ADEST Autonomous Driving Effects on Sustainable Transportation

& ADFE Autonomous Driving Fuel Economy

Public Report

Main authors:
Marcus Rothoff (VCC, Project Leader)
Hamid Zarghampour (TrV, Project Leader)
Emma Tivesten (VCC, Research Leader)
Trent Victor (VCC, Safety)
Anders Ödblom (VCC, Traffic Flow)
Torsten Bergh (Movea/TrV, Traffic Flow)
Björn Lindenberg (VCC, Energy Efficiency)

Contributing authors:
Safety (VCC): Magdalena Lindman, Fredrik Sangberg, Mikael Ljung Aust, Riyam Tayeh, Erik Hartelius, Fredrik Granum, Emil Ringwall, Sava Iancovici, Andrea Ivancic, Carl Persson

Energy Efficiency (VCC): Mitra Pourabdollah, Eric Bjärkvik, Klaas Burgdorf

Human Machine Interface (VCC): Robert Broström

Trafikverket (TrV) and Movea: Peter Kronborg, Per-Olof Svensk, Magnus Palm

Datum: 2019-10-31
Projects within the FFI sub-program *Traffic Safety and automated vehicles* (in ADEST) and *Efficient and Connected Transport Systems* (in ADFE)

FFI Fordonsstrategisk Forskning och Innovation

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Glossary and abbreviations:

ACC	Adaptive Cruise Control
AD	Autonomous Driving (AD). Driving where the vehicle takes full responsibility for all aspects of the driving task, allowing the driver to disengage from driving. For the purpose of this report, the term unsupervised automation is used as a synonym to AD.
ADAS	Advanced Driver Assistance System
ADEST	Autonomous Driving Effects on Sustainable Transportation (project name)
ADFE	Autonomous Driving Fuel Economy (project name)
AV / AVs	Automated vehicle / Automated vehicles
Baseline	An initial set of data to which the performance of the technology under study is compared to. In this report, baselines refer to datasets from real-world driving including crashes, near-crashes, and driving situations where a human driver or AD function is not expected to perform an evasive maneuver (e.g., an empty plastic bag flying in the air).
Conflict situation	Classification that aims to describe (only) the movement of the involved road users in relation to each other before the crash or near-crash. A conflict situation does not include any information about why the crash occurred or the crash circumstances (e.g. traction lost, driver's distraction, light conditions, etc.).
Crash	A collision with an object or other road user, a road departure, and/or a vehicle rollover.
ODD	Operational Design Domain. The specific conditions under which the automated vehicle is designed for including type of road environment and driving conditions (e.g., light, weather, road surface conditions).
Near-Crash	A situation that could easily result in a crash, that requires a rapid evasive maneuver by one or several involved road users and/or results in a very small margin (e.g., distance in time and space) to another road user, object, or a road departure.
SUMO	Simulation for Urban Mobility. Open source microscopic and continuous road traffic simulation package.
THd	Time History data (THd) format. Numerical description of a critical traffic situation where each time step, in a delimited time leading up to the impact (or proximity time in case of a near-crash), depicts the vehicle trajectories, the road environment, the participants and their characteristics.
VISSIM	Commercially available microscopic and continuous road traffic simulation package.
VISUM	A software system for transportation planning, travel demand modelling, and network data management.
Wizard of OZ (WoZ)	An experimental platform that is used for simulating a technology in a real vehicle that is not yet available in production. The platform can be used on test track or on public roads.

1 Sammanfattning

Den här rapporten ger en kortfattad översikt för projekten ADEST (Autonomous Driving Effects on Sustainable Transportation) och ADFE (Autonomous Driving Fuel Economy), som bedrivs som en del av forskningsplattformen Drive Me. Trafikverket och Volvo Personvagnar är parter inom projekten som delfinansierats av FFI/VINNOVA. Projekten består av fyra arbetspaket: **testprober** (prototypbilar med automatiserad körning), **trafiksäkerhet**, **trafikflöde**, och **energieffektivitet**. Trafikflöde omfattas av egenskaper hos trafiksystemet så som restid, kapacitet, robusthet, och punktlighet. Området energieffektivitet omfattar även av ljud och koldioxid-emissioner.

