, usability, punctuality, and safety. For this reason, the project has been implemented together with a group of partners to engage companies and their employees throughout Sweden.

The pilot project had three key partners:

- **AB Volvo**, which initiated and runs the project and is ultimately responsible for the implementation of the pilot project
- **DFDS** to adapt parts of the infrastructure at the port area and recipient of the transport
- **Platzer** is the real estate owner for most of the transportation route

The transportation system's interface was open to simplify integration for future initiatives and actors. The purpose was also to not limit business value in closed systems.

**IVL** Swedish Environmental Research Institute was a partner in the application to contribute knowledge about life cycle analyses and **Chalmers** to contribute to research and development of communication.

The **Swedish Transport Administration** has been an external reference partner for knowledge building and expert opinion and support regarding issues related to safety and digital and physical infrastructure.

In addition to this, new job opportunities have been created within these future areas for the vehicle industry. The project has, among other things, contributed to increased knowledge and expertise in solutions for more sustainable transports.

## 4.1 Method

The practical work carried out in the project was divided into 16 work packages. These work packages were organized into horizontal and vertical work packages, as shown in Figure 2.

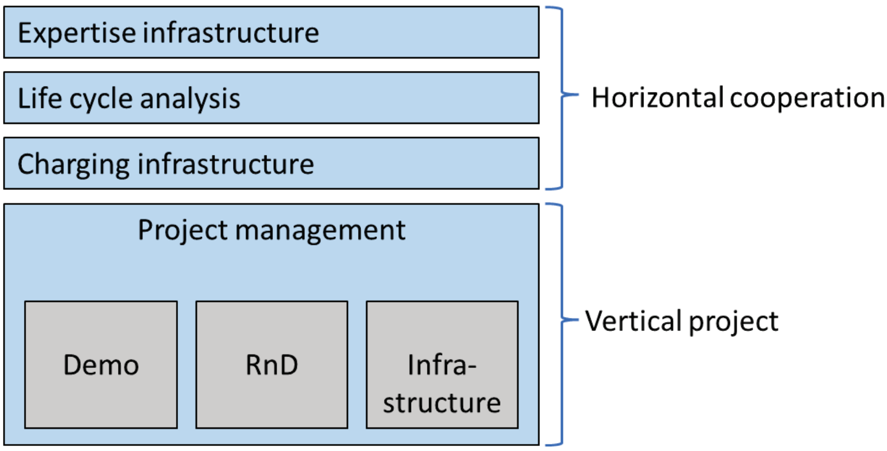


Figure 2 Division of the project into horizontal and vertical work packages

The horizontal work packages dealt with overall infrastructure issues, focusing on general aspects related to the management of the balance between infrastructure measures and automation measures, comparative LCA-based system analysis where the focus has been on evaluating the environmental performance of the new transportation system and charging of L4 automated vehicles, a knowledge-building work package on charging technology and charging infrastructure related to L4 automation technology.

To perform the vertical project, research activities were required but also activities that were directly enabling the demonstration of the transportation system. The vertical work packages were divided into three areas: Demonstration, Research and Development, and Infrastructure. The work packages related to demonstration dealt with the development, construction, and setup of the vehicles, mainly focusing on the electric drivetrain and setup of the vehicles in a total system to demonstrate and understand aspects related to the system's energy efficiency and scaling effects. Large amounts of vehicle logging and operational data from the test activities have been collected and analyzed. Parts of the demonstration have been showcased on an event basis for invited parties, according to work package V1. The work packages categorized according to research and development were carried out at the forefront of knowledge in the field of autonomous and connected vehicles. The project has delivered unique knowledge regarding perception, vehicle control, and communication in the autonomous transportation system. Three of the work packages have focused on adapting the infrastructure and conducting a safety analysis, establishing a digital infrastructure. The focus has been on delivery quality such as, capacity, robustness, usability, punctuality, safety, and environment and health. Table 1 below presents a summary of the purpose of each work package.

Table 1 Summary of the purpose for all the work packages in the application

| Component | No | Workpackage | Purpose |
|---|---|---|---|
| Horizontal Expertise infrastructure | H1 | Methodology for adaptations of infrastructure related to L4 automation | Method development for infrastructure adaptations, i.e. dimensioning the infrastructure in relation to the vehicle's characteristics at L4 automation. |
| Horizontal LCA | H2 | Comparative LCA-based system analysis. | Evaluate the environmental performance of the new transportation system against normal flows at both component and system levels to contribute to reduced emissions. |
| Horizontal Charging infrastructure | H3 | Charging of L4 automated vehicles | Knowledge building of charging technology and charging infrastructure related to L4 automation technology. |
| Vertical | V0 | Project management | Project management of the overall application including horizontal parts |
| Vertical Demo | V1 | Demonstration and communication | The demonstration including communication of the demonstration |
| Vertical Demo | V2 | Construction and building of system, including vehicles | A physical control tower and nine vehicles are enablers for the demonstration of the transportation system |
| Vertical Demo | V3 | Automation and building of gate systems | An autonomous gate is an enabler for the demonstration of the transportation system with energy usage savings |
| Vertical Demo | V4 | Powertrain | The vehicles' electric drivetrain is an enabler for the demonstration of the transportation system as well as for sustainable development in the long run |
| Vertical Demo | V5 | Charging | There are several charging solutions for electric vehicles developed. The purpose of this work package is to add the aspect that the vehicle is autonomous and thus has different requirements in the development of charging solutions. Both on-board and off-board devices will be developed for the demonstration. |
| Vertical RnD | V6 | Vehicle motion management, traffic situation management | Develop autonomous driving for new areas, such as roundabout driving and opposing traffic. |
| Vertical RnD | V7 | Perception | Development of a perception system that is sufficiently advanced for safe driving even without a safety driver |

| Component | No | Workpackage | Purpose |
|---|---|---|---|
| Vertical RnD | V8 | Product safety | Prove that the transportation system can be operated in a safe manner towards people and the environment. The work package will further develop the current dialogue that AB Volvo has established with the Swedish Transport Agency, the Swedish Transport Administration and the Swedish work environment agency. This will in the future contribute to increased traffic safety as the human factor is eliminated. |
| Vertical RnD | V9 | Virtual control tower and communication | Development of a virtual control tower whose responsibility is to control, guide and integrate the autonomous vehicle fleet. The research focus is on software and data such as route and planning of activities must be kept updated and how a virtual representation of the autonomous vehicle can be made available and described. |
| Vertical RnD | V10 | Test, verification and validation | Simulation of the transportation system as a whole and thus testing and validation of demonstration parts and research in combination. |
| Vertical Infrastructure | V11 | Adaptations of infrastructure | Adaptation of the road section for the demonstration in accordance with the technology's maturity and future infrastructure |
| Vertical Infrastructure | V12 | Digital infrastructure | Demonstrate the requirements and possibilities of automated vehicles based on digital infrastructure |
| Vertical Infrastructure | V13 | Overall safety analysis | Linked to the work package on product safety for iteration of safety measures. The focus is on infrastructure with the aim of generating a safety analysis for the specific route. |

# 5. Objective

The project has had a wide range of goals related to designing and building base vehicles for demonstration, providing vehicles with intelligence based on research results, and digital and physical infrastructure. The main objectives of the project are presented below:

1. Demonstrate a high level (L4) of automation functionality in a platform for self-driving, electric, and connected freight transportation, leading to safer transport with reduced number of accidents in the future, as the human factor that currently causes most accidents will be eliminated.
2. Research and close knowledge gaps in automation, electromobility, and connectivity through studies at low TRL levels.
3. Increased understanding of the interaction between vehicle automation and energy efficiency, with an increased understanding of the energy efficiency perspective of the system before and after the implementation of the project and the scalability of the overall transport solution.
4. Develop a virtual and physical autonomous transport system to optimize accessibility, efficiency, and emissions for fully electric, fully automated, and connected vehicles. This will lead to increased possibility to reach a future fossil-free society. The project will be able to show:
    a. 100% reduction of several emissions such as particulates and nitrogen oxides.
    b. Significantly reduced noise level compared to today's transport work on the current route.

   c. At least 50% energy efficiency, which will be compared to a corresponding fossil-energy-based drive line.
   d. Reduced CO2 emissions when renewable energy sources are used compared to today's transport work on the current route.
5. Specify and develop an electric drive system including energy storage that meets the performance requirements for the autonomous vehicle and contributes to reducing greenhouse gas emissions, increasing the chances of reaching emissions targets by 2030.
6. Investigate and develop several types of charging technology such as inductive charging, conductive charging, and traditional charging with contact (manual/robotic) and subsequently define and systemize a new type of charging solution together with the necessary infrastructure to support the vehicle's autonomy
7. Integrate the chosen drive line and charging system into the vehicle architecture and install the charging infrastructure.
8. Conduct initial testing and commissioning of the integrated drive line to ensure functionality and optimized setting of parameters.
9. Automated and connected gate for the entry and exit of vehicles, including associated software to meet energy efficiency requirements linked to necessary project conditions, as well as software for monitoring all movements within the port area.
10. Analysis of life cycle perspectives with different scenarios and comparison with today's type of transportation work on the current route as well as analysis of life cycle perspectives on components such as energy storage and other essential components from the current perspective
11. Infrastructure Adaptations
    a. Analyze the road stretch and perform adaptations according to the requirements
    b. Perform assessment of needs and complete a consequence analysis
    c. Design adaptations of the infrastructure for the specified road stretch in the pilot
    d. Complete the construction of the infrastructure
12. Digital Infrastructure
    a. Perform a digital communications analysis for the specified road stretch in the pilot
    b. Conduct an analysis of needs of traffic monitoring and traffic management
    c. Perform an IT security analysis
    d. Complete the construction of digital infrastructure for the current road stretch in the pilot
13. Overall Safety Analysis
    a. Conduct an overall safety analysis for the specified road stretch in the pilot
    b. AB Volvo conducts a safety analysis based on ISO26262
    c. Apply systematic safety work and develop a safety plan with general safety principles

d. Apply relevant rules for electrical safety
e. Verify safety of the developed technology before it is applied in the demonstration

## 5.1 Originality

AB Volvo is and has been actively involved in several research and demonstration projects related to automation, connectivity, and electrification, such as Auto Freight, ASP Autopilot Site to Plant, I-dolly, and ASETS - Automated safe and efficient transport system. There are synergies with several previously approved automation projects, but TranzPORT is unique in the world as the project works with all three technology areas, fully connected, fully automated, and fully electric in a complex traffic system on public roads without a driver.

# 6. Results and achievement of objectives

## 6.1 Work package H1 Methodology for adaptations of infrastructure related to L4 automation

The purpose of the work package is to understand how both digital and physical infrastructure should be designed in the future, that is, to specify what the infrastructure should be dimensioned for in relation to the characteristics of the vehicle and the requirements related to the systematic implementation process.

Below you find a summary of the work done in work package V11 and the methodology used to come to this result. In addition, the learnings taken from work package V11 has been summarized into a methodology for dimensioning infrastructure based on the requirements of the autonomous vehicle. The report findings have been shared horizontally where especially the Swedish Transport Administration has both contributed and received insights on the deliveries in this work package.

Work package V11 involved the analysis of a route, design and construction of needed adaptations, and completion of these with compliance to Sweden's traffic legislation.

### 6.1.1 Result of the safety analysis

The Swedish Transport Administration describes the area as adapted for long and heavy transports. The route has straight and wide roads. Exits to office, parking and industry facilities are wider than normal and roundabouts are adapted to heavy transports as well. As a result of putting the practicality of heavy transport as the main consideration on this road, lower consideration is given to pedestrians and cyclists compared to other city and national road networks. As an example, it is possible to drive much faster than the defined speed limit of 50 km/h in the area where pedestrians and cyclist are moving through unprotected and in an unpredictable way. The Swedish Transport Administration also adds that independently of this project, the area does not fulfil the current standard of a similar area that would have been built today.

To conclude, the Swedish Transport Administration sees the following infrastructure adaptations as recommended to be able to conduct autonomous driving in the area:

- Even though the speed limit is set to 50 km/h in the area, higher speeds can be expected. It is recommended to decrease the speed limit to 40 km/h and introduce speed limiting road bumps to increase the speed compliance. In addition, rebuilding of pedestrian/bicycle road is recommended. Height increases of pedestrian walks in relation to the road is also recommended to decrease the speed and decrease risk for collisions.
- Several parking lots are located close to the route. The current layout enables people to move to and from these parking lots in an unpredicted way outside the defined pathways. A possible solution to this problem is to build barriers to canalize pedestrians to walkways and pedestrian crossings.
- Amplify and add missing lane markings to make it clear for all traffic participants where to position vehicles etc.

In detail, the Swedish Transport Administration highlights 39 points of concern marked in Figure 3.

Figure 3 Points of concern on the route

## 6.1.2 Result of the Perception, Driver and Vehicle domain analysis

Table 2 below shows a summary of the Volvo domain requirements.

Table 2 Summary of the Volvo domain requirements

| Explanation | Proposed infrastructure adaptation | Domain requirement |
|---|---|---|
| Lane markings and signs | Lane markings and signs need to be enhanced in order for the sensors to determine road boundaries and rules, and as a result, provide correct behavior and localization of the vehicle. | Perception |
| Illumination of road | Install light poles where needed to ensure sufficient illumination in order to for sensor to detect obstacles and provide correct localization of the vehicle. | Perception |
| Enhance localization | In order to enhance the ego vehicle's ability to predicts its position (localization) fixed landmarks need to be implemented. | Perception |
| Vegetation | Remove vegetation beside the road in order to remove the risk of overhanging branches disturbing the sensors. | Perception |
| Connecting roads to main road and roundabouts | The right of way should be unambiguous. Yield or stop sign should be implemented. | Driver |

| **Explanation** | **Proposed infrastructure adaptation** | **Domain requirement** |
|---|---|---|
| Traffic from pedestrians and cyclists | Complement with rail or fence between road and pedestrian/cyclist road in order reduce the exposure for situations where the ego vehicle need to predict a behavior from these traffic participants. However, fences should not restrict the vehicle's vision. | Driver |
| Speed | In order to make other vehicle's movement more predictable it is recommended to reduce the speed through speed reducing measures such as speed bumps. | Driver |
| Bus stop | Having bus stops in a separate lane can create challenging situations where a bus pulls unpredictably back into the main lane and should be avoided. It is recommended that the bus stops in the main lane. | Driver |
| Intersection where the ego vehicle needs to make unprotected turns | Traffic light-controlled intersection in order to reduce the exposure for situations where the ego vehicle need to predict a behavior from other vehicles. | Driver |
| Road conditions | It is recommended to fill any potholes in order to avoid any unpredicted vehicle movements. | Vehicle |

### 6.1.3 Implemented adaptations

Figure 4, Figure 5 and Figure 6 illustrate some examples of adaptations that have been implemented. Table 3 below present each category of implementation where each category is given a color to enhance the examples.

Table 3 Categorization of implementations

| Color | Category of implementation | Comment |
|---|---|---|
| Orange | Vehicle path | Amplify and add missing lane markings in order to make it clear for all traffic participants where to position vehicles etc. |
| Green | Signs | Makes the traffic situation clear for both manual and autonomous vehicles. |
| Blue | Pedestrian paths | Instead of a fence/rail, a so called GCM support is implemented to separate pedestrian pathways from vehicles. |
| Yellow | Enhance lighting | Required for the performance of the perceptions system. |
| Red | Height differences | Creates a clear difference where vehicle drives and where pedestrian walks. |

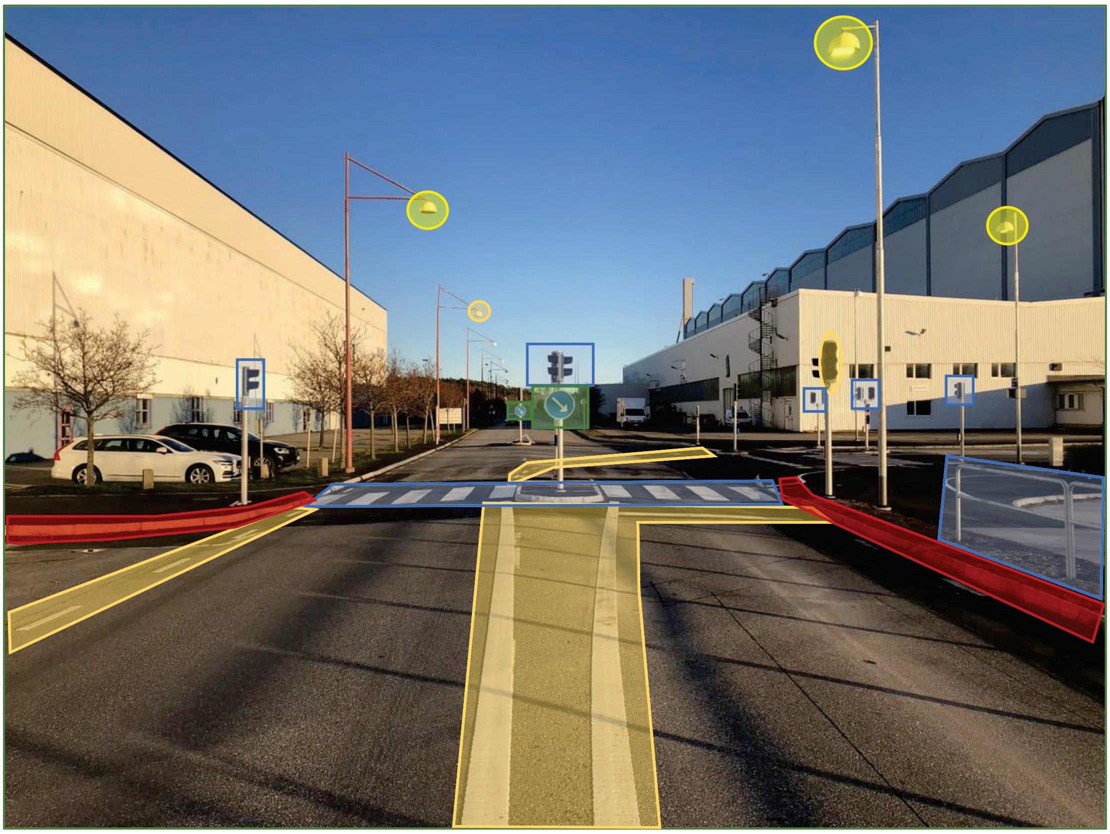

Figure 4  Example of implemented adaptations

Figure 5  Example of implemented adaptations

Figure 6 Example of implemented adaptations

When it comes to the dimensioning of the digital infrastructure, please refer to work package V12 described in chapter 6.14.

## 6.2 Work package H2 Comparative LCA-based system analysis

The TranzPORT project aims to develop and evaluate electric and autonomous road transport systems. One of the desired effects is decreased impact on the climate and the local environment. It is however known that the production of the electrical drive line, with its traction batteries and electrical engine as main parts, has substantial impacts on the material sourcing and component manufacturing stages. This part of the project has the goal to assess the environmental performance throughout the entire life cycle for the autonomous electrical solution as compared to the conventional diesel truck solution in operation today. The activities in work package H2 were divided into two main streams, i) an operational analysis of the planned transport solution and ii) and Life Cycle Assessment (LCA) of the production and operation of the autonomous system as developed in the project.

### 6.2.1 Life Cycle Assessment

The plan was that this life cycle assessment (LCA) would include the full life cycle with a so-called cradle-to-grave perspective. This means that the study includes emissions all the way from mining of materials to recycling of material at the end-of-life. However, the draft results from the screening LCA only include results from cradle-to-gate due to delayed data collection and the early end of the project. This

means that only results from extraction of materials and refining is included. The impact on climate change is presented per truck. The LCA follows the methodology and practices defined in the Volvo Group LCA Guidelines which follow the ISO standards 14040:2006 and 14044:2006.
The goal of the study is to evaluate the environmental impact of the new transport system compared to the same transport using current technologies. The current technology is defined as the FH diesel and FH electric compared to the autonomous FH electric. Table 4 shows information about the three evaluated trucks in the screening LCA.

Table 4. Information about the vehicles.

| | FH Diesel | FH Electric | FH Electric automated |
|---|---|---|---|
| **Batteries** | N/A | 3 x 90 kWh | 3 x 90 kWh |
| **Driveline** | I-Shift with D13 TC | I-shift with 3 Electric Machine | I-shift with 3 Electric Machine |

## 6.2.2 Material production

The BOMs (Bill of Material) were fed into Volvos material data management system to obtain detailed material content data (reported by suppliers as Material Data Sheets, MDS) of the parts. For the large lithium-ion batteries, the data for the modules was received from the supplier directly. The material data obtained were mapped to a pre-defined set of materials which is then connected to appropriate datasets in the LCA software GaBi. Production of the materials is modelled in GaBi using ready-made datasets (LCI data), which includes information about used resources and emissions for producing e.g., 1 kg of a specific material.
Engineering estimates about the automation kit that is included on the FH electric to make it autonomous was provided by Volvo in 2019 and updated information on the new automation kit could not be obtained before the project end. Results for the automation kit should therefore be seen as an estimation since the data is old and uncertain.

## 6.2.3 Results (until project closing)

From Figure 7 we can see how the addition of batteries in FH Electric is the main difference, and a clear hot spot, compared to FH Diesel. It contributes to about 30% of the climate impact from the production of FH Electric. Steel, cast iron and aluminum are the three materials with the highest impact on climate change for the FH diesel. Printed Circuit Board (PCB) is the material category that stand out the most as it has high climate impact, about 10% of the total while low weight <1% of the total. Hence, it has high climate impact per kilogram of material.

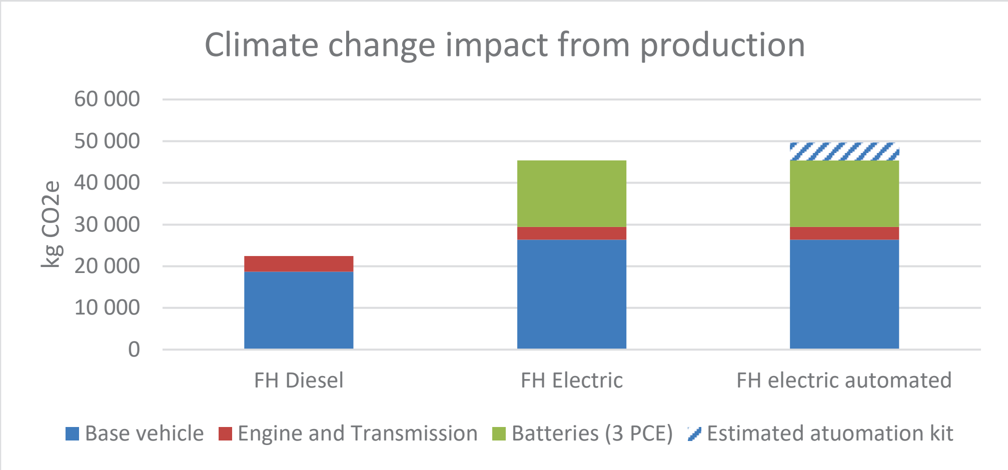

Figure 7. Results for production of the three vehicles.

When moving from diesel trucks to electric trucks we can identify an increase in impact from production of materials, components, and the truck. This increase is in large due to the addition of batteries. Moving from an electric truck to an autonomous electric truck shows an increase due to the added components from the automation kit. This increase should be further investigated. It is important to note that without including the whole life cycle there is no way to judge the environmental performance of the whole transportation system. Only looking at the cradle-to-gate gives an indication that the FH electric autonomous needs to be more energy efficient in the use phase than the FH electric to have the same or less impact on climate change for the whole life cycle. The transport and logistics investigation indicates significant energy savings with electrification.

### 6.2.4 Transport and logistics investigation

The transport solution developed in the project was planned to replace the present operations using manual diesel trucks. A detailed investigation of the actual performance of the different systems was planned, with the main goal to make the operational phase of the LCA based on as accurate data as possible. The plan was to make a detailed mapping of the present transport solution covering parameters such as actual fuel consumption, actual driving route, distance, and driving pattern (speed, acceleration), the operational weight of the vehicle, route turnaround times, productivity, and characterization of the vehicles and fuel qualities used. The plan was to work closely with the contracted hauler operating the present shuttle. This part of the project was however put to pause by the Volvo Logistics and Transport Purchasing organization due to business-related matters. While waiting for a new possibility to start the data collection project we pursued the plan to construct a generic energy modelling application and try it out using case-specific data on vehicle types, load configurations, distances, road types, and transport distances.
The energy model is based on mapping the driving routes used by the present and the suggested system. The route is then divided into sections based on the nature of the traffic along the route. Differences such as rated speed, presence of other traffic, and traffic regulations (max speed, traffic lights, crossings, etc.) were used as an assessment of the traffic situations experienced on each section of the route. These differences were then mapped with the road-traffic situations available in the HBEFA[1] model. In this

[1] HBEFA: The Handbook Emission Factors for Road Transport, see https://www.hbefa.net/

way could the modelled energy use per segment be analyzed for the different vehicle concepts, cargo loads, and distances, see Figure 8 below.

| Aktivitet | Process | Operationtyp | Hastighet (Km/h) | HBEFA Vägtyp | Trafiksituation | LCU_w (%) | Fordonstyp | Euroklass | Bränsletyp | Input (fuel) (MJ/km) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Positionering av lastbil för lastning vid aktuell containerstack | driving | 20 | URB/Access/30 | Free flow | **0%** | HCT-4 TEU | 6 | Diesel SE | 13,7 |
| 2 | Positionering av lastbil för lastning/lossning vid aktuell containerstack, l | driving | 20 | URB/Access/30 | Free flow | **12%** | HCT-4 TEU | 6 | Diesel SE | 16,0 |
| 3 | Positionering av lastbil för lastning/lossning vid aktuell containerstack | driving | 20 | URB/Access/30 | Free flow | 57% | HCT-4 TEU | 6 | Diesel SE | 24,6 |
| 4 | Positionering av lastbil för lastning/lossning vid aktuell containerstack | driving | 20 | URB/Access/30 | Free flow | **86%** | HCT-4 TEU | 6 | Diesel SE | 29,8 |
| 5 | Positionering av lastbil för lossning vid aktuell containerstack | driving | 20 | URB/Access/30 | Free flow | **97%** | HCT-4 TEU | 6 | Diesel SE | 31,5 |
| 6 | Positionering av lastbil för lastning vid aktuell containerstack | driving | 20 | URB/Access/30 | Stop&go | 0% | HCT-4 TEU | 6 | Diesel SE | 39,6 |
| 7 | Positionering av lastbil för lastning/lossning vid aktuell containerstack | driving | 20 | URB/Access/30 | Stop&go | 12% | HCT-4 TEU | 6 | Diesel SE | 43,5 |
| 8 | Positionering av lastbil för lastning/lossning vid aktuell containerstack | driving | 20 | URB/Access/30 | Stop&go | 57% | HCT-4 TEU | 6 | Diesel SE | 58,1 |
| 9 | Positionering av lastbil för lastning/lossning vid aktuell containerstack | driving | 20 | URB/Access/30 | Stop&go | 86% | HCT-4 TEU | 6 | Diesel SE | 66,9 |
| 10 | Positionering av lastbil för lossning vid aktuell containerstack | driving | 20 | URB/Access/30 | Stop&go | 97% | HCT-4 TEU | 6 | Diesel SE | 69,8 |

Figure 8. Example of operational options and related energy use by diesel vehicle type HCT-4 TEU.

An application was built using the Excel program making it possible to swiftly build any combination of route segments and calculate the resulting energy use for the different transport solutions. The routes used by the present operation and the planned route for the autonomous and electrical solution was modelled and the energy use per transported 40 feet container was compared. In Figure 9 below is the list of route segments identified for the electrical solution presented.

| Sträcka | Trafiksituation | Vägtyp | LCU_w (%) | Process | Aktivitet | Tid | Distance (km) | Driving (MJ) |
|---|---|---|---|---|---|---|---|---|
| | parked | Terminalyta | 0% | Lastning/lossning av container på lastbil | 11 | | 0 | 0 |
| V 1b | Free flow | URB/Access/30 | 100% | Körning ut från DFDS terminal i Arendal | 5 | | 0,23 | 1,6 |
| V 2 | Free flow | URB/Access/30 | 100% | Körning på allmänväg (Terminalvägen, Arenda | 5 | | 1,41 | 10,0 |
| V 3 | Free flow | URB/Access/30 | 100% | Körning i roro terminalen | 5 | | 0,31 | 2,2 |
| V 4 | Free flow | URB/Access/30 | 100% | Körning i roro terminalen | 5 | | 1,3 | 9,2 |
| V 5 | Free flow | URB/Access/30 | 100% | Körning på allmänväg (Nordatlanden) | 5 | | 0,77 | 5,5 |
| V 6 | Free flow | URB/Access/30 | 100% | Körning in i APM terminal | 5 | | 0,69 | 4,9 |
| V 7 | Free flow | URB/Access/30 | 100% | Positionering av lastbil före export container l | 5 | | 0,44 | 3,1 |
| | parked | Terminalyta | 0% | Lossning | 11 | | 0 | 0,0 |
| V 8 | Free flow | URB/Access/30 | 0% | Körning ut APMT efter export contaner lossnir | 1 | | 0,53 | 2,1 |
| V 9 | Free flow | URB/Access/30 | 0% | Körning i roro terminal innan tomcontainers la | 1 | | 0,6 | 2,4 |
| | parked | Terminalyta | 0% | Lastning av tomcontainer | 11 | | 0 | 0,0 |
| V 10 | Free flow | URB/Access/30 | 0% | Körning i roro terminal efter tomcontainers la | 1 | | 0,68 | 2,7 |
| V 3 | Free flow | URB/Access/30 | 0% | Körning i roro terminalen | 1 | | 0,31 | 1,2 |
| V 2 | Free flow | URB/Access/30 | 0% | Körning på allmänväg (Terminalvägen, Arenda | 1 | | 1,41 | 5,6 |
| V 1a | Free flow | URB/Access/30 | 0% | Positionering av lastbil för lastning/lossning vid aktuell containerstack | 1 | | 0,34 | 1,4 |
| | | | | | | Sum: | **9,0** | **52** |

Figure 9. Energy modelling for the autonomous and electric solution.

## 6.2.5 Results (until project closing)

The different solutions can thus be compared in terms of energy use. As an example, were the total energy use for the present diesel solution (diesel HCT 2 trailers, 4 TEU capacity) assessed to 170 MJ (TTW) per 40-feet container while the electric solution (FH + trailer 2 TEU capacity) yields 52 MJ (Grid To Wheel) per 40-feet container. The main reason for this difference is the improved energy efficiency of the electric drive train.

## 6.2.6 Suggestions for further work

- Collect better data on the components needed for the automation kit.
- Investigation of the environmental effects of data transmission for autonomous vehicles.
- Establish baseline for data transmission for non-autonomous vehicles to be able to compare.
- Investigate the environmental performance/LCA of the additional infrastructure need for autonomous vehicles.

## 6.3 Work package H3 Charging of L4 automated vehicles

Within this work package Volvo investigated and evaluated several charging concepts, including manual charging through a regular CCS 2 inlet (Preferably DC charging), however low power AC charging is also possible. One concept related to CCS charging is to use a robot operated charging engagement (ROCSYS have been the base for the study). Sequential overnight charging remains to be investigated. The other main charging solution that has been evaluated is inductive charging (From Momentum Dynamics) which was chosen for its ease of use and lack of moving parts. This is believed to give high uptime and few reliability problems. The system is modular, one plate on vehicle and one corresponding module in the ground, and each module is capable of 75 kW of charging power. The modules can be combined and provide up to 300 kW of power with 4 modules (130 kW with 2 modules have been demonstrated with an early prototype system). The latest generation of the charging pads are mounted flush with ground (see chapter 6.7).

## 6.4 Work package V2 Construction and building of system, including vehicles

### 6.4.1 Construction and build of vehicles

Vehicles have been built in different generations for different purposes. The development between the generations is part of the learning curve within the project and can be divided in:

- Generation 1 – Data collection vehicle diesel powertrain
- Generation 2 – Engineering vehicles diesel powertrain
- Generation 3 – Engineering vehicles electric powertrain

The workflow of the builds has also been developed based on the experiences and therefore the time for development and builds has been decreased between the generations and the number of vehicles in each generation. These generations of builds are described more in detail below.

#### 6.4.1.1 Generation 1 – Data Collection vehicle diesel powertrain

This was the first integration of the Perception sensor kit with aim of short lead time of build to be able to start to collect the data on different routes and traffic situations. The sensor integration was done on a bulbar. Learnings from the build of the first generation was mainly the Design Demands on the installation as well as the Automotive Grade on components to be used in vehicle.


Figure 10  First generation of Data Collection vehicle with perception system mounted

### 6.4.1.2 Generation 2 – Engineering vehicles diesel powertrain

The second integration of the AD-kit had the aim for a more integrated design as well as development of an actuated ADS-vehicle with a Safety Driver solution. The vehicles to be used for development activities both in Sweden and US running in parallel for more efficient development. Two complete units with tractor & trailer were built on exact same chassis specification.


Figure 11 Second generation of Engineering vehicles at testing in Gothenburg and California

In this generation Sensor Cleaning System concept was developed which also has a Volvo patented design US2022/0362788.


Figure 12 Testing on performance of sensor cleaning capacity as well as water intrusion

For the second generation of integration, the project also developed trailers with automatic container locks together with an external supplier. These automatic container locks can be controlled by the AD-system in the truck with integrated lights to be able to see status on the locks during transport.

Figure 13 Automatic trailer locks with LED light indication

In second generation of the builds the project learned a lot in many different areas like Calibration Dependencies, Safety Driver implementation, Sensor Cleaning, Cloud communication and was as very good foundation for the third generation of the builds.

#### 6.4.1.3 Generation 3 – Engineering Vehicles electrical powertrain

Third generation of integration had the aim to build the AD-system in an electrical vehicle. The complete design was made as well of manufacturing of parts when the project came to a halt. This build was the move towards a production scalable solution with focus on safety for VRU.

#### 6.4.1.4 Construction and build of vehicles conclusions

During the time of project running and generation of builds many learnings and findings to be used in future project was achieved. These findings were not only Volvo-internal but also together with many of the suppliers of different components and systems.
As this is new technology, there are not many off the shelf solutions and one of the interesting parts of the builds was to find out these solutions within Volvo Autonomous Solutions or together with external partners. The builds have also developed many patents in different areas to be used in future projects.

### 6.4.2 Analysis of the total transport system

The main objective with this work package is to perform system optimization. This means mainly to identify the feasibility to fulfil the daily productivity demand. A map illustrating the transportation mission is given in Figure 14. Some comments to the figure are:

- Filled containers are picked up at 1, DFDS logistic center. Here, vehicles can also be charged.
- Containers are unloaded at 5. Sometimes empty containers are picked up and moved back to 1. It can also be the case that a vehicle moves without container from 5 to 1.
- The distance travelled on road is approximately 3 km.

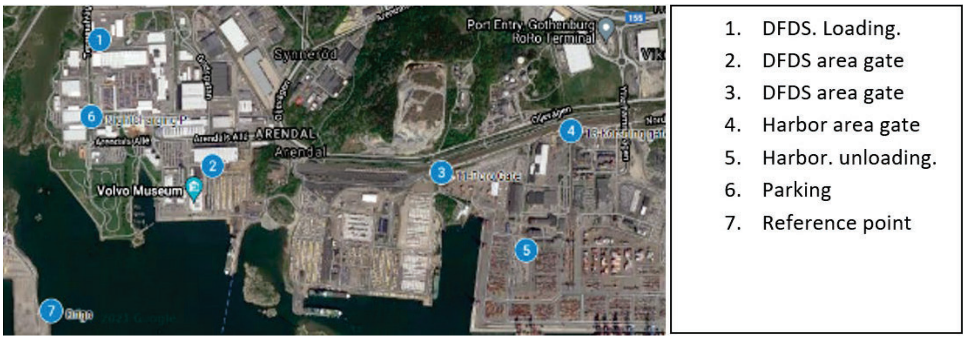

Figure 14 Transportation mission.

The problem has been approached using a linear programming-based mission scheduling. The objective is to maximize the resource usage, i.e. utilize as many missions as possible. One aspect the optimization must consider is that number of vehicles, at some positions, for example goods handling, is restricted. This is illustrated in Figure 15; missions are distributed in time in such a way that vehicles are not crowded at charging and/or goods handling positions.

Figure 15 Mission sub-set.

A requirement is that 40 transportations per day is desired. Analysis highlighting if this is feasible or not will now follow.

Figure 16 presents an example result, assuming a full working day, i.e., 13 hours. The x-axis is time. The upper plot shows all the missions (named shift in the plot), and the middle plot is number of operating vehicles. The indication is that the productivity is 49 transportations per day and at least 4 vehicles are needed.

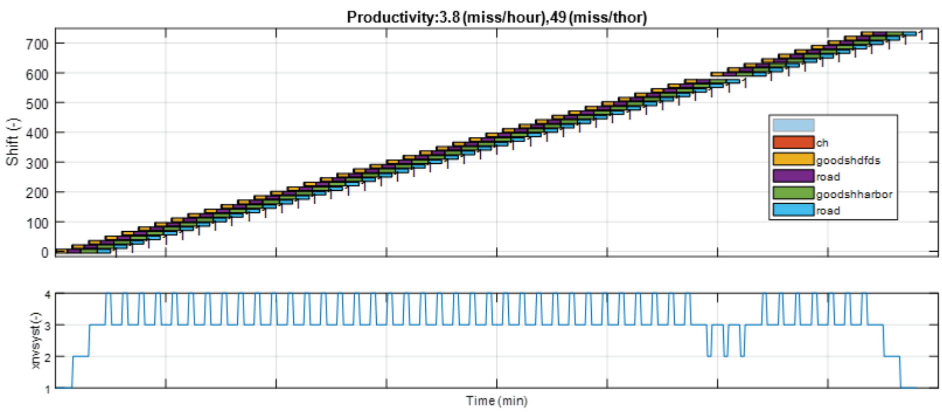


Figure 16 Analysis result. 40 km/h road speed.

In an alternative analysis, presented in Figure 17, the road speed is lowered from 40 km/h to 10 km/h. The consequence is that more vehicles (7-8) are needed to manage the productivity requirement.

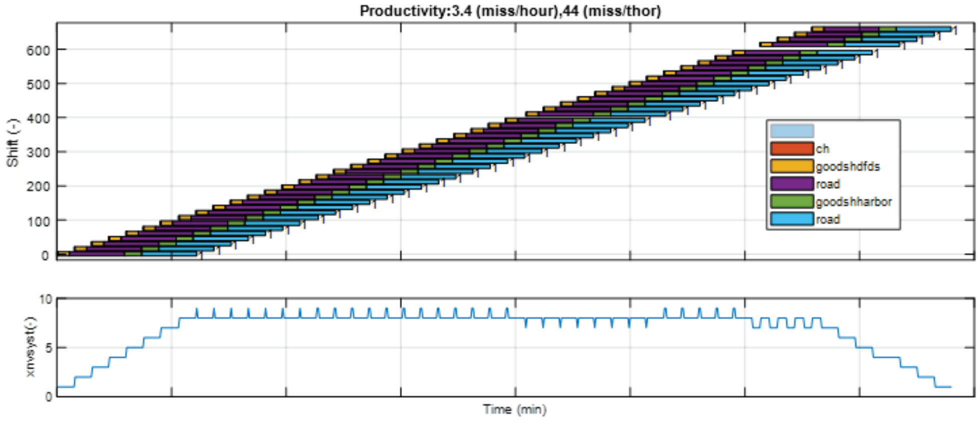


Figure 17 Analysis result. 10km/h road speed.

One conclusion from the transport system analysis is that it possible but challenging to fulfill the productivity demand, the marginal is small. Another insight is that lower road speed drives for a need of more vehicles.

### 6.4.3 Virtual vehicles built and integrated in the system

One objective of this report is to provide nine virtual vehicle models built and integrated with the software. A vehicle model, in this context, consists of:

- A plant model representing the physics of a tractor-semitrailer
- Actuators and base vehicle controls
- Motion management control logic
- Environment (road, wind…)

This is depicted in Figure 18.

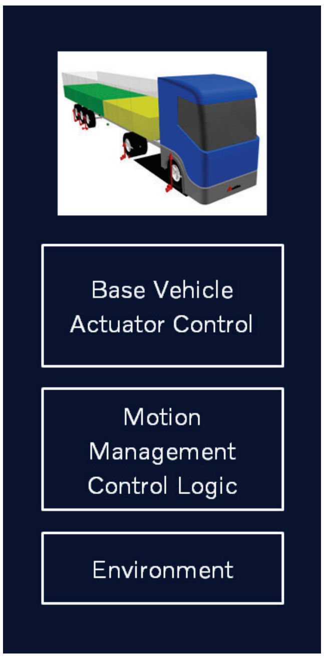


Figure 18: Components of a vehicle model

The defined vehicle model is now ready to receive commands from a driver. The idea is that this complete vehicle model not only represents the physics of the tractor-semitrailer, but also provides the same interface used by an autonomous driver to communicate with the tractor-semitrailer. This means that a driver software should be able to send the same requests using the same interface definition to the virtual model as it would on the actual truck. This is achieved by defining three main interfaces seen in Figure 19.

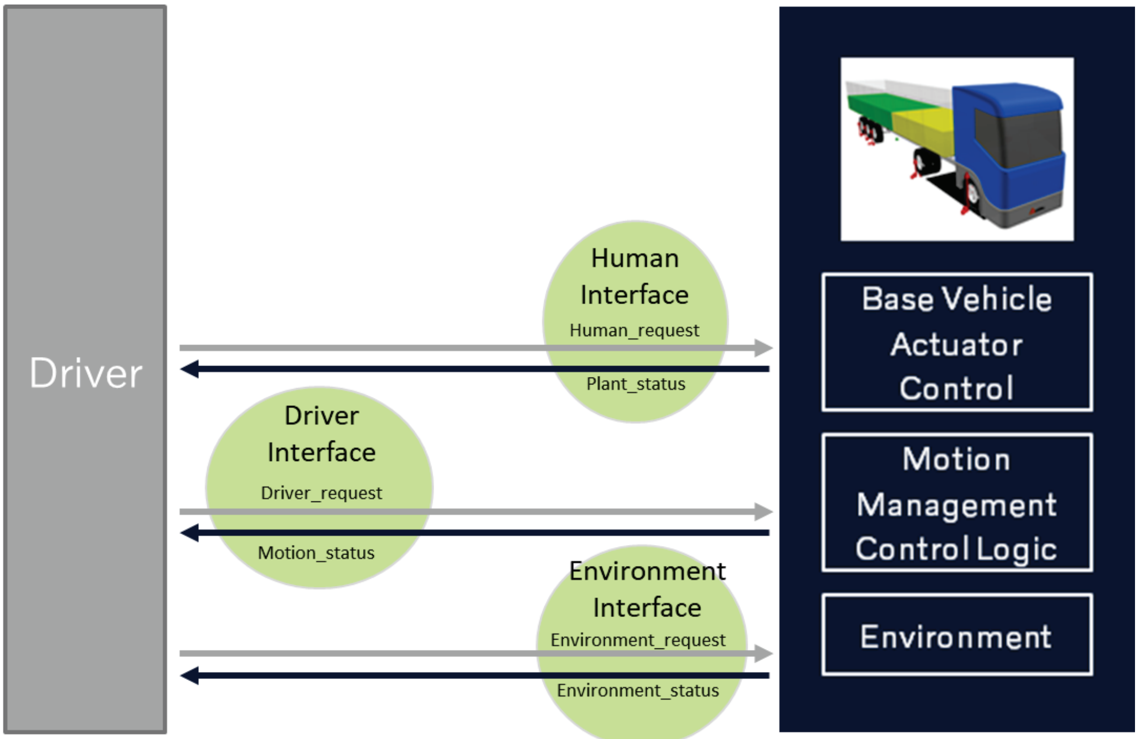


Figure 19: Interfaces to communicate between driver, motion management and plant

- Driver Interface: This is the interface that the autonomous driver would use, both on the physical truck and the virtual model.
- Human Interface: This is a direct interface to the Plant model. This allows a human to interact with the virtual plant model directly and skip the Motion Management layer, which represents a human manually driving the truck. This interface is usually used to handle the virtual models in a software environment (i.e., drive the model around manually) or for safety driver interventions.
- Environment interface: This interface presents the environmental factors for the virtual plant model. Such environmental factors could be road friction and road profile. The trailer payload is also considered to be part of the environmental interface.

## 6.4.4 Model development

### 6.4.4.1 Plant model

To achieve that, vehicle models are being developed based on the object oriented Modelica language which allows for modular and hierarchical modeling. The intention is to use such models in the Functional Mockup Interface (FMI[2]) framework, an open interface standard for sharing models among different simulation tools and test environments. The models are developed in a modular manner, where each model can be parametrized to fit the actual physical truck. The modules of the model can be seen in Figure 20.

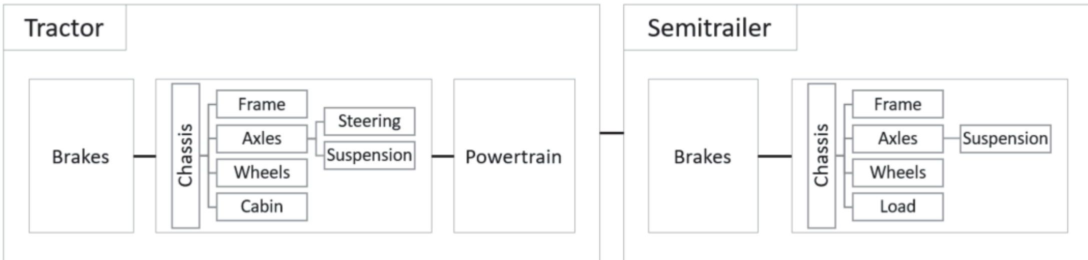


Figure 20: Module structure of virtual vehicle model

### 6.4.4.2 Integration of motion management control logic

One of the most important aspects of the provided model is that it beyond vehicle dynamics, also contains motion management controls. The intention here is to include the exact same portable motion management code that would be deployed on vehicle ECUs, but in a virtual environment and connected to the plant model. In other words, the model closes the loop for motion management control and provides the required feedback for the controls and logic to work. The reasons behind such integrations are numerous, but most importantly, this allows for better regression testing of the AD stack in a virtual environment where quick feedback loops are attainable, evidently increasing the productivity and efficiency of AD development. This also allows for testing the integration of AD stack with the vehicle automation interface in a virtual environment without having to rely on physical vehicle testing. An example of such virtual logic testing is shown in Figure 21, where a Driver is required to follow a certain sequence of commands in order to activate Autonomous and Motion modes using the Driver Interface. This is required before starting to send motion commands to drive the vehicle.

[2] https://fmi-standard.org/

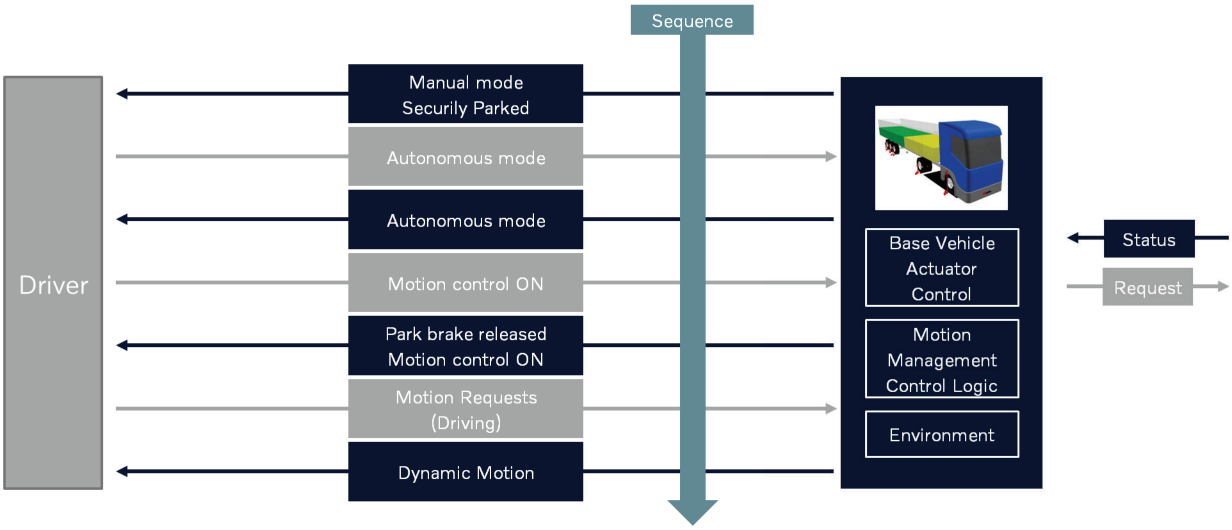


Figure 21: Example transition diagram for actuating vehicle

### 6.4.4.3 Base vehicle actuators control

In virtual environments, where the models are deployed, the holistic behavior of the complete vehicle is what matters. For that reason, the fidelity of models needs to be understood in order to decide what level of actuator models and controls need to be included. For this project, and for the purpose of carrying out regression testing on AD stack, certain aspects of actuator controls were discarded while maintaining the requirements for the Motion Management to behave as expected. For example, the logic for engaging or disengaging the park brake, or the logic for choosing gear mode is simplified enough for the Motion Management control logic to function correctly.

### 6.4.4.4 Integration in simulation environments

Interfacing control signals, which are sampled by nature is more straightforward when compared to interfacing physics. Hence, it is very important to understand where the physics interface is. In the setup for this project, this interface narrows down to the tire road interaction. In the provided model, each wheel has a defined contact patch which is described by its road height, road inclination in 3D as well as road friction. Those define the physical interface when integrating the vehicle model in a 3$^{rd}$ party simulation environment.

Another difficulty to consider when integrating a vehicle model in a simulation environment is the simulation execution speed of the model. In essence, the main reason for using a vehicle model is to increase productivity, which entails that a vehicle model is expected to run faster than a real vehicle. There are many factors that affect the computational performance of a model, some of which are related to the structure of differential equations that define the model, the solver performance, the number of states, the size of logged data from the model, the communication between the vehicle model and the simulation environment, the sampling rate of the mode etc. All those aspects can be tuned depending on the application in hand. In fact, the provided models achieve a simulation speed up to 3 times faster than real time (in current computer hardware environments used) while maintaining relatively high-fidelity dynamics.

### 6.4.5 Model Validity

As with any model of a physical system, perfect reality is never achieved. A model, by default, is always a simplified abstraction of the observed physics. The trick is first and foremost knowing the use case of the model, then knowing the limits and acceptance levels which would consider a model to be useful in specific scenarios. The questions to be answered drive the model fidelity required. For that reason, the strengths and weaknesses of the virtual models are considered here.

Strengths of the presented virtual models:

- Modularity: It is simple to switch between the modules shown in Figure 20.
- This allows for having different model configurations as well as different model parameters.
- FMI standard compatible: The FMI standard provides numerous advantages that increase the usability of the models and foremost allows model authoring- and deployment environments to develop in their own pace.
- Trailer payload handling capability: the presented models can handle a change in payload on the trailer during simulation. This capability is not trivial since several parameter changes happen when a trailer is loaded, and a virtual model should be able to handle those changes to ensure valid behavior and dynamics under different loading conditions.

It comes to no surprise that the models have their short comings. The acknowledgement of such weaknesses serves to understand the outcome behavior of the model and provide room for improvement. Some of the short comings that the presented models suffer from are:

- Simplified electric powertrain: The powertrain module used in the virtual model for the time being represents an ideal electric machine, parametrized with diesel truck characteristics. There is a great margin for development and improvement in the electric powertrain module that would enhance the performance of the virtual model.
- Lumped steering model: The steering system on the trucks is a complex system which introduces numerous components. In the provided models, the steering module is lumped in the sense that its components and compliances are aggregated into one component with values that represent the characteristics of the complete steering system. For autonomous driving, lateral control is a key component for ensuring safety. This puts a high expectation on having an accurate steering system in the virtual models. This includes the steering gear as well as its controllers.
- Simplification assumptions: Those assumptions are found throughout the model and are performed to ensure a quick solving time of the model while making sure not to degrade the integrity of the model validity. There are numerous reasons to consider such assumptions, some of those reasons can be controlled by the engineers, but others, like wind gust assumptions are tough to model correctly. An example of such an assumption would be the payload distribution on the semitrailer. This of course plays a role in the position of the center of gravity of the semitrailer as well as its moment of inertia, hence affecting the model's dynamics and behavior.

Having the short comings in mind, a simple comparison of the model is made against an existing tractor-semitrailer. The model is parametrized towards the tested tractor-semitrailer, which has a diesel powertrain and is used for data collection. A single lane change maneuver is considered. Figure 22 shows the lateral dynamics log signals of the physical tractor-semitrailer in blue and the traces of the simulated virtual model in red. The steering wheel angle that is input from the driver on the actual truck is used to steer the virtual model. The test is carried out at 30 km/h which is the speed at which the vehicle would be driven when negotiating maneuvers in the context of this project. The figure shows that the model provides reasonable behavior in comparison to the actual physical tractor-semitrailer.

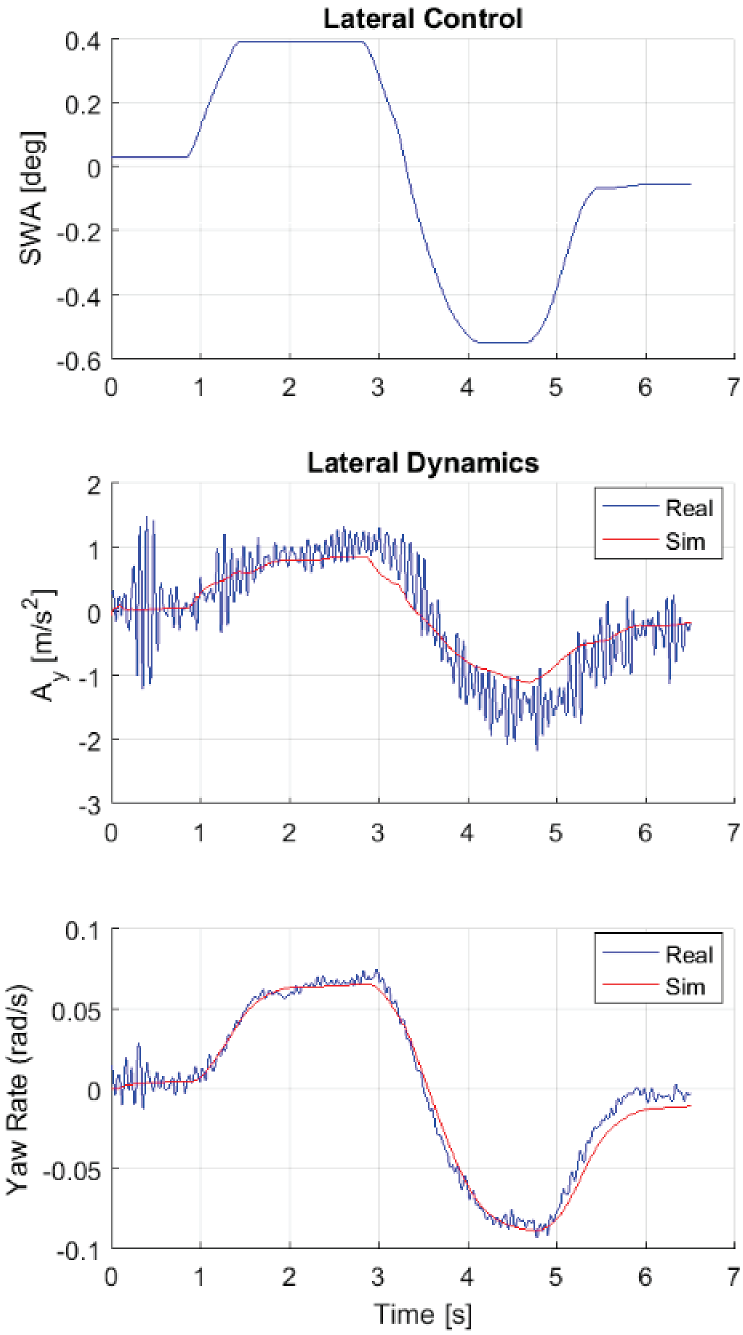


Figure 22: Comparison of virtual model against a physical tractor-semitrailer in a single lane change maneuver

### 6.4.6 Analysis of energy consumption improvement before and after implementation of demonstration project in the total transport system

This chapter highlight the following questions:

- What is the fleet energy consumption in terms of kWh electricity per time unit?
- What is the fleet energy consumption in terms of liter diesel per km?
- What is the expected fleet productivity?
- What is the fleet owner ship cost for electric and conventional powertrains?

In some sense the analysis resembles the analysis presented in chapter “Analysis of the total transport system”. That main difference is that a more detailed simulation model has been used. Another difference is that previous analysis was not able to estimate energy consumption.

This chapter presents results from the Java based simulation tool. A tool that can simulate virtually any site. There are 300 white dots in Figure 23. These dots form a directed graph and represent the route where the vehicles (4 in the figure) are moving. The time between two linked dots is fixed, the distance between dots defines a speed estimate. Small distance means low speed. Recall chapter “Analysis of the total transport system”. The higher road speed of 40 km/h has been assumed in the analysis presented in this chapter. In addition, the earlier chapter motivates the analysis of 5 vehicles.

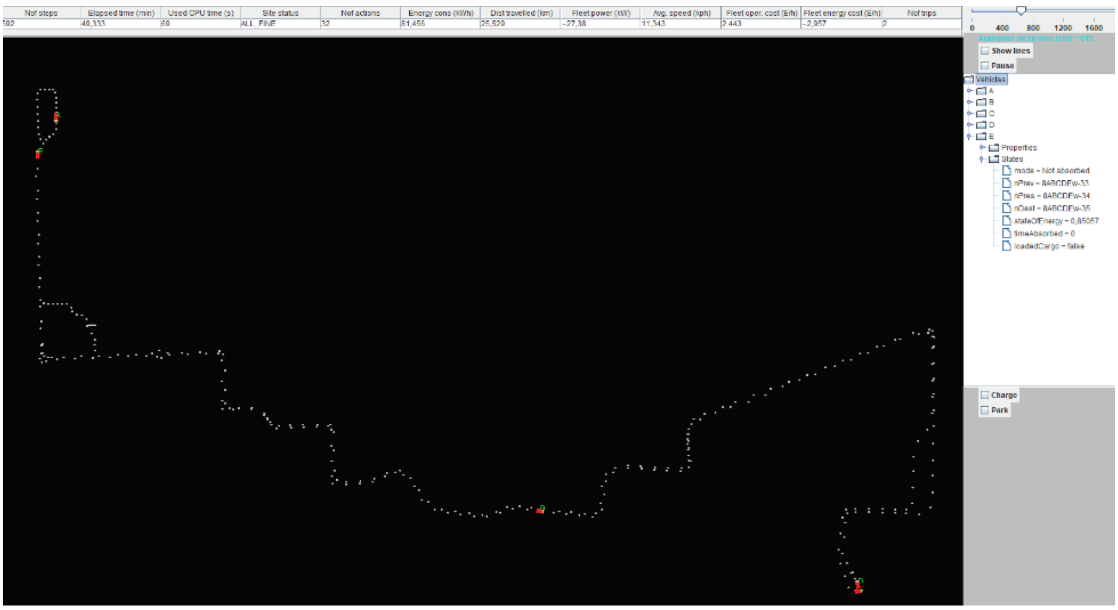

Figure 23 Graphical user interface of site simulation tool.

A full electric vehicle with 5 battery packs is the primary powertrain variant. For comparison, a diesel variant, and an electric vehicle with smaller battery, three packs, are added. Another simulation setup is that five vehicles are operating for 3 hours of real-world operation.

Results are presented in Table 5 below. Following reflection can be made:

- The electric powertrain is much more expensive, the 5-pack electric vehicle powertrain costs ~200 kEuro, many more times than the diesel powertrain.
- The energy consumption of the electric vehicle variants is ~30% of the diesel variant. This is explained by better powertrain efficiency and the fact that electric vehicles can store kinetic and potential vehicle energy.
- The daily number of missions is 44 (11*12/3). This fulfils the daily requirement of 40 missions.

Table 5 Simulation results. Five vehicles operating in 3 hours of real-world operation.

| powerTrainType | pricePowertrainEuro | electrictyConsumptionKWh | dieselConsumptionLiters | nofMissions | fleetTravelledDistanceInKm |
|---|---|---|---|---|---|
| Diesel | | 0 | 102 | 11 | 112 |
| Electric5pack | | 389 | 0 | 11 | 112 |
| Electric3pack | | 369 | 0 | 11 | 112 |

An owner ship cost analysis will now follow. Three questions are highlighted:

1. Is the energy cost savings in an electric vehicle higher than the cost of added hardware?
2. Is the battery degradation a critical aspect?
3. What is the consequence of lowering battery cost and/or increasing battery lifetime?

Energy and vehicle hardware costs are projected on a yearly basis by:

$$cost_{own} = cost_{fuel} + cost_{electricity} + cost_{hardwaredepr} + cost_{batterydegradation} \text{ (E/year)}$$

The terms including fuel and electricity are straight forward. Yearly total fleet consumption is multiplied with price per unit fuel or energy. The conversion between hardware price (€) and yearly cost (€/year) is done by an annuity calculation:

$$a = annuit(p, R, i, n) = \left(\frac{R}{(1+i)^n} - p\right) \cdot \frac{i}{1-(1+i)^{-n}}$$

where *p* is the price of the hardware, is *R* the rest value, *i* is the interest rate (-) and *n* the economic lifetime (years). The results are presented in Figure 24 and Figure 25.

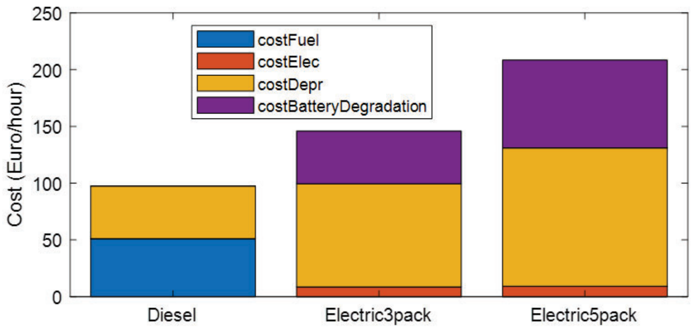


Figure 24 Base case

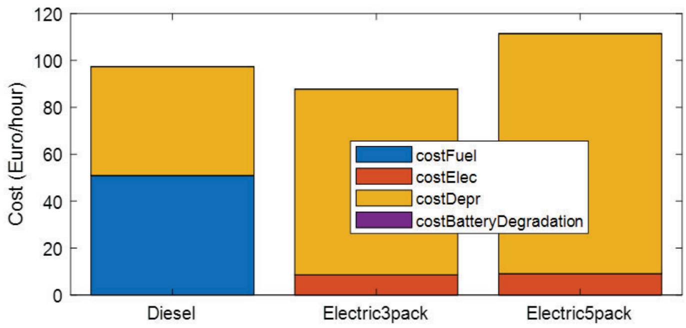


Figure 25 Increased battery lifetime and lower battery cost. Increased battery lifetime means that the maximum possible of number of full charge-discharge cycles are doubled. Lower battery cost means that battery price is decreased by 25%.

Conclusion from this chapter:

- Electric vehicles are approximately 3 times more energy efficient than conventional vehicles.
- Also, a more detailed site simulation tool indicates that productivity targets can be met.
- It is a close race between conventional and full electric powertrains. One need to be careful when comparing the technologies, multiple parameters influence the selection.
- Ongoing and rapid improvements in battery technology speaks in favor for electric powertrains as the long-term solution.

### 6.4.7 Physical control tower concept

A basecamp is defined as a closed area from where daily autonomous operations is steered, controlled, monitored, and maintained. Some of the key capabilities are cargo management, gate/site management, vehicle execution monitoring, teleoperations, workshop, parking with charging, and possible also customer reception area/show room. A control tower is a part of the base camp from where it could be possible to monitor the autonomous transport solution and perform tele operations and problem solving. Several different solutions and locations for the base camp and physical control tower were investigated within the project.

#### 6.4.7.1 Control tower

The control tower could in theory be remotely operated and placed anywhere. The autonomous trucks however must have a base camp near the route to ease for autonomous drive from and to the base camp. A base camp near the route also minimizes the first and last distance driven empty to and from the pickup point and it also enables convenient park and charge when all the deliveries have been fulfilled for the day or when the battery needs to be recharged. Since the autonomous trucks still require some human interaction to operate, such as washing and maintenance, a co located base camp and control tower on a property along the route was chosen in the project, although it was never inaugurated. A base camp combining control tower functionality with parking and other facilities such as a workshop was also estimated to facilitate commercial operation and streamline the initial testing process.

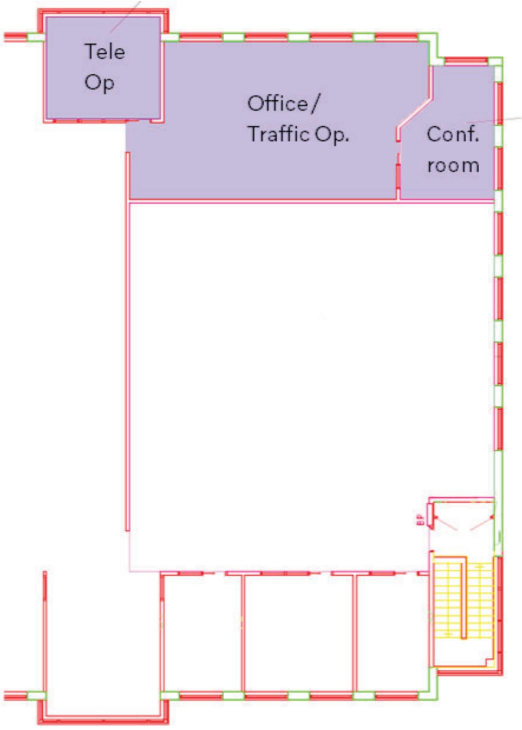


Figure 26 Control tower layout

The control tower, see Figure 26, was planned to mainly consist of an open office for traffic operation, monitoring, and planning and two flexible conference rooms. Central in the room layout would be the monitoring of the transport and operational status but the flexible layout would also be adapted for the staff, such as safety drivers, to prepare and focus. A team would work together with fleet management, cargo management, infra management, gate and site management, surveillance, service management and instant deviations handling. The layout and workstations allow for easy switching between logistic operations and a problem-solving area. The functionality of the virtual control tower is described more in detail in work package V9 in chapter 6.11.

Next to the open office are two conference rooms. The larger of the two was intended to be used for teleoperation of the vehicles if necessary. From the teleoperation rig the operator could enable a switch from autonomous to manual operation of the vehicles from control tower. The operator would also be able to stop the vehicle and set aside. Since the teleoperation require full focus, the room would have increased security with limited access. Apart from being equipped with the necessary hardware to operate a vehicle from a distance it should also be furnished with sound dampeners and curtains to minimize disturbances to the operator. The second conference room could be used as a room for focused problem solving, traditional conference room or as a dedicated room for traffic operation if necessary. Purposely, the control tower was to be installed on the second floor with a view over the yard to monitor where the vehicles are being parked and charged. In conjunction with the control tower are also the basic facilities like dressing room, toilet, lunch-, and rest room.

### 6.4.7.2 Yard and facilities

Adoptions were prepared for the dedicated basecamp to handle the autonomous processes and minimizing the need for manual intervention was prioritized when developing the layout of the yard. Some of the actions that could require manual activities are moving vehicles inside the yard, connecting the trailer to the vehicle, connect the vehicles to a charger and drive the vehicle to a workshop or maintenance. A yard layout was therefore investigated with two gates to enable a convenient drive through, as can be seen in the Figure 27. The parking spaces, all in rows along a side, are long enough to room the truck with the trailer attached and allow swift drive-in parking and take off in autonomous mode. Wireless charging was furthermore investigated, as described in earlier chapter, to reduce the need for a person to start the charging of the vehicles.

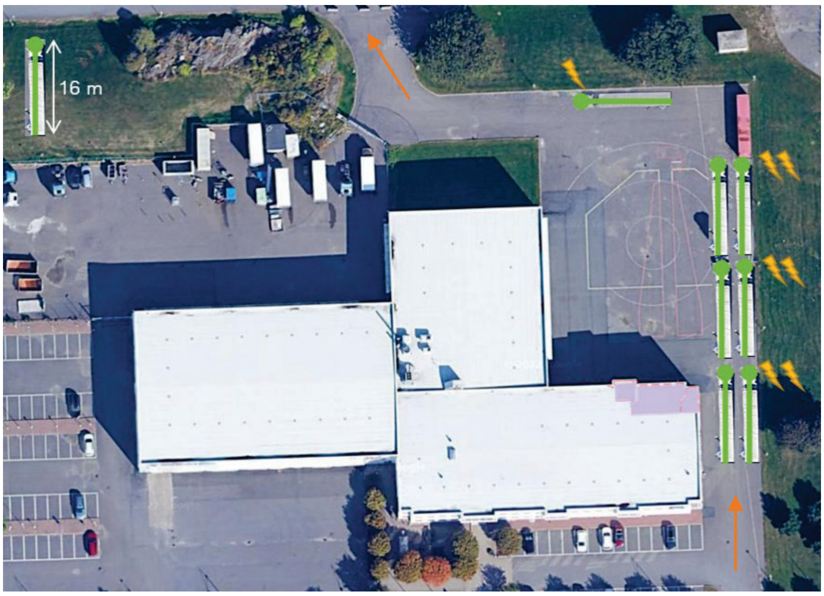

Figure 27 Layout of the yard surrounding the base camp and setup of charging infrastructure. The orange arrows indicate the direction of the autonomous traffic flow.

Several different charging setups have been discussed and analyzed during the project as alternative to inductive charging. An analysis of the vehicle's battery capacity and charging needs were conducted during 2021 when the project was restarted. It was concluded that during normal circumstances the vehicles can perform their daily operation on a single charge. Conventional charging at Volvo's physical control tower was therefore planned to be implemented. Each vehicle would have a dedicated primary AC charger for overnight charging. An additional DC fast charger with multiple dispersers could also serve as overnight charger for multiple vehicles but also for fast charging if needed during the day or to handle deviating events such as moving the vehicle due to need of maintenance.

A dedicated area in the terminal was prepared for safe parking with fence surrounding the properties. The gates that are open during daytime, when the vehicles are operating on the route, would close during the night to prohibit unauthorized access when the vehicles are parked and charged. The area is also under specific camera surveillance that is integrated into existing surveillance systems. Additional lights with motion sensors would also be installed to enhance the surveillance but also the AV capabilities of the vehicles, and thereby the safety inside the yard.

For minor preventive maintenance and daily care of the vehicles the facilities would also offer a workshop and a truck wash to take care of the vehicle and the precise sensor system.

## 6.5 Work Package V3 Automation and building of gate system

A software has been built to accommodate the autonomous vehicle whilst the vehicle is on DFDS controlled sites. The DFDS software is responsible for managing the site and the logistics capacity at the site. The software is a visual representation of DFDS Logistics Contracts and Gothenburg RoRo Terminal, and the software can be extended to any DFDS site as it is building on geo-references. The software is integrated into existing DFDS logistics and terminal management system, thus making other vehicle and equipment visible that are on site. As it is integrated into DFDS Logistics, the software is also capable of predicting traffic situations that may impact the availability of resources and autonomous vehicles. Two smart gates are integrated into the software for controlling entering and exiting of gates for the autonomous vehicles, thus enabling the remote and automated opening and closing of the gates. All security and transport related information is expected to be handled digitally, thus enabling a fully automated gate transit with no human intervention.

Figure 28 Smart gate at DFDS Logistics Center

Figure 29 Smart gate at Gothenburg RoRo Terminal

## 6.6 Work package V4 Powertrain

Two electric driveline systems have been designed, built and tested in the vehicles. The first vehicle was built with a prototype system based on Volvo bus Topology and TVS (Traction voltage system), in this version we used two motors connected to a 2-speed gearbox, resulting in approximately 2*130 kW of power continuously. This was considered enough given our mission in the relatively flat harbor area and max 40 km/h of speed. The battery capacity was about 130 kWh divided between 3 batteries. The future vehicles will be based on our newly developed driveline for HD vehicles utilizing 2 or 3 motors connected to a 12-speed gearbox (At least 2 or 3 times 130 kW), and probably around 250 kWh of available energy (4*90 * SoC window 70 %). The SoC (State of Charge) window can be adjusted pending the need versus life of battery.

## 6.7 Work package V5 Charging

As mentioned in H3 work package several charging concepts have been investigated and evaluated, incl manual charging through a regular CCS 2 inlet (Preferably DC charging, however low power AC charging is also possible. One concept related to CCS

charging is to use a robot operated charging engagement (ROCSYS have been the base for the study). Manually operated overnight charging has also been investigated. The other main charging solution that has been evaluated is inductive charging (from Momentum Dynamics) which was chosen for its ease of use and lack of moving parts, this is believed to give high uptime and few reliability problems.
The system is modular (one plate on vehicle and one corresponding module in the ground) and each module is capable of 75 kW of charging power. The modules can be combined and provide up to 300 kW of power with four modules (130 kW with two modules have been demonstrated with an early prototype system). The latest generation of the charging pads are mounted flush with ground.

## 6.7.1 Background

When introducing an autonomous transport solution utilizing battery electric trucks (or machines) the need for a feasible charging system occurs. The system requirements depend on a lot of factors, such as:

- Vehicle configuration, PTO solutions etc. and how much energy (battery capacity) that can be fitted to the vehicle
- Number of vehicles.
- GCW (Grosse combination weight) and payload
- Transport operation, cycle time etc.
- Route length and topology
- Operation hours/shift
- Power supply infrastructure
- ODD (Operational design domain), ambient temperature and other environmental parameters.

There are at least two principal solutions for charging of the transport system. One of them is “overnight” charging, where the vehicles are charged during non-operation hours and the charging is enabled by either manual operation or some kind of “automatic” charging system. This solution requires that the vehicles have a period where they aren’t in operational use. The other solution that can be considered is charging during the operational hours, when the opportunity appears (during loading, unloading etc.) or in a charging scheme. This solution requires some kind of “automatic” charging system.

Furthermore, there are two principal solutions for transfer of energy during the charging operation, conductive and inductive charging, in this project it has been have chosen to perform some tests with inductive charging.

## 6.7.2 Charging system evaluation

### 6.7.2.1 Purpose

Build knowledge regarding different types of charging systems during autonomous operation of a transport system utilizing battery electric vehicles.

#### 6.7.2.2 Method and research questions

A high level QDCF assessment of different charging concepts was performed. Based on the assessment inductive charging was selected for a deeper study including a demonstration/test using the prototype vehicle we built as part of work package V2. In order to build knowledge and perform the needed tests the supplier Momentum Dynamics was chosen as a partner. Manual charging with CCS interface was considered a known solution so decided to not focus on that. An additional area that needs more study is charging power versus size of energy storage on vehicles for different transport operations and cycle times.
Concepts related to overnight charging also remains to be investigated and concluded, the main questions here are related to number of charging stations vs number of vehicles and charging power including needed grid power.

### 6.7.3 Results and deliverables

#### 6.7.3.1 High level QDCF assessment

The following concepts were evaluated, focusing on solutions used within the Volvo Group.

**<u>Brief presentation of CCS charging interface</u>**

The Combined Charging System (CCS) is a standard for charging electric vehicles, which uses the Combo 1 and Combo 2 connectors to provide power up to 350 kilowatts. These two connectors are extensions of the IEC 62196 Type 1 and Type 2 connectors, with two additional direct current (DC) contacts to allow high-power DC fast charging.

The Combined Charging System allows AC charging using the Type 1 and Type 2 connector depending on the geographical region. Since 2014 the European Union has required the provision of Type 2 or Combo 2 within the European electric vehicle charging network. This charging environment encompasses charging couplers, charging communication, charging stations, the electric vehicle, and various functions for the charging process such as load balancing and charge authorization.

Figure 30 **Connectors**: Combo 2 (left), compared to IEC Type 2 (right). Two large direct current (DC) pins are added below, and the four-alternating current (AC) pins for neutral and three-phase are removed.

## Conductive charging systems

### Oppcharge

| Q | D | C | F |
|---|---|---|---|
| **Onboard:**<br>Bus bars and communication components in production today. Protective cover etc probably sensitive<br><br>**Offboard:**<br>Reliability of horizontal mechanical movement unknown. | Concept fully integrated in Volvo control system for production.<br><br>**Onboard:**<br>Bus bars and communication components in production. Protective cover?<br><br>**Offboard:**<br>Horizontal movement require to be design and production.<br><br>Initial testing can be done with minor modification to standard charger (as long as vehicle have no trailer) | **Onboard:**<br>Low. Simple design, bus bars in production.<br><br>**Offboard:**<br>HW:<br>1,5-2MSEK +<br>arm modification, 200kSEK+<br><br>Development<br>Modified arm:<br>700kSEK+ | 300kW+ of charge power<br><br>20-60 s connection time<br><br>Automatic connection<br><br>Require restricted area for charging (moving parts, exposed electrical parts)<br><br>**Onboard:**<br>~20kg<br>~2x2x0.2m<br><br>**Offboard**<br>2000kg+ |


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Figure 31 Pantograph with access to vehicle from above

### Schunk

| Q | D | C | F |
|---|---|---|---|
| Proposed concept under development at VCE.<br><br>Inverse concept (pantograph on vehicle) in operation.<br><br>Resistance towards dirt, dust and humidity unknown<br><br>**Onboard:**<br>Female connector made for offboard use mounted at 4,5m+ over road surface.<br><br>**Offboard:**<br>Several mechanical actuators made for mounting at vehicle roof.<br><br>Unknown effects from mounting component in new direction | Approx 20w lead time for pantograph and female connector (VCE experience)<br><br>Previosly integrated with Volvo control system at AE level.<br><br>**Offboard:**<br>Arm re-design and modification 10+ additional weeks.<br><br>Uncertain certification status of offboard components | **Onboard**<br>Approx 40kSEK/vehicle<br><br>**Offboard**<br>HW:<br>1,5-2MSEK<br>Arm modification, 100kSEK+<br><br>Development<br>Modified arm: 500kSEK+ | 150kW+ of charge power<br><br>20-60 s connection time<br><br>Automatic connection<br><br>Require restricted area for charging (moving parts)<br><br>**Onboard:**<br>~20kg<br>Volume<br><br>**Offboard**<br>2000kg+ |

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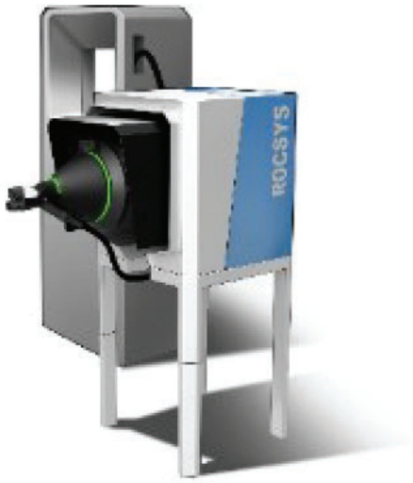
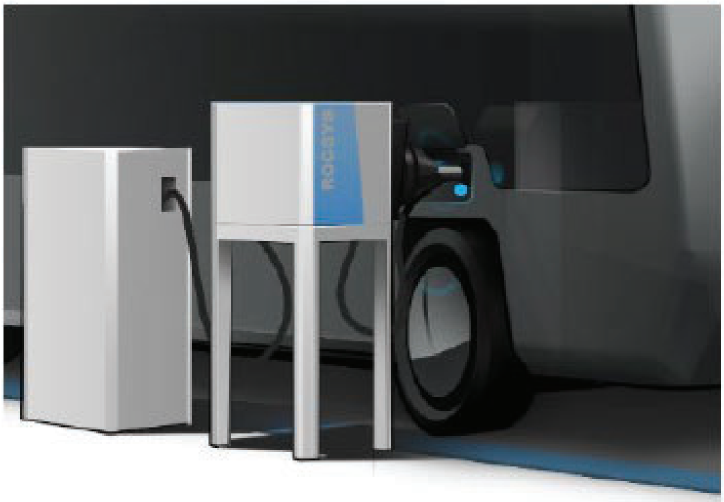
Figure 32 Pantograph with access to vehicle from underneath

**Regular CCS2 charging interface managed by charging robot from ROCSYS.**

This system has not been evaluated and concluded within the project.

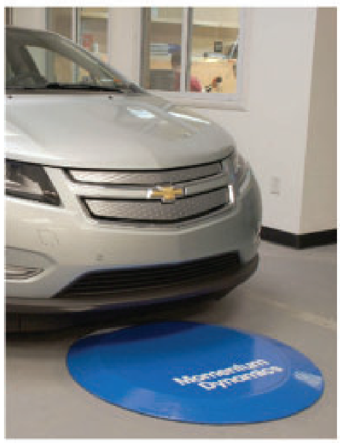



**Inductive charging system**

## Momentum dynamics

| Q | D | C | F |
|---|---|---|---|
| Tested under pilot conditions.<br><br>Impact from positioning accuracy on efficiency unknown.<br><br>Impact on efficiency from dust and dirt unknown.<br><br>Components in prototype production | No established production process.<br><br>Engineering resources possibly a constraint.<br><br>Previosly not integrated with Volvo control system.<br><br>Vehicle to charger communication delivered by supplier.<br><br>System in operation under US legal conditions. Uncertain status for EU.<br><br>Functional HW available August 2018 | **Onboard:**<br>150kSEK/vehicle (~50kSEK/50kW of charge power)<br><br>**Offboard**<br>HW: 700kSEK/charger | 150kW+ of charging power<br><br>5-30s connection time<br><br>May require restricted area for charging (magnetic fields)<br><br>**Onboard:**<br>Gen 1: 270kg<br>Gen 2: ~50 kg<br>3x1m2 + 100l<br><br>**Offboard**<br>1000kg |

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### 6.7.3.2 General conclusions

The conductive systems have a lot of moving parts and where therefore in this study judged as less robust when compared with inductive charging solutions. Hence, we choose to proceed with evaluation of inductive charging. The latest version of the studied inductive charging system is mounted flush with ground and can easily be driven over by vehicles, snow ploughs, road sweepers etc.

## 6.7.4 Inductive charging system presentation

The full inductive charging solution is provided by Momentum Dynamics, and it includes a ground unit and a vehicle unit. The ground unit consists of a ground plate with a coil and a control and communication unit. The vehicle unit consists of several components, connected to the battery in parallel. Each component has a coil and its own control and communication unit. To charge, the coils in the vehicle must be aligned with the coils on the ground, with a tolerance of 125 mm in any direction. Within this range the power will derate if the vehicle and ground coils are not perfectly aligned. Control of the system is enabled via CAN communication. The system has a modular design which means that it can be sized depending on the need. It’s built up by a charging receiver on the vehicle that is matched with a corresponding transmitter in the ground assembly. The transmitter is then connected to a charging cabinet that can be placed up to 30 m from the “charging pads” (transmitters). Up to six charging plates can be used. (Up to 300 kW is possible with four charging plates). The test vehicle was equipped with two charging plates, enabling a theoretical charging power of 150 kW. The system can be tuned for different heights (between receiver and transmitter), depending on the need and type of vehicle. Charging works from 3 cm (although slight derate in charging power) 10 cm verified ok =>17 cm ground clearance.

The weight of the pads on the vehicle is as follows:

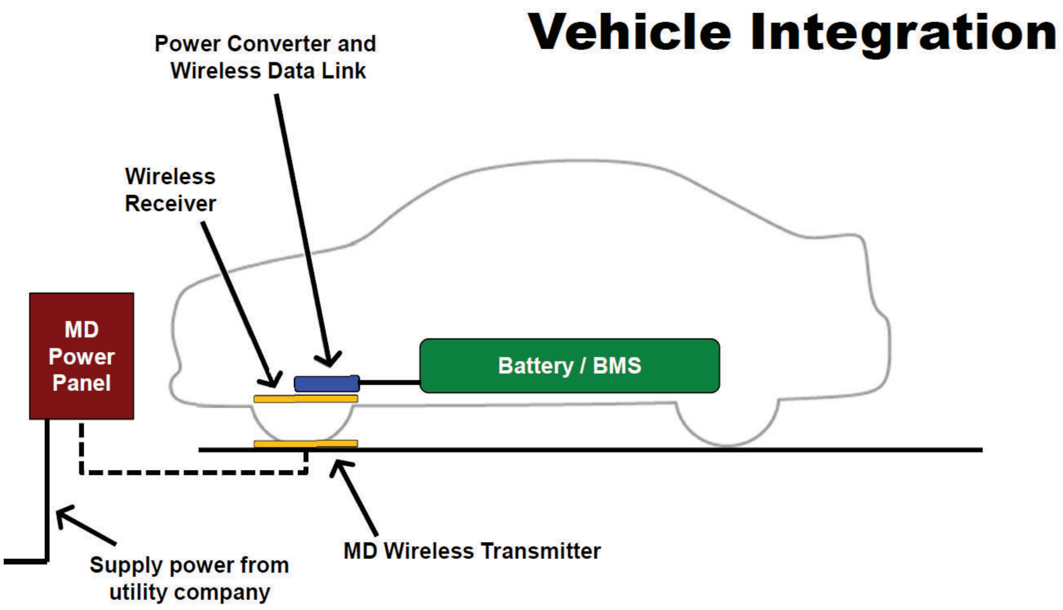
1. Gen 1 on-board - 115kg per pad
2. Gen 2 on-board - 35kg per pad

The weight of installation material (brackets, hoses etc.) needs to be added.

Table 6 System Operating frequencies

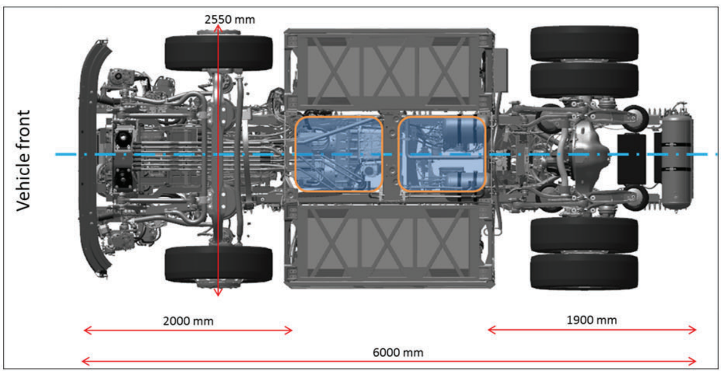
| Signal | Nominal Frequency | Min/Max Frequency | Power Level |
|---|---|---|---|
| **Power Transfer** | 85kHz | 79kHz/90kHz | Up to 75 kW |
| **Inductive Comms GA TX** | 13.56 MHz | 13.553-13.567 MHz | FCC part 15 Compliant |
| **Inductive Comms VA TX** | 40.68 MHz | 40.66-40.7 MHz | FCC part 15 Compliant |
| **Cellular Communications** | 3G: 1900/2100 mhz<br><br>4G LTE:<br>Band 3 - 1800 mhz<br>Band 7 - 2600 mhz<br>Band 8 - 900 mhz<br>Band 20 - 800 mhz | 3G/4G LTE compliant Radio | CE 3G/4G LTE compliant Radio |

### 6.7.4.1 High level system description




### 6.7.4.2 Example of vehicle installation

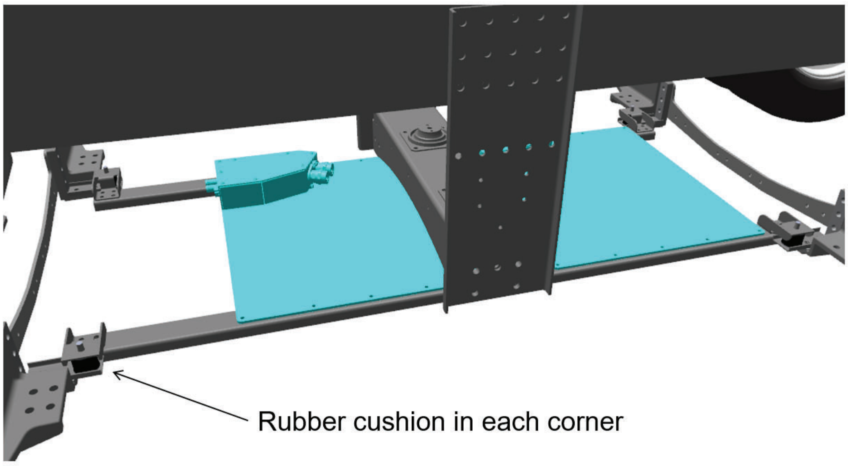
**HW vehicle installation**



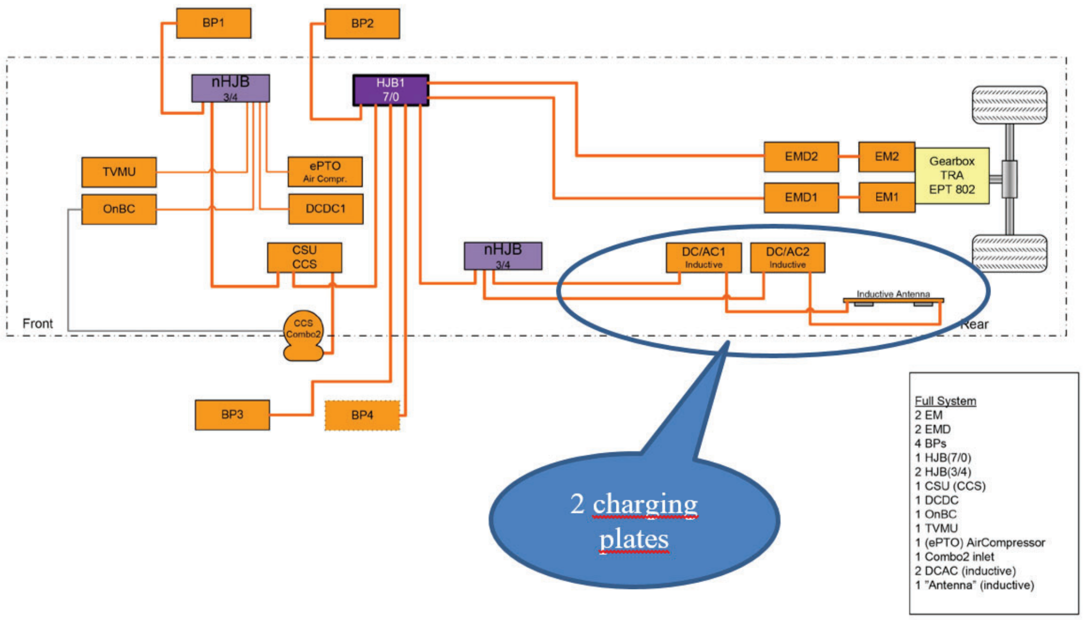

- Draft position agreed
- Mounting points updated, impact under evaluation
- Coolant requirements agreed

**ISO top view**

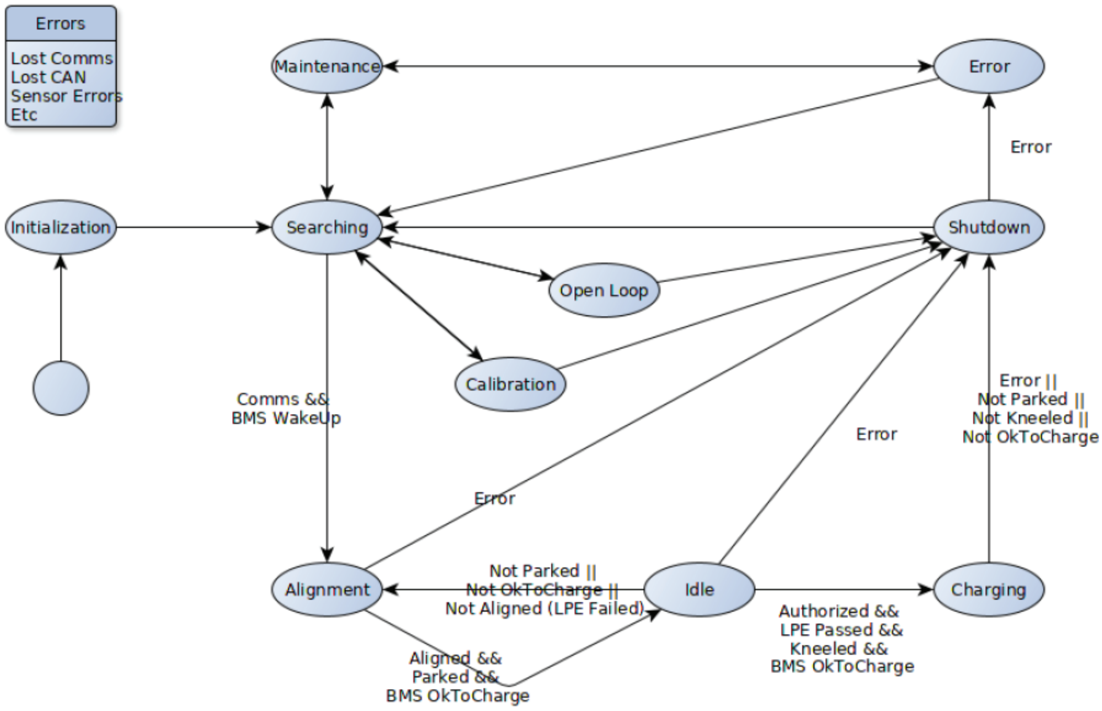
**Detailed view**



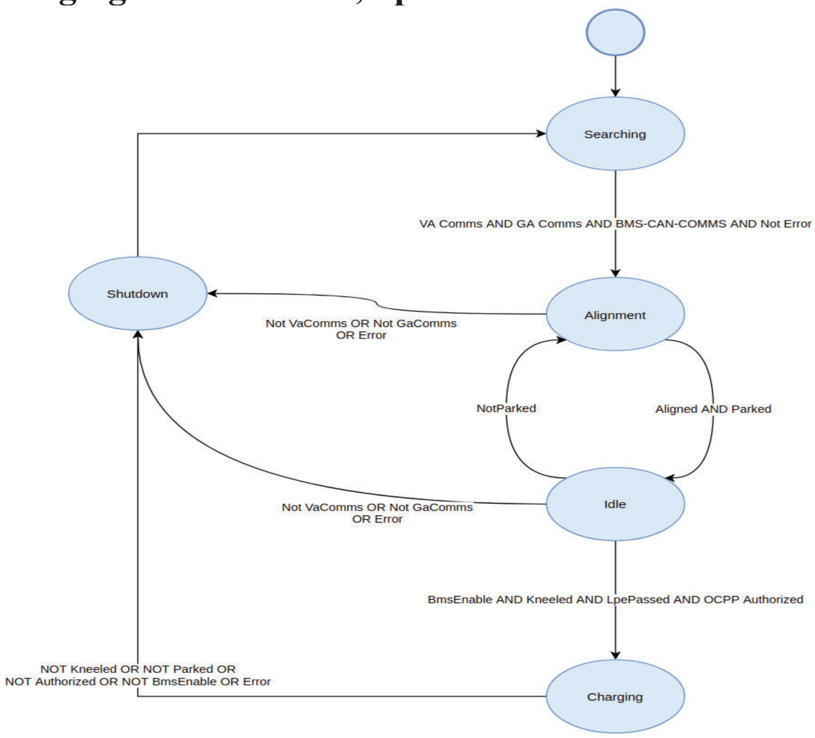

### 6.7.4.3 Example of vehicle system topology



### 6.7.4.4 Charging state machine during testing




### 6.7.4.5 Charging state machine, updated version




### 6.7.4.6 Charging sequence/control

While the charger is active it will try to establish communication with the ground unit. When it is close enough to set up communication it will continuously check its alignment with the ground plate and send this information to the driveline control unit, which will forward it to the vehicle control unit to help guide the driver or autonomous system. The charger will handle the control of the charging on its own, only requiring the current request, battery voltage and voltage limit to be supplied from the driveline control unit. The current request should be ramped up with a maximum slope of 50 A/s. When ramping down it's possible to send a current request of zero and let the charger ramp down on its own or ramp down the current request from the driveline control unit. The maximum slope when ramping down is 100 A/s, except for emergencies when it can shut down immediately. Since the inductive charger will constantly search for communication with the ground station or calculate how well aligned it is when it has established communication it is beneficial to let it go to an idle state when this is not needed.

#### 6.7.4.7 Fault/error handling

If the charger detects an error during charging it will immediately start ramping down the current and send *Charger Ready = False* to the vehicle as well as setting an error code describing the error. The driveline control unit should then send *Charging Status = Error* to the vehicle control unit and after the charging is shut down it should send *ExternalChargerConnected = False*. After the component is restarted, it will automatically attempt to start the charging process again if it is still aligned and allowed to charge.

#### 6.7.4.8 Foreign object detection between the receiver and transmitter pads

- This test as defined in IEC 61980 is to determine if a foreign object of various sizes and types of metals is between the pads when starting to charge. The test was passed as defined in the standard.
- If an object is introduced while charging at full power, it will be detected, and the system will shut down protecting the system and surrounding property.
- This functionality was not included in the early prototypes and therefore not tested.
- The latest generations of this system (With additional hardware) have passed the tests according to the 61980 FOD requirements

#### 6.7.4.9 EMF information

1. Output power: System is limited to 100A per pad, at ~600V the combined power with 2 VA pads is 120-130kW
2. EMF: Meets FCC, IEEE, and ICNIRP industry standards across the operating power range. Testing done relative to ground/vehicle pads with ~150 mm magnetic air gap. Emission inside the vehicle and around the vehicle are below ICNIRP 1998 standards.

#### 6.7.4.10 EMF data from testing

Below is testing data from the pads at 525V and 100A, at 18" away from the pad. The position is the location around the pad and TOP refers to directly above the pad.

| Description | Position | Measured Instantaneous Value (uT) |
|---|---|---|
| GA and VA 2C on TT,<br>Z-Gap = 120 mm<br>Vehicle Battery = 525V<br>Vehicle Current = 100A | 0°<br>45°<br>90°<br>135°<br>180°<br>225°<br>270°<br>315°<br>Top | 4.3<br>2.9<br>10.1<br>2.4<br>7.1<br>5.2<br>12.5<br>3.7<br>3.2 |

#### 6.7.4.11 Efficiency

- Gen 1 was stated as 92% efficiency as measured; however, this was without a PFC front end (Power factor correction (PFC) circuit).
- Gen 2 has PFC meeting CE Mark standards affecting efficiency.
- The measured efficiency was performed per the test requirements from Intertek per IEC 61980-3. Worst case alignment was taken beyond 61980-3 requirements.
- IEC 61980-3 requires 85% efficiency at nominal alignment and 80% efficiency at worst case misalignment.
- Best estimation for the moment is 88-92% efficiency depending on the output power level, alignment, z-gap etc.

### 6.7.5 Test results

Two tests have been performed with two generations of the system (both in prototype stage). The latest version (Gen 3) hasn't been tested. The test was performed 2019 and 2021. The first test focused on verification of the control system and that the implemented functions were working as intended. The second test was focused on demonstration that we could charge the vehicle with >100 kW.

#### 6.7.5.1 Test results from the first test (performed 2019)

Charging with 35 kW (55 Amps) for approximately 50 min (until fully charged, 80-100 %) succeeded. The communication between the vehicle and the charging station also worked as intended. When the vehicle requests a certain charging power, the station responds with correct power. A unique charging protocol for inductive charging was developed and used. Temperatures were logged on the charging plates (60 deg C, limit is 85 deg C)

Table 7 Functional test results

| No | Objective | Test | Result | Observations/Improvement areas |
|---|---|---|---|---|
| 1 | To test<br>1) The station is detected by the vehicle assembly<br>2) Confirm following CAN signals for values - Charger_AlignmentFlag = charger nearby | Vehicle parked approximately 8-10m from the ground assembly | Passed | Charger AlignmentFlag toggles between charger nearby and partially aligned, which is not correct. The flag should go to partially aligned only when the vehicle is positioned above the ground assemble, but is misaligned |
| 2 | To confirm that charging does not start when vehicle is put into Inductive charging mode but is not aligned to ground assembly. Following values should be reported on CAN signals<br>1. Charger_AlignmentFlag should in all position show “charger nearby”<br>2. Charger_ChargerReady = 0<br>3. BMS_OkToCharge = 0 | Starting 6m away from ground assembly, Vehicle parked, kneeled and put in inductive charging mode.<br>1. Vehicle is subsequently parked closer to ground station in steps like 4m, 2m, 100m. | Passed | Same as in test 1. Charger AlignmentFlag toggles between charger nearby and partially aligned.<br>The alignment flag should have always shown charger nearby |
| 3 | Charging the vehicle with 50 Amp current | Vehicle is fully aligned, parked and kneeled and put into induction charging mode. | Passed | • The output current as shown on CAN, Charger_OutputCurrent fluctuates between 48.8 A – 52Amp.<br>• It takes 9s for the charger to ramp-up the current |
| 4 | Charging can be terminated by the vehicle<br>• BMS_OkToCharge is set to ‘0’ | The vehicle is moved out of Induction charging mode | Passed | |
| 5 | Charging terminated by station | | Passed | |
| 6 | Station is able to supply current as requested by the vehicle | Vehicle parked, kneeled and put into inductive charging mode | Passed | |
| 7 | E-stop during charging from vehicle side | Emergency stop pressed on vehicle while the charging is in progress | Passed | |
| 8 | Station is able to ramp down the current as requested by the vehicle | Charging initiated Vehicle starts ramping down the current request and the station follows the request | | |
| 9 | Charging when vehicle is slightly mis-aligned | | Passed | |
| 10 | Over Voltage limit of 25V set on the station. The vehicle | | Passed | |
| 11 | Over current protection functionality of the charger<br>Charging should be terminated if vehicle request current higher than 25A | Current limit of 25Amp set on the station.<br>Vehicle starts ramping up the current up to 25A. | Passed | |
| 12 | Charging gets terminated when the current request from vehicle = 0 | | Passed | • The current resolution of sensor in vehicle assembly is not good at the lower spectrum, between 0-5A<br>• Charger_OutputCurrent still reports some current (1-3Amp) even though the vehicle was not drawing current. |
| 13 | Charging does not start when HPCU sends BMS_OkToCharge = 1, but the vehicle is not ready to charge | | Passed | |
| 14 | Checked for Isolation failure | • Parameter set in HPCU software for expected resistance | Passed | |

| No | Objective | Test | Result | Observations/Improvement areas |
|---|---|---|---|---|
| | | value, if the measured | | |
| 15 | Charge until SOC = 100%<br>• Charging terminated by HPCU when SOC = 100% | • SOC = 80 % at the start of charging<br>• Target SOC = 100% | Passed | • Cooling of Vehicle assembly not efficient.<br>• Charger_AmbientTemp = 62° C |
| 16 | Charging does not start when error flag is set on the station side | | Passed | |
| 17 | Not possible to drive away the vehicle during charging | | Passed | |
| 18 | Charging at different kneeling heights | | | Do not have a figure here. But it is possible to charge with vehicle at driving height and lower.<br>Charging efficiency reduces when the vehicle is raised above “driving height” |

#### 6.7.5.2 Results from the 2nd test (performed 2021):

Start SOC: 79%

We charged with max 130 Kw up to 98%

**Alignment test:**

10 cm forward = ok

=>At least +/- 10 cm misalignment in all directions ok

**Height test:**

Charging works from 3 cm (although slight derate in charging power)

10 cm verified ok =>17 cm ground clearance.

The system can be tuned for different heights, depending on the need.

## 6.8 Work Package V6 Vehicle motion management, traffic situation management

In this chapter, the developed Vehicle Motion Management and Safety Driver concepts are described. The traffic situation management was developed by a technology partner outside the TranzPORT project and will therefore not be presented within this chapter.

### 6.8.1 Vehicle Motion Management

Within work package 6 we have developed an interface for communication between the virtual drive and the base truck. The communication is handled by a new ECU (electrical control unit) that enables the truck for autonomous drive. The ECU consists of a software called Vehicle Motion Management. The purpose of this software is to give the autonomous driver the possibility to precisely control the vehicle in lateral position by implementing a curvature controller. Additionally, there is an acceleration controller which aims to give the virtual driver the ability to both accelerate and brake with precision. When developing these functions, big focus has always been on the safety. The safety of the safety-driver has been kept in mind and the driver shall always be able to take full control of the vehicle in any scenario.

In addition to the VMM related parts of mode management and safety driver safety, acceleration and curvature limits were also implemented in the VMM SW. Functional design of a minimum risk maneuver concept was also carried out and the selected concept was agreed between NVIDIA and Volvo.
Within work package 6 we also developed motion estimator and applied extended information filter for 5 states:

- Variant of Extended Kalman Filter
- States – $[v_x,\ \dot{v}_x,\ \omega_z,\ \dot{\omega}_z,\ a_{y,bank}]$
- Kinematic measurement model supporting up to 5 axles
- Estimation at equivalent rear axle position
- Assumption: zero lateral velocity at equivalent rear axle

And used below measurements:

- Primary: $a_x$*, $a_y$, $\omega_z$, transmission output shaft speed, all available wheel speeds
    - These are used as measurements in the filter
- Secondary: Steering wheel angle, engine torque, gear, clutch open/closed, brake pressures, axle loads, ABS/ASR flags, axle lift status, axle steer angles, etc.
    - These are used to correct/adjust the measurements before being fed into the filter and to adjust the filter parameters

* Really $\dot{v}_x$ as sent on CAN

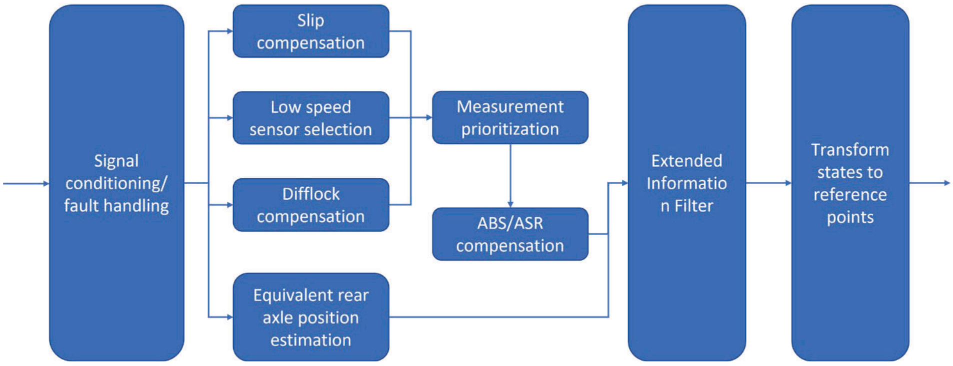


Figure 33 Estimation Structure

### 6.8.2 Safety driver concept

The Safety Driver solution in TranzPORT covers the use-cases of testing on test track as well as initial public road testing on a small scale. Its main purpose therefore is to enable testing of autonomous driving software while ensuring controllability to the safety driver, who is ultimately responsible for the safety of the vehicle combination. The autonomous driving software used in the tests has not been fully verified (due to that the project closed pre-maturely) as this requires testing in real traffic situations.
The concept consists of procedures for system engagement, disengagement (either forcefully by the safety driver in case of malfunction, or if the AD system gives up control due to performance limitations or insufficient situational awareness), and HMI components for displaying the status of the system and/or warnings to the safety driver.
For operation on public road, the safety driver is ultimately responsible for a safe vehicle. The safety driver concept needs to support this by fulfilling a number of basic safety goals. These were originally derived based on work done in other projects, but a dedicated TranzPORT risk analysis was performed. They limit the operational capabilities of the autonomous driving system to ensure that even in case of malfunction, the vehicle combination remains controllable to the safety driver and other traffic participants.
The following Figure 34 describes the workflow: A first version of this concept was defined and afterwards evaluated that an implementation according to this concept results in safety during the testing. If not, new or updated requirements are defined as input into the concept, and the process repeats.

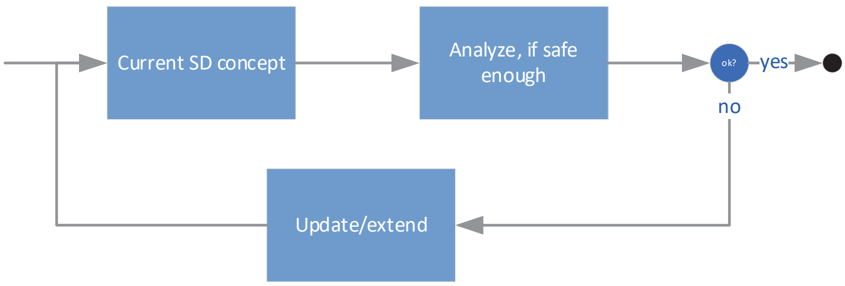


Figure 34 Overview of the way of working regarding the safety goals

#### 6.8.2.1 Overview of the solution

A simplified system view is shown in Figure 35. The complete autonomous system developed is contained in the right dashed box. The main purpose of the supporting processes on the left is to ensure safety between the vehicle and the surrounding traffic situation, by monitoring of the situation by the safety driver.

The shown off-board system is not a necessity and could be available at a later development phase. Its task of creating and distributing missions to a fleet of vehicles can be replaced in an early development phase by mission creation in the autonomous driving system or its equivalent replacement. Both alternatives are mentioned, as the full autonomous driving system might not be available for all tests. Yet, the safety driver concept needs to support all testing, even with early or even mocked versions of the AD system.
All interactions between the AD system and the base vehicle are routed via an interface node, which in a later stage of development may become part of the base vehicle itself. The emergency off button, which might not only be actuated by the safety driver, but also by another operator in the cab, at the very least needs to inhibit the communication via the interface node, e.g. by removing power. The other means of interventions shown in the diagram go through standard manual controls. These interactions are also routed to the interface node, to enable appropriate action.

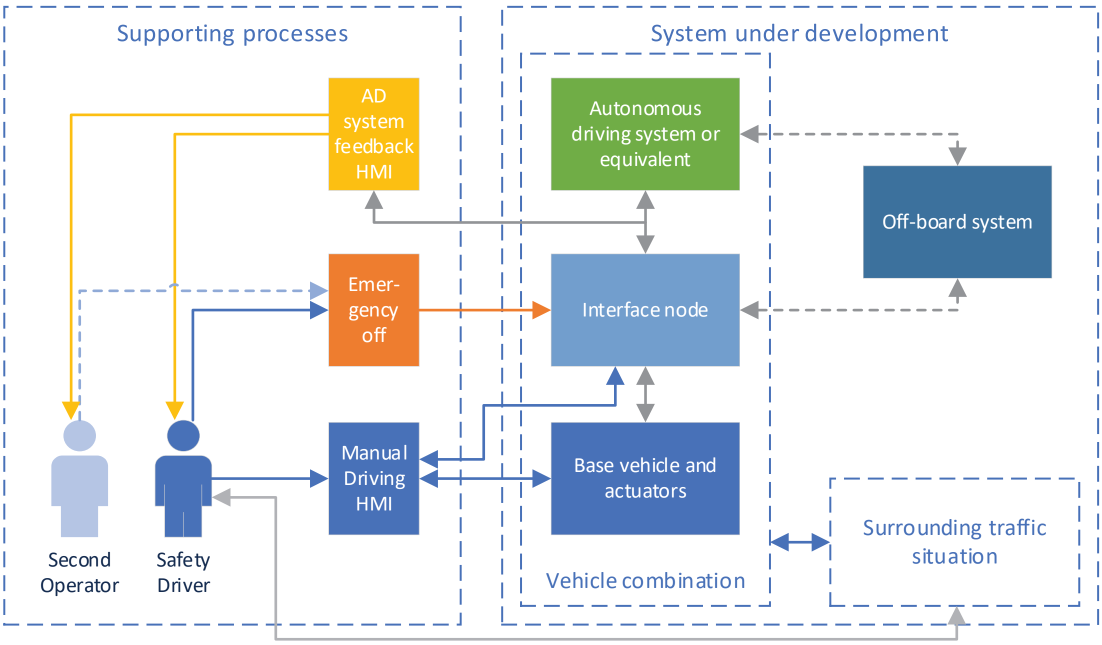



Figure 35 Simplified system component overview

The feedback HMI (yellow) is an addon display solely listening on the communication bus between interface node and autonomous driving system providing simple feedback. Additionally, the standard HMI available in the truck may be used for visual or auditory feedback. Teleoperation, while part of the final product to be developed, is excluded from the system view and this safety driver concept developed within TranzPORT.

## 6.9 Work package V7 Perception

For environment perception sensor technologies has been evaluated and a suitable sensor set has been developed for the scope of TranzPORT.

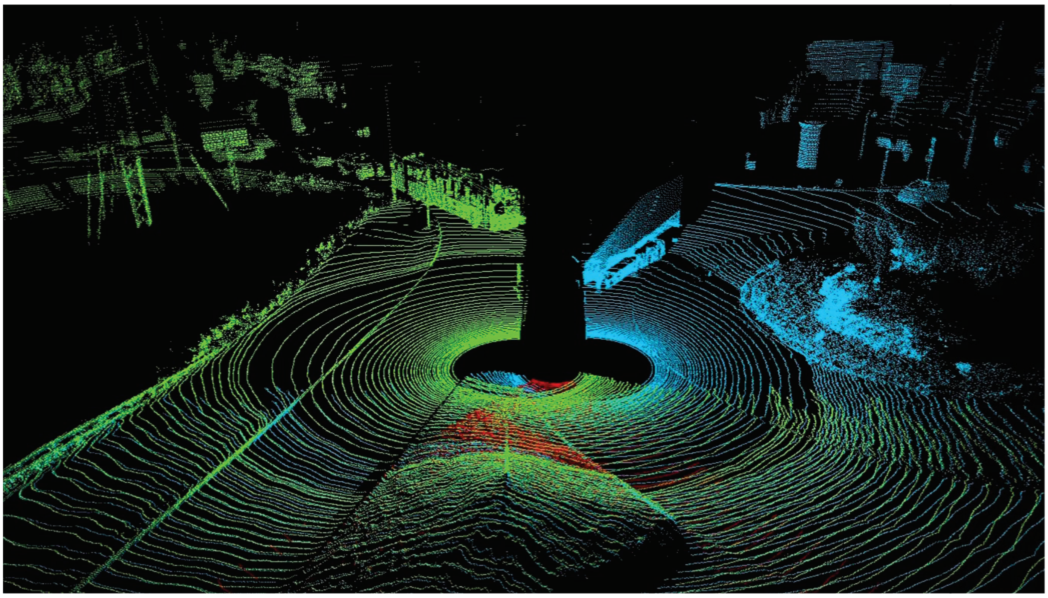


Figure 36 Perception using Lidar technology

### 6.9.1 The Latest Sensor Technology for L4 applications

The state of the latest sensor technology gives rise to optimism about the feasibility of bringing L4 autonomy to CV applications:

- **Communication technology is evolving to meet the requirements of L4 vehicles**
  New communication technology flavors are being developed and standardization work suitable for the automotive industry is ongoing. The goal is to increase the bandwidth to allow robust transmission of more sensor data in the demanding vehicle environment. High bandwidth communication technologies suitable for automotive use is thus required, and the report includes a primer on CAN, Ethernet and SerDes technologies.

- **There are safety standards that support the development of safe L4 vehicles**
  Safety standards applicable to public road applications, e.g. ISO 26262 and ISO 21448. The ISO 13849-1 safety standard is applicable for confined area applications. The standards provide guidance but are not fully mature yet. Work to improve the standards is ongoing within the automotive industry to further tailor them towards autonomous vehicles.

- **Sensor technology is developing rapidly**
  Fuelled by opportunities for ADAS and L4 applications, substantial investments are done annually in the sensor technology sector. The number of companies that develops sensors are growing steadily. New and improved models are brought to the market in a fast pace.

The sensor modalities evaluated includes both passive sensors, e.g. camera, GPS and IMU, as well as active modalities like Radar and Lidar. Some particular findings from the practical evaluations are included. Sensor's modalities have been compared, and conclusions are drawn.

- **Electromagnetic waves are the dominating physical phenomena utilized in sensing, but not the only one**
  The sensor modalities mainly perform measurements based on electromagnetic waves to supply information about the surroundings or ego-position. The main exception is the IMU modality, which rather measures acceleration caused by mechanical force and rotational rate. UltraSound Sensors (USS) use sound waves to perform distance measurements. USS is not covered by this report since it has not been used much for CVs. This may change going forward since some key players have started developing CV/machine versions of their passenger car USS solutions. In general, having sensors that makes measurement based on different physical phenomena increases the variety of input information to the perception software. If this information can be fused without causing confusion, chances are better to develop a successful L4 application.

- **Sensor modalities complement each other to deliver strong combined performance**
  Each sensor modality has strengths and weaknesses. No single modality is strong enough to solely deliver performance enough for autonomous driving, but they complement each other well. For example, a Lidar works well in darkness which is not the case for an RGB camera. On the contrary, an RGB camera enables interpretation of traffic signs where the Lidar is weak.

- **The sensor cost of an autonomous vehicle is a significant but manageable**
  Although the total cost of the sensors in a L4 vehicle is high, there is still a business case for autonomous driving since the cost of the human driver is removed. In addition, future CVs may no longer need a CAB, which will reduce the cost of the autonomous vehicle.

Finally, the overall conclusion based on current knowledge in the TranzPORT project is that the sensor technology has reached a level that seems to enable L4 applications for CVs. Although details on necessary range and resolution still needs to be refined, the outlook seems favorable and given the variety of sensor modalities available the combined performance seems good enough. Furthermore, the components are available on the market and the cost is acceptable. Having stated this, there are still some limitations worth mentioning. L4 autonomy generally means self-driving without human intervention within a geofenced area. Not all areas are suitable for self-driving with the sensors of today. For example, in extremely cold areas the current sensors do not perform very well. Similarly, in extreme weather conditions only the radar would deliver reasonable performance and relying on a single modality would not be safe. But in most geometric areas and environmental conditions, the current sensor technology does not seem to be a limitation for L4 autonomy. Naturally, a successful L4 vehicle also needs potent software solutions for interpreting the world around the vehicle based on the sensor data, planning how to drive, and controlling the actuators. All this needs to be achieved through redundant solutions to fulfil the safety requirements on the vehicle. And finally, perhaps the hardest challenge of them all is to verify and validate that the behavior of the vehicle is safe in public traffic where anything can happen. Thus, having sensors that seems to be good enough is an important step but only the first one along the road towards L4 applications!

## 6.9.2 Sensor set-up

A sensor setup defines what sensors are needed and where they are installed on the truck. The sensor set-up is also considering the synergies of using collected data from other vehicle type to allow for a greater coverage of driving scenarios.

### 6.9.2.1 Operating Design Domain (ODD)

The ODD defines the conditions for when the autonomous operation shall operate. It describes EGO vehicle, environment conditions, drivable area, static and dynamic/temporary obstacles.

### 6.9.2.2 Safety zones

Safety Zones are derived from Safety Goals. Modeling assumptions are derived from Operating Design Domain. Each safety zone is a 2D polygon derived from analyzing and modeling specific scenarios in the ODD. Parameters (speed, acceleration, timing, geometries, etc) are defined for each scenario.

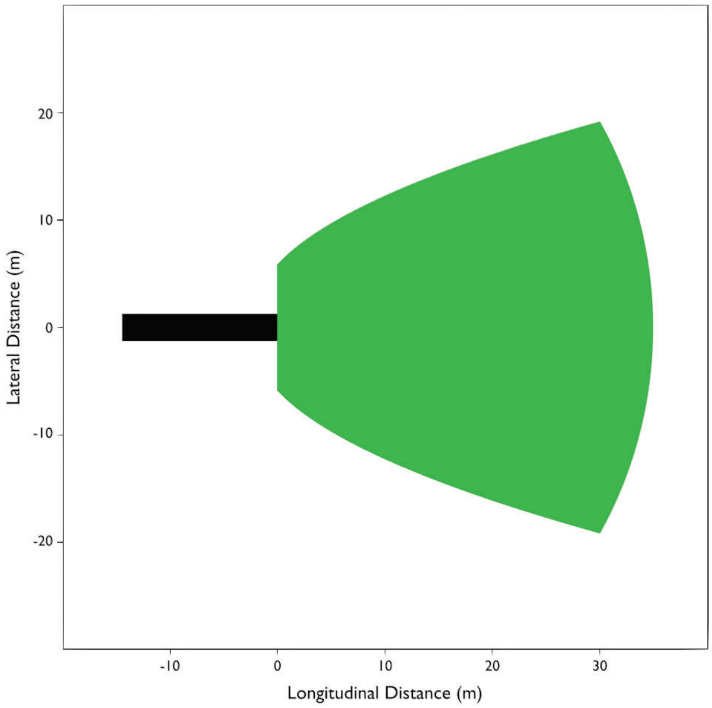



Figure 37 Safety Zone illustration

### 6.9.2.3 Truck sensor set-up

This section describes the sensor setup and sensor placement for FH-tractor-trailer combination. The perception sensor set combines both passive and active sensors for detection of objects, mapping, localization, and overall perception of the vehicle's surroundings. The sensor set includes cameras, radars, and lidars, as well as IMUs and

GNSS for vehicle position and odometry sensing. Sensor placement on left and right side of the vehicle are symmetrical. Each sensor modality is installed to cover the areas around the truck defined by safety zones. The short-range sensors are mounted around the tractor to provide an optimal coverage. The sensor setup is depending a lot on Field of View (FoV) and range required. For long range perception a high-resolution sensor with a narrower FoV must be used. For a wide coverage, high resolution sensors with wide FoV must be used, possibly overlapping long range sensors. Having several sensors and sensor modalities monitor the same area significantly decrease the risk of not correctly detect and classify a target or feature.

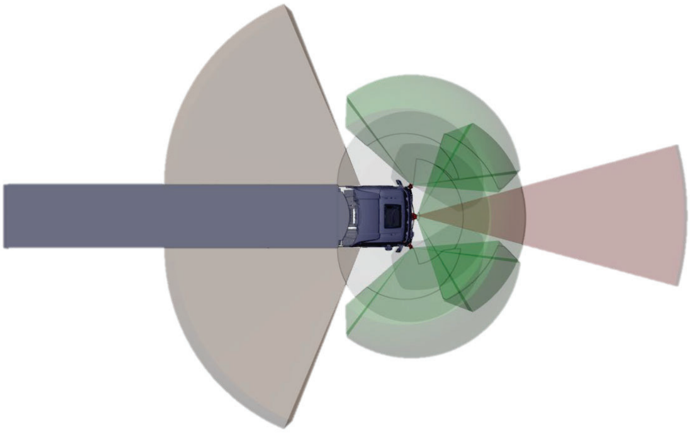


Figure 38 Camera Field of View

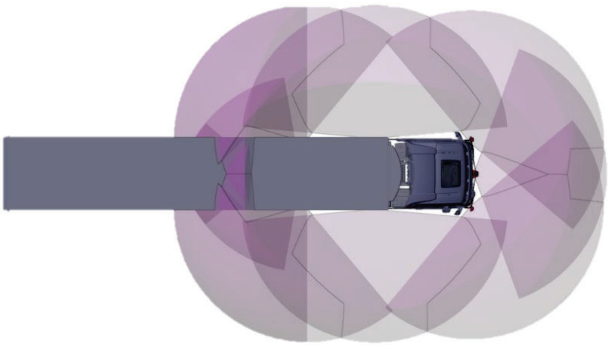


Figure 39 Radar Field of View

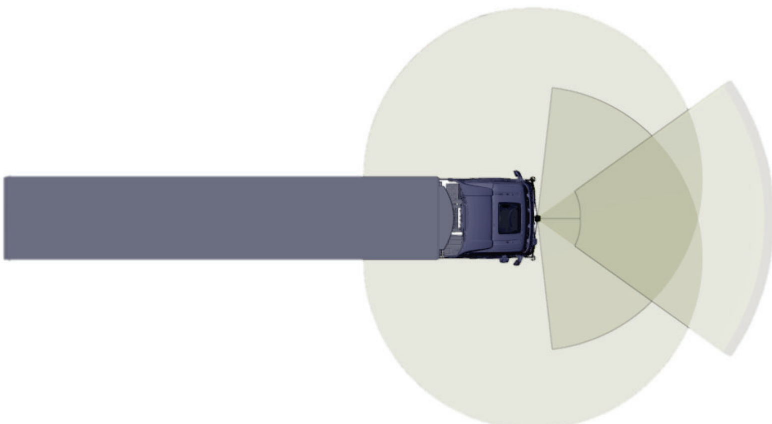


Figure 40 Lidar Field of View

# 6.10 Work package V8 Product safety

The overall goal of work package V8 is to develop an argumentation to show that an Autonomous Transport Solution (ATS) is safe. The work package has mainly investigated the following questions:

- Compared to an ISO 26262 Hazard Analysis and Risk Assessment (HARA), is there a need for additional risk assessments for an ATS and the autonomous vehicles?
- What are the applicable regulations for an autonomous vehicle compared to a manually driven vehicle?

Main achievements in this work package are the development of:

- A holistic safety approach to cover risks in all elements of an ATS.
- A safety process which integrates a safety strategy for mitigating risks for the ATS.
- An approach to ensure safety during development of an ATS which also considers a safety driver. As part of this, we submitted a complete application for trail operations on public roads with autonomous vehicles
- An approach for defining what can be considered as acceptable risk. (This is described as part of work package V13, but also applicable for V8.)
- An overview of the regulatory landscape in Sweden and EU for ATS based on road vehicles.
- An approach for applications of test permits from the Swedish Transport Agency for autonomous road vehicles.
- An approach for work split of fulfilling workplace regulations between developer of the ATS and the operator of the ATS.

## 6.10.1 Risk assessments for an autonomous transport solution

Figure 41 shows an overview of the different elements of an ATS. In addition to the autonomously enabled truck and the virtual driver controlling the truck, an ATS also includes elements such as off-board systems (Cloud), physical infrastructure, operations and service and maintenance. There is no single safety standard that cover autonomous vehicles and a complete ATS, and the approach in TranzPORT is to combine and use concepts from different safety standards to ensure that risks for the complete ATS are handled.

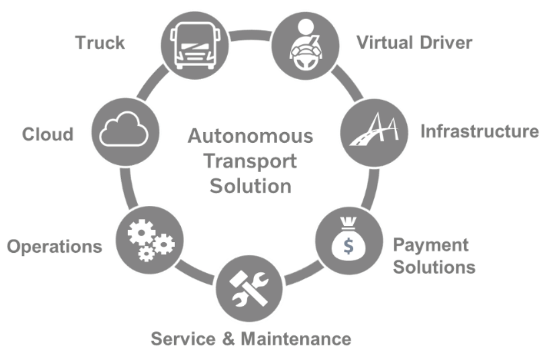



Figure 41 Elements of an Autonomous Transport Solution.

Figure 42 shows an overview of a safety process for the development of an ATS. The starting point is the definition of the transport solution, which is also the input to the risk analysis for the complete transport solution where risks are identified and estimated. For this work, the ISO 26262 HARA is not suitable as it focuses on hazards caused by malfunctioning behavior of E/E systems in a vehicle, and it will not identify all hazards applicable for an autonomous transport solution. Furthermore, many risk mitigations for an ATS may be realized using measures which are not in scope of ISO 26262.

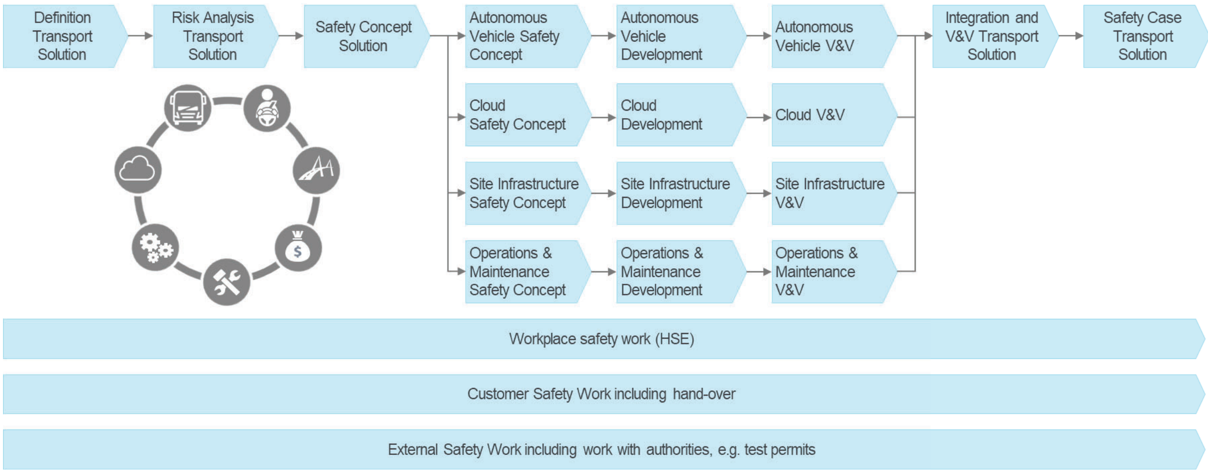



Figure 42 Overall safety process for an Automated Transport Solution.

We have defined an approach for doing risk assessment of an ATS. The risk analysis considers the different phases of the transport solution, e.g., operation and maintenance, and relevant hazards and situations for these phases are identified and evaluated to identify risks which needs to be mitigated. A risk mitigation is then defined, referred to as a high-level safety strategy, and allocated to the corresponding domains such as infrastructure, autonomous vehicle, or operations. A required downstream analysis is also identified, where the identified risks and risk mitigations are further analyzed. One example of a downstream analysis is the ISO 26262 HARA for risks which are addressed using systems in the autonomous truck. Another example of a downstream analysis is a dedicated risk analysis for testing during development where a safety driver can be considered as a possible risk mitigation, compared to the HARA which does not consider any persons in the truck, and where the health and safety of the safety driver is also considered.

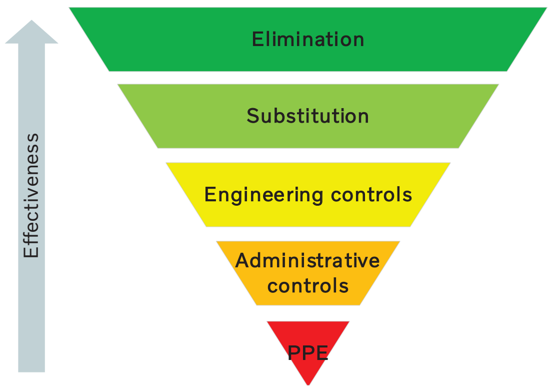



Figure 43 Hierarchy of controls

A hierarchy of controls are used to mitigate risks for the ATS, see Figure 43. Control methods in the top in the figure are more effective than the control methods in the bottom. Based on this approach, hazards can be controlled using:

- *Elimination* – Removal of the hazard at the source. This is the most efficient method of control but can also be the most difficult to implement. One example is to avoid specific traffic situations by selecting a different route.
- *Substitution* – Replacement of the hazard. For example, changing an uncontrolled traffic intersection to a traffic light-controlled intersection.
- *Engineering controls* – Isolate people from the hazard. In Pilot A, engineering controls mainly correspond to systems that are included in the autonomous vehicles.
- *Administrative controls* – Change the way people work. One example of an administrative control is training, which can be a potential measure for hazards which are related to the part of Pilot A that includes workplaces. However, this type of controls is difficult to implement for hazards on the public part of the route.
- *PPE* – Protect persons using Personal Protective Equipment. This is the least effective way to control hazards, and in a Pilot A context, also difficult to implement as vehicles will run on a public route.

### 6.10.2 Ensuring safety during trial operations

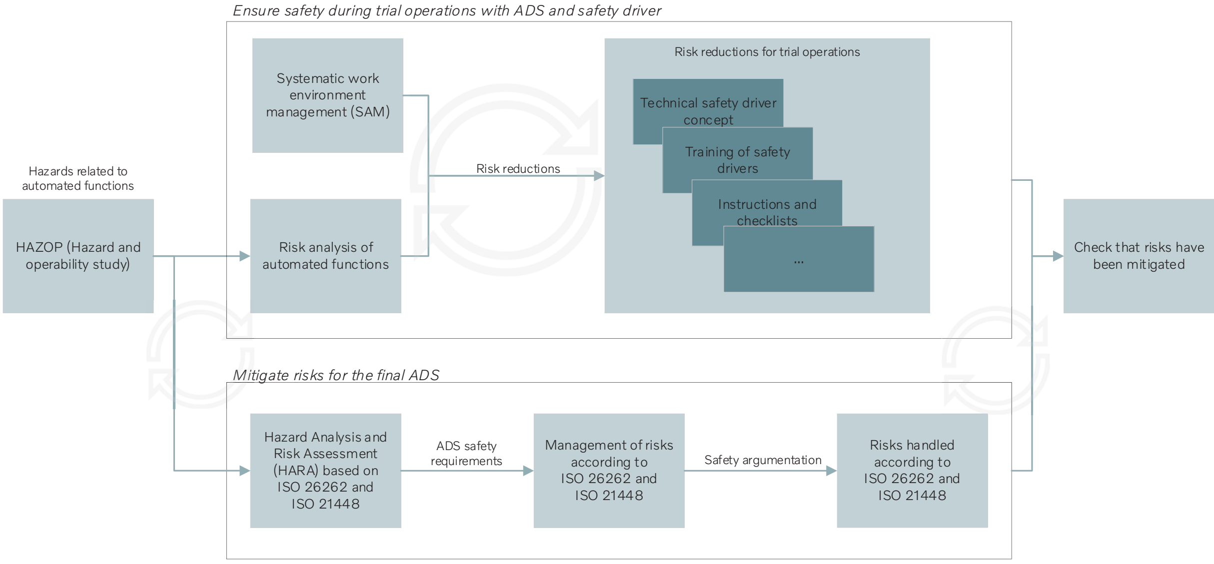



Figure 44 Overview of risk mitigation for trial operations and for the final ADS.

Figure 44 shows an overview of how risks are identified and mitigated for the autonomous truck, specifically the automated functions provided by the ADS. Prior to having a complete safety case for the final ADS, it is necessary to test the ADS on public roads during development, e.g., for data collection and validation activities. This is illustrated in the figure, where the upper part is applicable for trial operations, i.e., testing done with a dedicated safety driver in the truck, and the lower part focuses on the final ADS, i.e., having an automated truck without a safety driver. Risk assessment is an iterative process, and risk assessments needs to be updated if new risks are identified or if the maturity of the system changes. For example, if a risk is fully handled by the lower part of the figure, this is fed back to the risk assessments in the upper part of the figure.

The safety work for the trial operations includes two separate but complementary risk analyses. One of the analyses is a risk assessment that is done as part of the work for Systematic Work Environment Management (SAM). This risk assessment considers the safety driver's working environment and includes, e.g., risks related to the safety driver not being attentive or being distracted by other tasks. The SAM risk analysis is complemented with a risk assessment for the automated functions. The objective is to systematically identify and manage hazards related to the ADS and its automated functions. Hazards for the automated functions are identified using a HAZOP (Hazard and operability study), which is also the basis for the HARA that is done for functional safety (ISO 26262) and SOTIF (ISO 21448).

Throughout the development and operation of the ATS, different types of risk analyses need to be coordinated, and risks also needs to be communicated between the involved partners. For example, a risk that is identified by a port operator needs to be communicated to the operator of the ATS to ensure that all risks are handled. Similar, risks applicable for the port operator need to be communicated by the ATS operator.

### 6.10.3 Regulations for autonomous driving on public roads

Current regulations for type approval of road vehicles does not fully allow autonomous road vehicles. To handle this, the Swedish Transport Agency (Transportstyrelsen) provides a national regulation allowing testing of autonomous road vehicles (TSFS 2021:4), like many other European countries. This Swedish regulation is applicable for testing in areas that are not seen as confined. However, there is no clear definition of what a confined area is. For this project and the driving route, it was determined that the harbor areas are not confined areas in this sense and hence a test permit is needed for the complete route. The main reasons behind this decision were that there are manually operated vehicles with normal truck drivers in the harbor area. These truck drivers have limited training to the harbor area.

During the project, a test permit application was submitted to the Swedish Transport Agency according to TSFS 2021:4. It was extensive work behind this application. But, as the documents submitted for the application was needed for other reasons, this work was straight forward. Even if the test permit application was not completely handled by the authority, there was a feedback session on the application. The main advantages raised during this session was the clear structure, good content, and completeness of the documentation. In particular, it was mentioned that it was clear that the application was not a standalone work, but as a highly integrated part of the project, which was highly appreciated. The main outcome of this work is a structured approach for how test permit applications for autonomous road vehicles can be done, in particular for Sweden.

In addition to the regulations for road vehicles, there are applicable regulations from the Swedish Work Environment Authority (Arbetsmiljöverket). For this development, the main regulations are for Systematic Work Environment Management called SAM, (AFS 2001:1) and for Use of Work Equipment (AFS 2006:4). The SAM work is part of all partners normal work to ensure safety of employees.

Regarding the SAM-work prescribed by AFS 2001:1, the main activities in this project were related to risk analysis for test engineers and other roles. The risk analysis (see Section 6.10.2) identified risks where risk reduction measures were reduced to acceptable levels, e.g. by instructions and routines for operators incl. safety drivers. In addition, there were many good discussions with the partners in the harbor areas. It was clear that these partners also worked with SAM and would do risk analysis related to the change of replacing some manual transports with autonomous transports in their workplaces. The main result here was a safe working environment for the test engineers resulting from the SAM work within Volvo Autonomous Solutions. In addition, the main learning was that the existing way of working for SAM does not need to change due to the introduction of autonomous road vehicles and the responsibility split works well across partners in a partnership such as in this project. One smaller modification was done related to the risk analysis classification where controllability of test engineers working as safety drivers was introduced, in a similar way as described in the ISO 26262 standard.

Regarding the regulation for work equipment prescribed in AFS 2006:4, there are two main aspects to consider. The first aspect is related to the work equipment as such, i.e. product requirements. For this aspect, it was mostly Volvo Autonomous Solutions that had the responsibility to fulfill the regulatory requirements. The second aspect is connected to the use of the work equipment, i.e. operational requirements. These requirements were a shared responsibility of all project partners to fulfill. In the area of the product requirements, there were work needed to be done. The reason is that AFS 2006:4 treats work equipment that has been developed according to an EU directive, e.g. machinery and type approved road vehicles, differently compared to work equipment for which there are no EU directive. As there are uncertainties in the area of autonomous road vehicles and EU directives, it was determined to investigate AFS 2006:4 in this project with good learnings.

# 6.11 Work package V9 Virtual control tower and communication

## 6.11.1 Cloud

As part of work package 9, we developed a Cloud software dedicated to route and activity planning. The software allows for (1) scheduling and (2) transmission of one or multiple missions (i.e., instruction given to a vehicle) to the vehicle's virtual driver, as described in Figure 45:

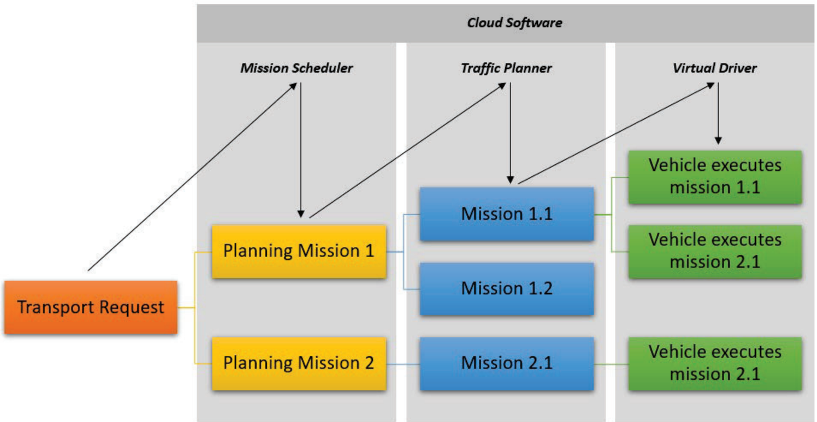



Figure 45 Autonomous Cloud software structure from Transport Request to mission execution.

The Transport Requests -a tangible transportation order between two defined spatial points- is received and processed in the Autonomous Cloud software. The Transport Request (or Work Order) is translated into multiple "planning missions" (e.g. "*send vehicle 1 from loading point A to unloading point B*"). The "mission Scheduler" will then schedule the different Planning Missions into a timeframe, based on vehicle availability. Those missions are then processed in the "traffic planner" to get a list of missions which can be executed by the fleet of autonomous vehicles, through their virtual drivers. Examples of missions can be "go to charging station", or "load on position X". An otherwise of the architecture of the Cloud Software we developed can be found below in Figure 46:

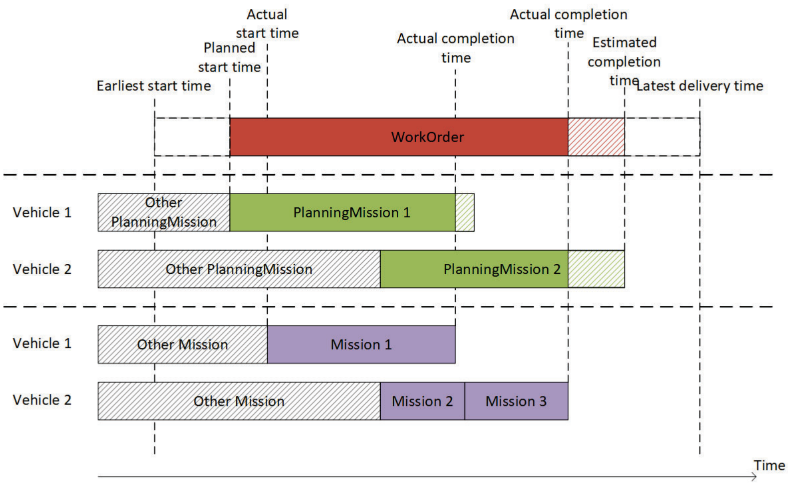



Figure 46 Autonomous Cloud Software high level architecture.

This Autonomous Cloud software was developed to also ensure a **virtual representation** of the autonomous vehicle fleet, made available in the Control Tower for site operators. Information such as (1) movement of autonomous vehicles on the roads; (2) fulfilment of the customer's Transport Request and (3) vehicle diagnostic information such as battery and charging status or speed profile could thus be available on a map to the site operators. Regarding static optimization of the transport system, please refer to chapter 6.4.2.

## 6.11.2 Dynamic fleet mission planning

Chalmers have conducted research in the following areas:

- Parameter estimation (mass, road slope) using neural networks[3]
- Dynamic fleet mission planning algorithms (using an interpretable approach)[4]

### 6.11.2.1 Parameter estimation

Here, a new and more accurate method for estimating vehicle parameters, such as mass and road inclination, was developed. The method differs from traditional, sensor or model-based ones, mainly in the sense that it uses a neural network for estimation. In particular, the sensor-based methods performs badly when high quality position estimates are not available. This situation might occur when e.g. the GNSS system cannot give an accurate position or no accurate maps are available for localization. The latter situation naturally holds for underground sites. The model-based approaches typically use recursive least squares (RLS) with Kalman filtering, which requires persistent excitation of the signals, e.g. engine torque. Our approach is to estimate mass and road inclination using feedforward neural networks (FFNNs), as shown in Figure 47. The results show a better accuracy compared to model-based methods, which (at best) achieve around 0.20 degrees RMS error for road grade, compared to 0.10-0.14 degrees in our case and around 0.02 (2%) RMS error for mass compared to around 0.01 (1%) in our case.

[3] Torabi, M, Wahde, M., and Hartono, P. Road Grade and Vehicle Mass Estimation for Heavy-duty Vehicles Using Feedforward Neural Networks, In: The 4 th international conference on Intelligent Transportation Engineering, pp. 316-321, 2019

[4] Wahde, M., Bellone, M., and Torabi, S:
A method for real-time dynamic fleet mission planning for autonomous mining, Autonomous Agents and Multi-Agent Systems, 33(5), pp. 564-590, 2019

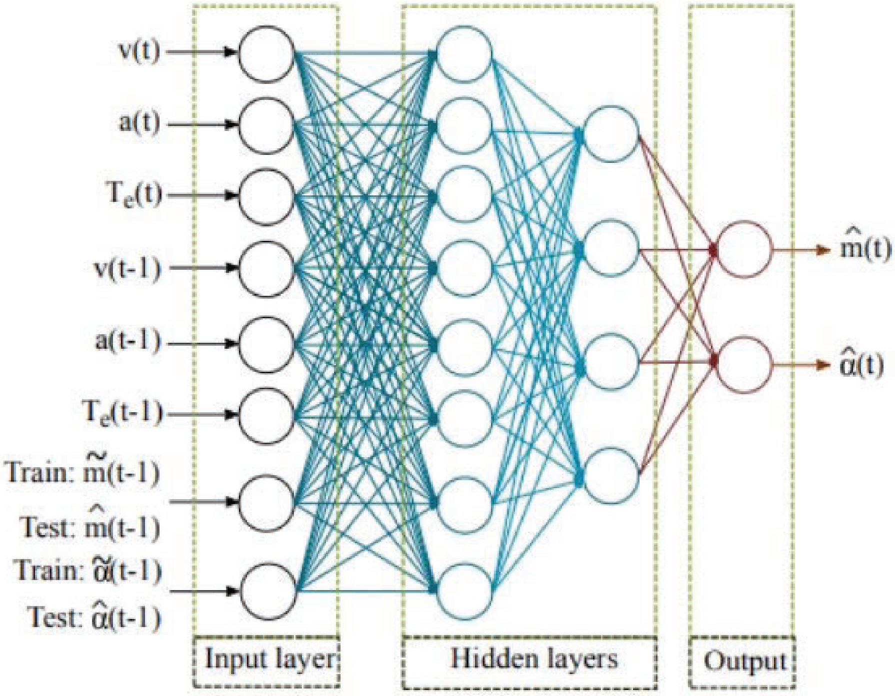



Figure 47 A schematic illustration of the fully connected feedforward neural network (FFNN) for estimating the vehicle’s mass and the road grade. The input consists of the velocity, acceleration, and engine torque at the current time step, along with their lagged realizations.

### 6.11.2.2 Dynamic fleet mission planning

Chalmers have developed a dynamic fleet mission planning algorithm that uses an interpretable approach. The algorithm dynamically generates collision-free trajectories (path and timing) for a set of vehicles operating together in an arena. Planning is conducted in a topological representation of the map, as shown in Figure 48. The dynamic fleet mission planning has the following features:

- By construction, all moving vehicles are always on collision-free trajectories.
- Vehicles at terminals (loading, offloading) request re-entry into the map, whereupon a collision-free trajectory is generated (if possible); see next slide.
- The optimizer maintains a queue (sometimes empty) of vehicles waiting for re-entry into the map.
- It also keeps track of causality, making sure that any trajectory changes only affect future times (relative to the time when the optimizer has finished its work).

The developed optimization method can, with relatively small changes, be adapted to a wide selection of transport problems. It also scales well when the number of vehicles is increased, measured by the number of completed missions per vehicle. In all, our research suggests the method to be highly applicable in many real-world cases.

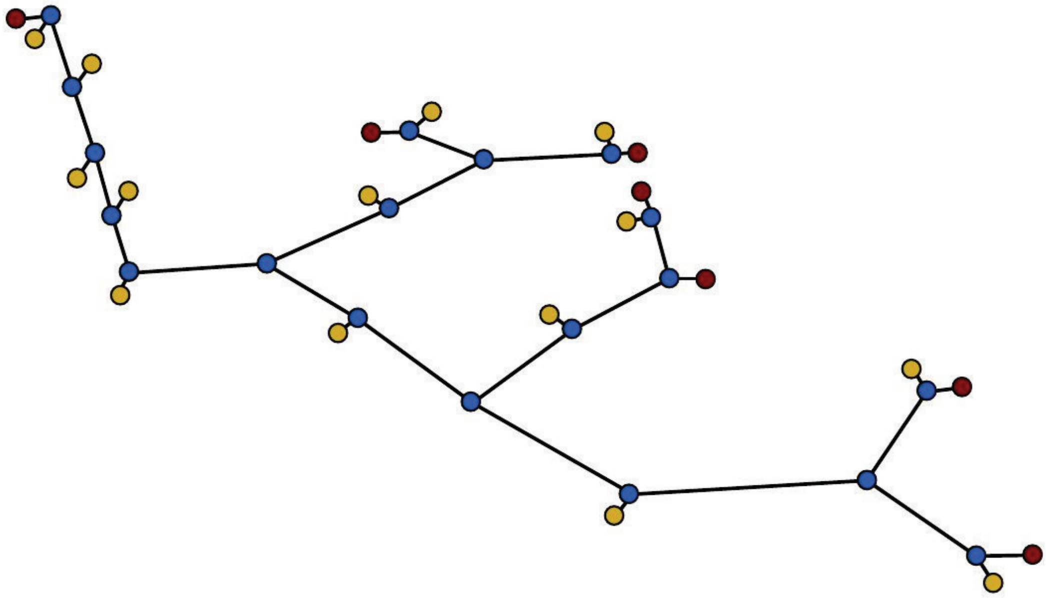


Figure 48 Topological representation of route used for dynamic planning. The red node in the upper left corner is the (prioritized) offloading site, and the remaining red nodes are the loading sites. All these nodes are collectively referred to as terminal nodes. All other nodes are either transit nodes (shown in blue), i.e. nodes at which a vehicle has a choice between two or more different future paths, or pause nodes (shown in yellow) where a vehicle can stop temporarily in order to let another vehicle pass. The vertical part in the left side of the map represents a steep, spiraling corridor leading down to the mining level, where several branches lead to the various loading sites.

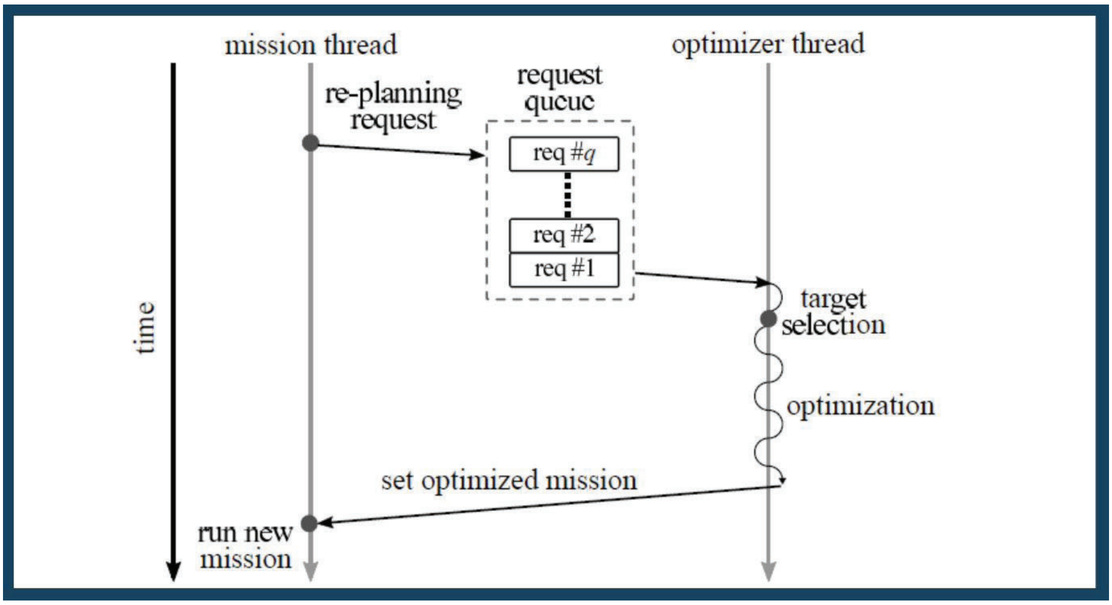



Figure 49 Representation of threads during dynamic fleet mission planning. The mission thread handles the real-time movement of each vehicle. Every time a vehicle emits a re-planning request, a signal is sent to the fleet optimizer to generate a new (static) fleet mission that will replace the current one (if the planning is successful).

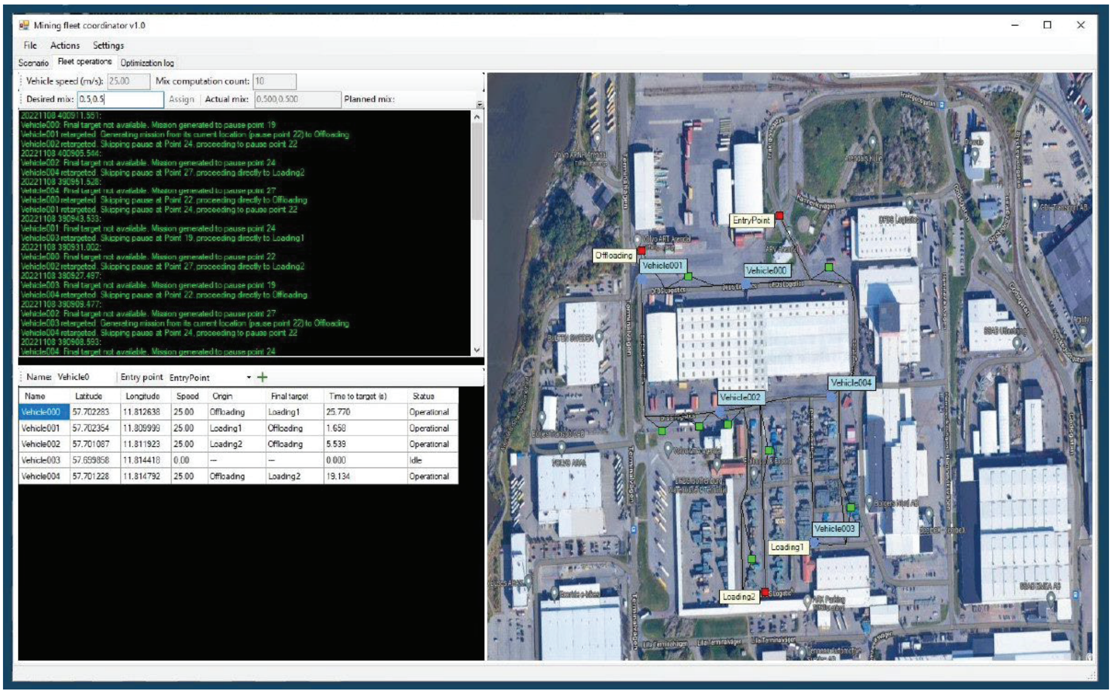



Figure 50 The simulation and visualization program showing optimization for the harbor route.

## 6.12 Work package V10 Test, verification, and validation

V10 has so far elaborated and agreed upon a V&V strategy with one of the partners of the project. Said strategy is the basis for the milestone named “M10.2: Preparation of methodology for V&V of for example safety/security of V2X between control tower and vehicle and for external HMI to other users of the road” and to elaborate the scenarios relevant to the milestone “M10.1: Preparation of relevant scenarios for public road”. The strategy outlines as well how the item delivered by the partner is to be tested as a safety element out of context and then how it shall be integrated with the rest of the system.

Verification and Validation of the system happened in several phases from Volvo and Nvidia wherein Volvo supported Nvidia for all the Base Vehicle related verification needs like tuning, calibration, and reporting gaps in Safety driver concept adaptation in AVCM according to the AD needs all the infrastructure support in Gothenburg at Säve and in California at Gomentum in the US. Nvidia took care of the verification of their AD HW and SW – Road runner, mapping & tagging of the test area and vehicle controls adaptation through the Safety driver implementation in AVCM.

**Volvo’s part:**

- AVCM (Automated Vehicle Control Module) HW
- Safety driver concept implementation Verification and Validation for each of the releases reporting bugs and improvements
- Safety driver (Test Engineer) to support with any Base vehicle (EV1&EV2- FH Trucks) baseline SW updates, calibration and tuning

- Infrastructure for testing – test track replicating the actual implementation site that includes lane markings, traffic lights & signs, barriers, test equipment like Balloon cars, dummies, tools like CANcase,etc
- Provided development support for the AD SW from Vehicle dynamics perspective
- Test track booking in Sweden and the US

**Nvidia's part:**

- Resource support for testing AD capabilities in the US and Sweden
- Providing the requirements for the test infrastructure
- Improving the stability of the system

### 6.12.1 Verification & Validation tools and Methodologies

The Verification and Validation of the whole system (AD and Base Vehicle) has been generally done in the Trucks (EV1 & EV2) twice or thrice every week where the Nvidia's AD SW releases were integrated with the VMM releases from Volvo.
Calibration and tuning of Nvidia's SW done in the weekly testing at Säve test track. Volvo supported Nvidia for these activities by providing test engineer who could support with all the Base vehicle SW and HW updates and with driving the truck as a Safety driver during the autonomous testing operations.

**Methodologies:**

- Hardware in Loop – dSPACE
- Vehicle Testing at Säve and Gomentum test tracks

**Tools:**

- CANoe/CANalyzer for CAN network monitoring and diagnostics
- Road Runner from Nvidia

#### 6.12.1.1 Data collection

We also had specific trucks for Data collection from the actual site area so that it can be analyzed and used for the development of Perception system and the AD software from Nvidia.

Below are pictures showing the automated vehicles used, implementation site and Säve Test track blueprint

Figure 51 EV1 test vehicle


Figure 52 Implementation site

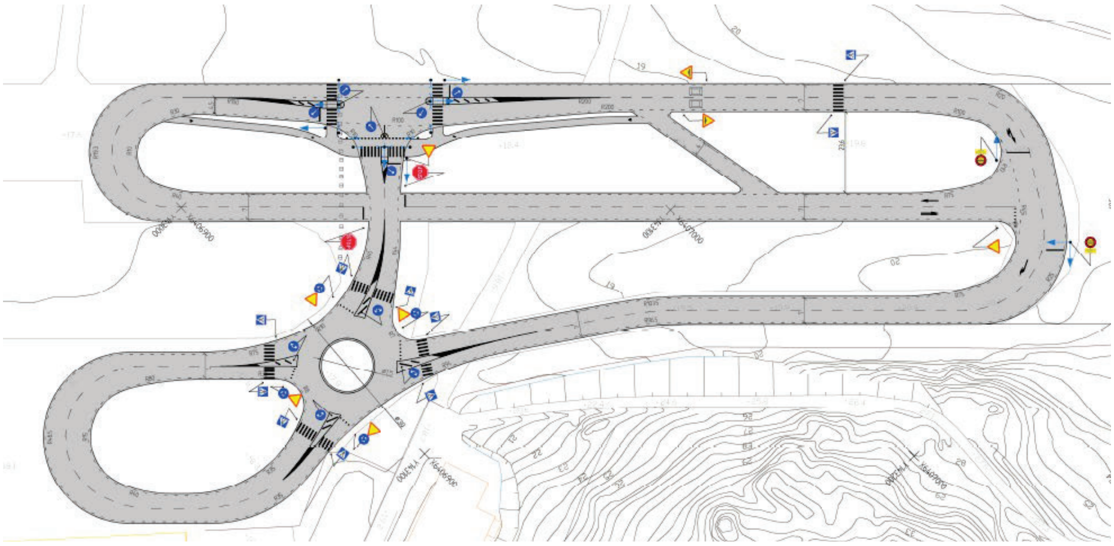


Figure 53 Säve test track layout

#### 6.12.1.2 Safety Driver concept SW testing

The Safety driver concept implemented by Volvo is primarily to provide Safety to the Vehicle and the backup driver if there is any malfunction in the AD system. AD would be overridden by this SW implementation in AVCM/VMM from Volvo. This SW is tested in the HIL setup and in the Vehicles EV1&2 in the test tracks at Säve and Gomentum. It has been tested by failure injections through CAN, Emulating AD I/O through CAN, explorative vehicle testing, etc. Driver interventions through Steering wheel take over, accelerator take over, seatbelt removal and door open to verify & validate AD to Safety driver system hand over.

#### 6.12.1.3 Progress in the activities until project closure

Verification and Validation activities happened for every AVCM SW releases from Volvo and AD SW release from Nvidia including their integration tests. Regression and Integration tests has been performed on all the releases. It has been completed to the stage where we had a stable AD & AVCM SWs to run on the site area without any unexpected halts. A new test track had been prepared as mentioned earlier at Säve test track to exactly replicate the actual site and further Safety and performance tests were planned to be executed in the Stable system.

## 6.13 Work package V11 Adaptations of infrastructure

The work intended in this work package was finalized. The result is a public infrastructure facility ready for autonomous driving. Summary of the infrastructure adaptations:

- Speed bumps
- Signage
- Yield signs in all approaching driveways
- Speed limitation signs
- Bus stops to be reconstructed according to requirements. Bus will stop in lane
- Pedestrian crossing adapted to bus stop
- Fences to avoid unexpected pedestrian crossings
- Upgrade light source to provide 5 lux on road
- Improve lane markings
- Three traffic light-controlled intersections

For more information on the methodology used and more results of the work done, see result of work package H1 in chapter 6.1.3.

## 6.14 Work package V12 Digital infrastructure

Local communication is deemed critical to the autonomous driving of vehicles. Indeed, if connectivity between the vehicles and the Control Tower is lost, operations will stop. As such, adequate cellular coverage needs to be available in the area, to allow continuous connectivity for the autonomous operations. Additionally, latency needs to be kept at a minimum (circa 50 ms) (from the Control Tower to the autonomous vehicles and back). Stable network connectivity is also necessary, to avoid spikes in latency, which could disrupt operations.

To ensure that the area has good cellular coverage, Work Package 12 investigated the opportunities and challenges involved. The first step was to decipher the existing 4G coverage in the area (see Figure 54). This was done by measuring the signal strength by logging bandwidth while simulating traffic on the network. Six weaker areas were identified along the route, but it was determined that the available cellular network was still sufficient, since only single megabits per vehicle are required during autonomous operations. For teleoperation, higher bandwidth needs could be mitigated by tele-operating only one single vehicle at the time.

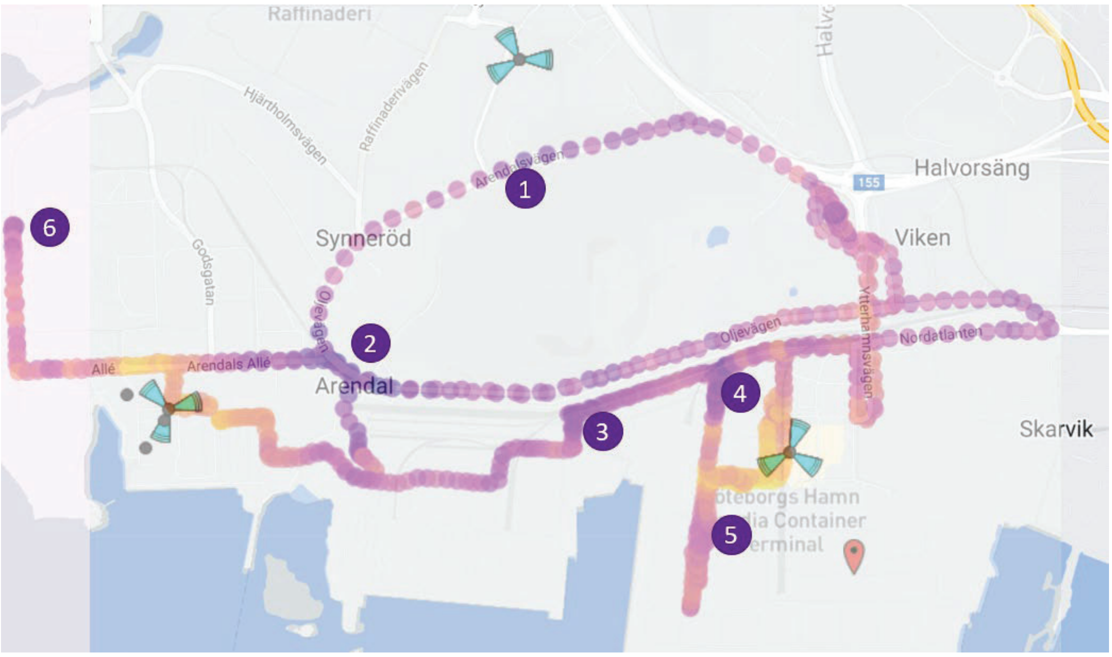


Figure 54 Signal from the public cellular network along the route (measured in dBm at frequency = 800 MHz). Label: Increasing signal from Purple (weaker) to Orange (stronger). The public 4G antennas are indicated in blue.

While discussions were initiated with network providers to investigate the possibility of creating a private 5G network, it was ultimately decided that using the existing public 4G network was sufficient. Creating a 5G network would be complex and expensive, with extended timelines. Additionally, the results of the 4G signal analysis showed that the existing public network was capable of meeting the network requirements for autonomous operation. However, from a cybersecurity perspective, an APN (Access Point Network) would be necessary, to provide an extra layer of protection to the encrypted traffic. The next step planned would be to test the network in "real" condition, with the decided-upon hardware (antennas, modems, APN Sim cards) on a vehicle of correct dimensions (especially, height). An overall cybersecurity assessment would also be required. In parallel, investigations were conducted to support autonomous vehicles interacting with manually driven vehicles in challenging scenarios. For instance, at one of the terminals, the route presents a scenario where 2 lanes merge into a single lane. To address this challenge, a solution based on short-range wireless communication (also known as V2X communication) was proposed. In this solution, the approaching autonomous vehicle would alert a smart road infrastructure using V2X communication, which would then engage a traffic sign to visually signal to the human-driver of the manual vehicle to give way to the autonomous vehicle.

## 6.15 Work package V13 Overall safety analysis

Work package V13 has addressed the following questions:

- How to define what can be considered acceptable risk?
- What risks are identified in the current route?
- How to use infrastructure adaptions as a mean for reducing risks?

In addition to the analyses supporting the infrastructure adaptions (see Work packages V11 and H1), a main achievement of this work package is a structured and holistic approach when reducing risks for a transport solution and autonomous vehicles. This approach considers infrastructure adaptions as well as systems in the truck when reducing a specific risk. Another achievement related to this work package is an approach for defining what can be considered acceptable risk for a specific route.

In general, risk is a function of severity of harm and the probability of occurrence of that harm. The probability of occurrence is further refined into:

- Exposure of something that can potentially cause harm.
- Occurrence of an event that can cause harm.
- Possibility to avoid or limit the harm, also referred to as controllability.

As described in work package V8, a hierarchy of controls are used to mitigate risks for the ATS. Figure 55 illustrates how a risk is reduced using the hierarchy of controls. The severity of harm and probability of occurrence is reduced to an acceptable level by using a combination of controls. Ideally, elimination by itself is used to reduce a risk but that is not always feasible for a public route, and a combination of substitution and engineering controls are instead needed. In areas which are not public, administrative controls and PPE can also be used in combination with the other controls

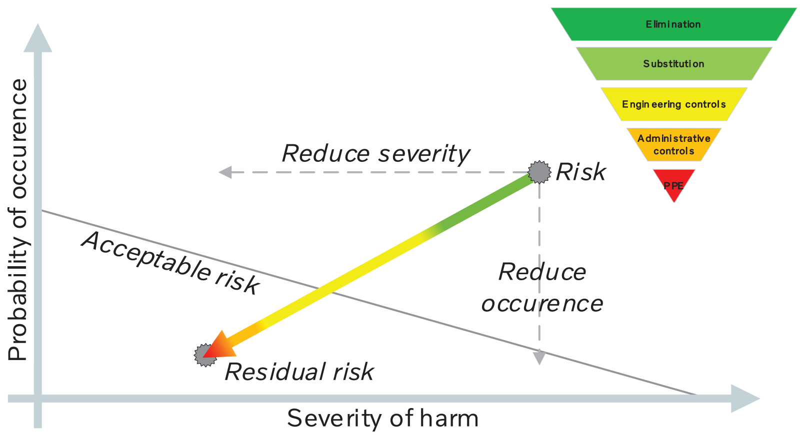



Figure 55 Risk reduction using the hierarchy of controls.

Infrastructure adaptions mainly corresponds to elimination and substitution for the route in TranzPORT. For an ATS operating in a confined environment, infrastructure adaptions can be used to implement engineering controls, e.g., by installing safety light curtains for preventing persons from accessing the autonomous trucks.

To define what can be considered as safe for an ATS and autonomous truck, i.e., what can be considered as acceptable risk, we have investigated a quantitative risk norm

(QRN). The premise is that a minimal requirement is that traffic safety shall not be negatively impacted by the introduction of autonomous vehicles.

A quantitative risk norm (QRN) for the ATS was calculated from accident statistics for human drivers using the following steps:

- Determine measures for severity.
- Determine a generalized description of the use-cases.
- Use the Swedish national database (STRADA) and count accidents in use-case generalization, grouped based on severity measure.
- Conduct an independent study with an independent team and sources of data to verify the results from the first steps.

### 6.15.1 Severity categories

The severity measure is based on ISS and grouped into four categories: *Fatal*, *Seriously injured*, *Moderately injured* and *Slightly injured*. One challenge is to transform the four categories of outcomes into severity classifications such as the ones used in ISO 26262, which are estimations of expected outcomes for some accident. For TranzPORT, we have used an initial conservative mapping.

### 6.15.2 Generalized use-case

The generalized use-case description with respect to accidents needs to consider the operational environment for the ATS. Examples of characteristics that were used for our work include:

- Accidents involving trucks (>3.5T)
- Speed limit of the roads <50km/h
- Relevant accident for the geographic location

### 6.15.3 Accident statistics

The Swedish national database (STRADA) was used to count accidents for each severity category, filtering on the generalized use-case. The data spanned over eleven years (2009-2019), and Figure 56 shows an overview of the results. An independent study was also performed with similar results. The ratio is roughly [1:2:4:>35] for the categories [Fatal : Seriously injured : Moderately injured : Slightly injured].

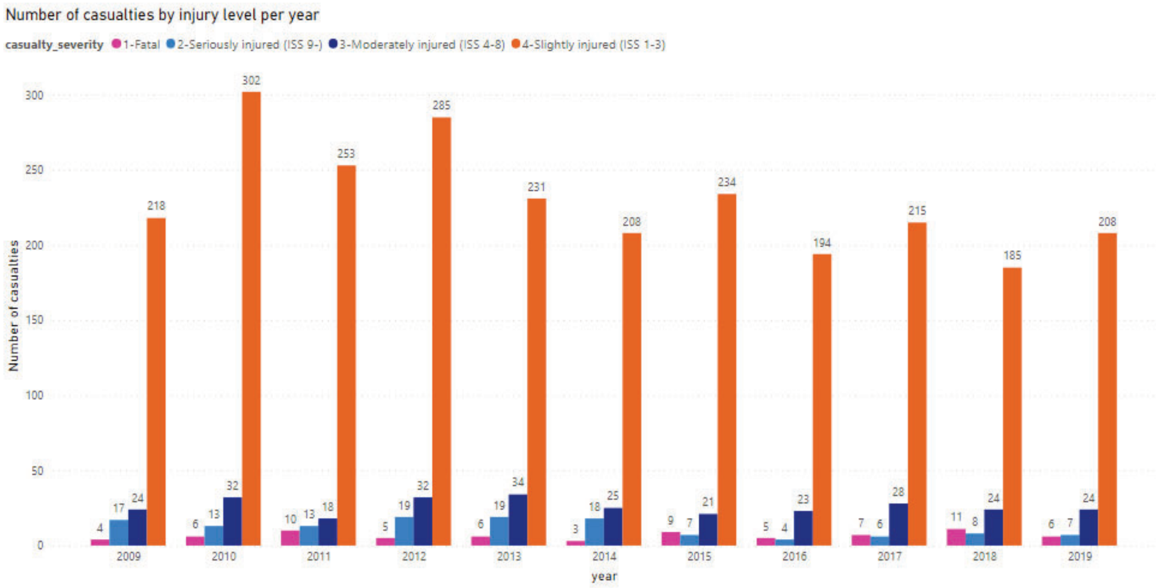



Figure 56 Accident statistics.

### 6.15.4 Accident rate

Calculating an accident rate based on the accident statistics also requires an understanding of how many kilometers. Furthermore, knowing at which speed those kilometers were driven is also needed to calculate the rate per hour. A conservative approach is to assume that all kilometers driven in Sweden were done on roads corresponding to the generalized use-case.

### 6.15.5 Infrastructure adaptions as risk reduction measures

Several infrastructure adaptions have been performed on the route, and some of help to reduce different risks. Table 8 provides an overview of infrastructure adaptations and how they can potentially contribute to reduce a risk. The effectiveness of the different adaptions is not evaluated in this work, it is instead evaluated during the validation of the ATS and the autonomous trucks.

Table 8. Example of infrastructure adaptions and how they can impact risks.

| **Infrastructure adaptation** | **Addressed risk elements** | | | |
|---|---|---|---|---|
| | *Severity of Harm* | *Exposure of persons to the hazard* | *Occurrence of a hazardous event* | *Possibility to avoid or limit the harm* |
| Lowered speed limit and speed reduction measures | ✓ | | | ✓ |
| Controlled intersections | | ✓ | ✓ | ✓ |
| Stop in lane for buses | | ✓ | | |
| Level crossings with barriers | | | ✓ | |

## 6.16 Achievement of project objectives

As the project was closed before the demonstration on the intended route was carried out, some of the main goals of the project were not achieved. However, many activities were carried out, and as a result, a large part of the project goals in chapter 5 were successfully achieved. See Table 9 below for a complete overview of the achievement of project goals. The overall weighted achievement of goals is estimated to be around 70%.

Table 9 Compilation of the fulfillment of the main objectives of the project

| Objective no | Description | Achievement of objective | Estimated achievement of objective [%] |
|---|---|---|---|
| 1 | Demonstrate a high level (L4) of automation functionality in a platform for self-driving, electric, and connected freight transportation, leading to safer transport with reduced number of accidents in the future, as the human factor that currently causes most accidents will be eliminated. | The project did not reach the status where level L4 was demonstrated as the safety driver could not be removed. Demonstration of level L3 was achieved on the test track but not on the public route, which means that this objective was not fully met. | 25% |
| 2 | Research and close knowledge gaps in automation, electromobility, and connectivity through studies at low TRL levels. | Several activities have been performed and results related to automation. electromobility and connectivity are described in chapter 6. | 80% |
| 3 | Increased understanding of the interaction between vehicle automation and energy efficiency, with an increased understanding of the energy efficiency perspective of the system before and after the implementation of the project and the scalability of the overall transport solution. | Activities have been performed e.g. by simulation of the transport system from an energy efficiency perspective (see chapter 6) | 100% |
| 4 | Develop a virtual and physical autonomous transport system to optimize accessibility, efficiency, and emissions for fully electric, fully automated, and connected vehicles. This will lead to increased possibility to reach a future fossil-free society. The project shall be able to show: | See below | N/A |
| 4a | 100% reduction of several emissions such as particulates and nitrogen oxides. | Basic LCA performed by IVL | 80% |
| 4b | Significantly reduced noise level compared to today's transport work on the current route. | No comparative measurements done | 0% |
| 4c | At least 50% energy efficiency, which will be compared to a corresponding fossil-energy-based drive line. | As the selected target vehicle was a recently developed fully electrical tractor (BEV) that was delivered to the project in 2022Q4, this objective has partly been fulfilled, even though the operation never was started. | 50% |
| 4d | Reduced $CO_2$ emissions when renewable energy sources are used compared to today's transport work on the current route. | As the selected target vehicle was a recently developed fully electrical tractor (BEV) that was delivered to the project in 2022Q4, this objective has partly been fulfilled, even though the operation never was started. | 50% |
| 5 | Specify and develop an electric drive system including energy storage that meets the performance requirements for the autonomous vehicle and contributes to reducing greenhouse gas emissions, increasing the chances of reaching emissions targets by 2030. | As the target vehicle was a resent developed fully electrical tractor (BEV) that was delivered to the project in 2022Q4, this objective has been fulfilled, even though the operation never was started. | 100% |
| 6 | Investigate and develop several types of charging technology such as inductive charging, conductive charging, and traditional charging with contact (manual/robotic) and subsequently define and systemize a new type of charging solution together | A number of investigations and tests have been done (see chapter 6) | 100% |

| Objective no | Description | Achievement of objective | Estimated achievement of objective [%] |
|---|---|---|---|
| | with the necessary infrastructure to support the vehicle's autonomy | | |
| 7 | Integrate the chosen drive line and charging system into the vehicle architecture and install the charging infrastructure. | Driveline and charging system have been integrated into the vehicle architecture (BEV), but installation of charging infrastructure was not done. | 50% |
| 8 | Conduct initial testing and commissioning of the integrated drive line to ensure functionality and optimized setting of parameters. | The BEV drive line has been tested and been commissioned by DFDS. | 100% |
| 9 | Automated and connected gate for the entry and exit of vehicles, including associated software to meet energy efficiency requirements linked to necessary project conditions, as well as software for monitoring all movements within the port area. | Automated and connected gate for the entry and exit of vehicles, including associated software was implemented and tested | 100% |
| 10 | Analysis of life cycle perspectives with different scenarios and comparison with today's type of transportation work on the current route as well as analysis of life cycle perspectives on components such as energy storage and other essential components from the current perspective | IVL has performed a subset of the LCA | 50% |
| 11 | Infrastructure Adaptations | See below | N/A |
| 11a | Analyze the road stretch and perform adaptations according to the requirements | Analysis completed and adjustments made on current route. | 100% |
| 11b | Perform assessment of needs and complete a consequence analysis | Assessment of needs and investigation of impact performed | 100% |
| 11c | Design adaptations of the infrastructure for the specified road stretch in the pilot | Design of adaptations of infrastructure finalized | 100% |
| 11d | Complete the construction of the infrastructure | Construction of the infrastructure finalized except at the APMT terminal area | 80% |
| 12 | Digital Infrastructure | See below | N/A |
| 12a | Perform a digital communications analysis for the specified route in the pilot | Digital communications analysis for the specified route done | 100% |
| 12b | Conduct an analysis of needs of traffic monitoring and traffic management | Analysis of needs performed | 100% |
| 12c | Perform an IT security analysis | IT security analysis not performed | 0% |
| 12d | Complete the construction of digital infrastructure for the current road stretch in the pilot | Construction of digital infrastructure partly done along the selected route | 70% |
| 13 | Overall Safety Analysis | See below | N/A |
| 13a | Conduct an overall safety analysis for the specified route in the pilot | Overall safety analysis for the specified route in the pilot finalized | 100% |
| 13b | AB Volvo conducts a safety analysis based on ISO26262 | Safety analysis based on ISO26262 performed | 100% |
| 13c | Apply systematic safety work and develop a safety plan with general safety principles | Systematic safety work applied and a Safety Plan with general safety principles has been developed | 100% |
| 13d | Apply relevant rules for electrical safety | Applied in the BEV development | 100% |
| 13e | Verify safety of the developed technology before it is applied in the demonstration | The safety verification was not started | 0% |

When it comes to the benefits for Sweden, there are several positive side effects of the project:

- TranzPORT has contributed to a good network and discussion between the automotive industry and authorities such as the Swedish Transport Administration and the Swedish Transport Agency, particularly in issues related to regulations, traffic safety, and infrastructure, which is necessary to establish self-driving vehicles on public roads.

- TranzPORT has established cooperation between academia and research institutes on issues such as LCA analysis and development of algorithms for transportation optimization, which has resulted in doctoral work and publication of results.
- TranzPORT has cooperation with actors such as DFDS, APMT, and Port of Gothenburg on how an automated transport system should be designed in terms of transportation and logistics in ports.

## 6.17 The project's contribution to FFI's goals:

In addition to the project-specific goals, there are also overarching FFI goals listed below, with comments on how the project has succeeded in contributing to these:

- Develop a solution that can help reduce the number of injured and killed in traffic
    - *The solution was not fully developed to measure this effect, but research shows that automation is a promising technology for achieving these effects.*
- Establish a contact point between authorities, industry, and academia for a real-life demonstration that is long-term
    - *Contact points have been established that will continue to be valuable in the future even if the project did not reach the demonstration stage.*
- Strengthen the R&D capacity in the field of transport systems with fully electric, fully automated, and connected vehicles in Sweden to secure industrial competitiveness and thus job opportunities
    - *The R&D capacity in the field has definitely been strengthened in Sweden through the project, which has both secured industrial competitiveness and job opportunities*.
- Provide great visibility for FFI and for the parties, including authorities, that participate in or finance the work
    - *Although the project was not demonstrated by showing the complete automated transport solution without safety drivers, some visibility has been created both through participation in the FFI conference in 2022 and through the final seminar and limited demonstration that was carried out in February 2023.*
- Generate data and knowledge that can be used in future projects to evaluate effects at the system and societal level and contribute to policy and standard development
    - *Both data and knowledge have been generated that have already been used in ongoing projects.*
- Collaboration with companies, academia, institutes, suppliers and other OEMs, both within and outside of Sweden
    - Collaboration between companies, academia, institutes, and suppliers has been extensive, for example, between Volvo, the Swedish Transport Administration, Nvidia, DFDS, Platzer, Chalmers, IVL, the Swedish Transport Agency, the Swedish Energy Agency and Vinnova

# 7. Dissemination and publications

## 7.1 Dissemination

The project and the results have been presented both at internal meetings within each partner's organization and at the following external forums and conferences:

- 2019-01-28, Volvo internal project kick-off
- 2021-03-21, Project presentation at the portfolio board of the Swedish Transport Administration for strategic initiatives
- 2021-10-24, Workshop session during the 9th Scandinavian Conference on System & Software Safety, Gothenburg
- 2022-03-30, Presentation at the FFI conference in Stockholm
- 2022-10-17 – 2022-10-18, Workshop with the Swedish Transport Administration, DFDS, Vinnova and the Swedish Energy Agency in Gothenburg
- 2022-10-20, Presentation on the 10th Scandinavian Conference on System & Software Safety, Gothenburg
- 2022-11-14, Chalmers presentation of results at CampX, Gothenburg
- 2023-02-08 – 2023-02-09, Internal Final Seminar and demo with DFDS, Chalmers, IVL, Vinnova, the Swedish Energy Agency and the Swedish Transport Administration in Gothenburg

At the end of the project, a TranzPORT Final Seminar was held as a physical and online event on February 8$^{th}$ 2023, with around 20 participants, and on February 9$^{th,}$ 2023 a demonstration with the EV1 development vehicle was performed at Säve test track.

| How are the project results planned to be used and disseminated? | Mark with X | Comment |
|---|---|---|
| Increase knowledge in the field | X | Yes, in all areas included in the project. |
| Be passed on to other advanced technological development projects | X | A lot of the technologies developed can be used in other applications like in the mining and quarry segment. |
| Be passed on to product development projects | X | A lot of the technical concepts developed can be passed on to ongoing product development projects |
| Introduced on the market | | No plans to introduce on the market within the next couple of years. |
| Used in investigations / regulatory / licensing / political decisions | X | Used in future investigations |

## 7.2 Publications


- Torabi, M, Wahde, M., and Hartono, P. Road Grade and Vehicle Mass Estimation for Heavy-duty Vehicles Using Feedforward Neural Networks, In: The 4th international conference on Intelligent Transportation Engineering, pp. 316-321, 2019
- Wahde, M., Bellone, M., and Torabi, S: A method for real-time dynamic fleet mission planning for autonomous mining, Autonomous Agents and Multi-Agent Systems, 33(5), pp. 564-590, 2019

# 8. Conclusions and future research

The TranzPORT project has been researching and developing a transportation system on a limited scale (however, unusually large for a pilot) to efficiently and safely build new knowledge and develop the technology. AB Volvo has ambitious plans to scale up the developed technologies and find new types of applications in the form of both longer transportation routes and more complex transportation tasks. The project has focused on adapting infrastructure and vehicles of a completely new type that have been presented at low speeds. However, in a developed form, the concept could be applied at high speeds in dedicated lanes on public highways. Figure 57 shows examples of potential future scaling of the project.

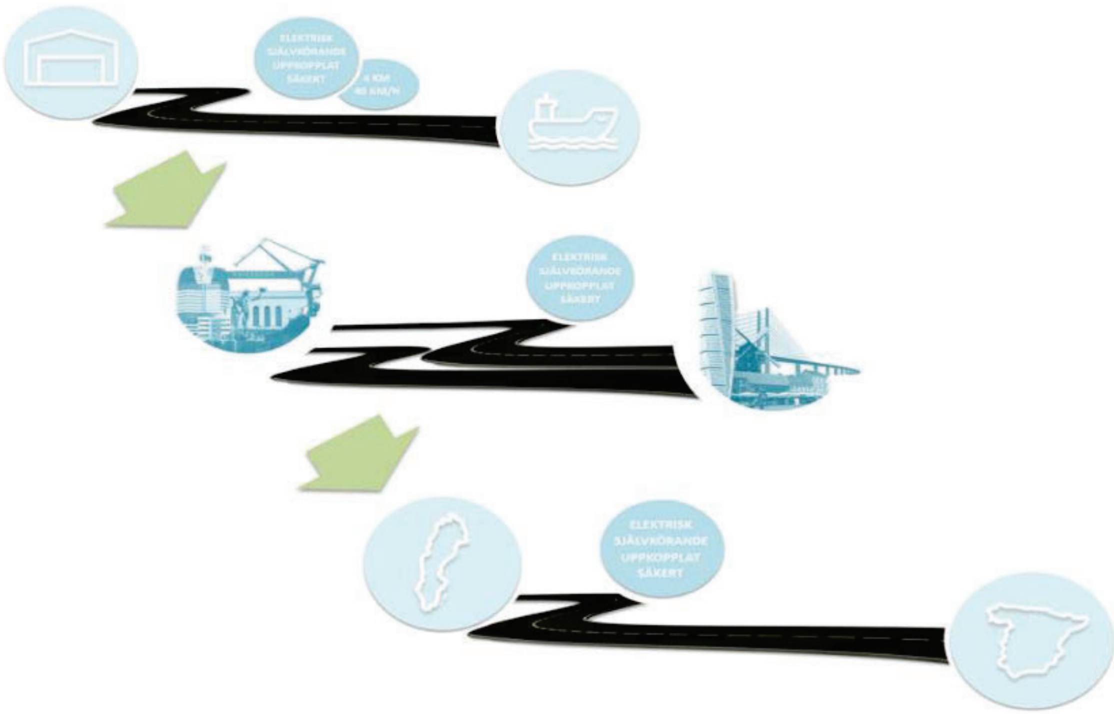



Figure 57 Examples of possible future scaling of the concept with increased complexity

The developed technologies will therefore be able to be used in other applications and contexts in the future than what is the focus of this project. It can be advantageously used in cities, where congestion and noise pose major problems for residents. Because this transportation system is autonomous and electric, it is possible to use it at night when there are fewer people in cities and fewer vehicles on the roads. This would not only mean improved traffic safety as fewer vehicles travel at the same time as pedestrians, but also reduced congestion during rush hour traffic as many freight transports can be handled during uncomfortable working hours. In the future, a hub-to-hub system will be a potential solution for the increasing transportation needs and the type of transportation solution developed in this project could have a great significance for transportation between hubs and for further transportation into cities and communities. The vehicles in this transportation solution collect large amounts of data, such as information about road conditions, queues, traffic accidents and so on. The user potential of collected data is great, such as potentially used by other vehicles and SOS Alarm to increase traffic safety and contribute to social benefit.

AB Volvo's assessment is that the project and the three technologies developed has opened up for new transportation solutions and business solutions that society has not yet taken advantage of, which in itself has made this project unique. AB Volvo and partners believe that the project results, even though the project was prematurely closed, will have long-lasting effects that are difficult to estimate today, like the internet was at the beginning of this century.

The Volvo Group is a global player with high ambitions in automation, electromobility and connectivity. A combination of AB Volvo's ambitions, the Swedish collaborative climate, and the fact that there are other Swedish actors who also want to drive development forward means that together we have driven a unique world project with the potential to cause a paradigm shift in the transportation industry. The potential of this transportation solution is of central interest to understand this project. AB Volvo's assessment that there are clear productivity, environmental and traffic safety gains.

# 9. Participating parties and contact persons

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