Syftet med projekten är att skatta effekten av framtida autonoma fordon på säkerhet, miljö, och effektiviteten för hela trafiksystemet. Funktionen är begränsad till torrt väglag, bra väder, bra ljusförhållanden, och är designad för en provsträcka som utgörs av Göteborgs ringled. Ringleden består huvudsakligen av motorväg med separerade körriktningar där skyltad hastighet är 70 eller 80 km/h.

Testprober utvecklades som innehåller en uppsättning av sensorer och mjukvara som gör att funktionen anpassar bilens körning till alla omgivande trafikanter och objekt. Bilens körning planeras på strategisk, taktisk, och operationell nivå. Dessutom används två principer för säker körning: en förutseende (precautionary safety) som anpassar körningen till potentiella konflikter, och en kollisionsundvikande (collision avoidance) som agerar om en kritisk situation uppstår. Ett exempel på precautionary safety är att om bilen närmar sig en stillastående bil på vägrenen, så saktar bilen in och ökar avståndet i sidled (ex. byter fil eller ligger längre till vänster i filen) för att vara förberedd om en skymd fotgängare plötsligt går ut i vägbanan. Av säkerhetsskäl får testproberna köras på provsträckan av professionella testförare som är speciellt utbildade för uppgiften.

Säkerhetsarbetet fokuserar på att uppskatta den potentiella säkerhetseffekten av autonom körning. En fältdatastudie visar att det inte är möjligt att uppskatta säkerhetseffekten med ett stort antal körda kilometer, vilket innebär att ett konfliktscenario-baserat tillvägagångssätt behövs. Konfliktsituationer från fältdata (verkliga olyckor och kritiska incidenter) rekonstrueras, och används som input till datorsimuleringar för att studera effekten av autonom körning i jämförelse med en kravnivå som motsvarar en uppmärksam, skicklig, och erfaren förare. Resultaten från studien visar att automationen har en stor kollisionsundvikande potential.

En serie experiment på provbana visar att det finns en uppenbar risk att förare utvecklar en allt för hög tillit till automation som upplevs som stabil och tillförlitlig, men som ändå kräver att föraren övervakar körningen och är beredd att ingripa i vissa situationer. Baserat på dessa resultat förslår vi en ny beskrivning för olika typer av automation utifrån förarens roll (förarstöd, enbart passagerare, omväxlande), där förarens roll och ansvar alltid tydligt kommuniceras oavsett typ av automation.

Effekten av autonoma fordon (Automated vehicles, AVs) på trafik har analyserats med trafiksimuleringar, empirisk-analytiska metoder samt analys av olycks-, incident- och trafikdata. Eventuella ändringar i resebeteende eller efterfrågan är utanför projektets omfattning. AVs som kör försiktigt i förhållande till mänskliga förare, kommer reducera fordonskapacitet och orsaka stora trafikproblem vid befintliga flaskhalsar i urbana motorvägssystem. Å andra sidan, deras förväntade förmåga att undvika olyckor och incidenter kan ta bort tillhörande kapacitetssänkningar och trafikstörningar så att variationer i daglig restid skulle minska avsevärt.

Resultaten av trafiksimulering visar att trafikflödet påverkas marginellt av att introducera en andel med 20 % försiktiga AV i rusningstidstrafik på stora delar av ringleden. Dessa AVs har en reglering som liknar adaptiv farthållare fast med lägre acceleration i låg hastighet i trafik, kör upp till 70 km/h, följer hastighetsbegränsningar, och byter fil som en mänsklig förare. På dessa delar av ringleden är det nära fritt trafikflöde, vilket också motsvarar mer än 95 % av det svenska motorvägsarbetet. Å andra sidan, där det är kapacitetsproblem redan utan AVs, såsom på den östra delen av ringleden, ger dessa AVs upphov till kraftigt ökade köer med 20-45 % ökning i medelrestid för hela rusningstimman. Av samma skäl blir trafiksystemet mindre robust mot trafikstörningar då dessa AVs löser upp köer långsammare än mänskliga förare. Autonoma försiktiga körfältsbyten skulle ytterligare försämra kapaciteten. Diverse olika koncept som använder AVs för att förbättra trafikeffektiviteten har diskuterats i ADEST-projektet. Utmaningar för AV-relaterade ändringar i motorvägsinfrastruktur, samt möjligheter med digital infrastruktur, belyses i projektet. I urbana motorvägssystem med korta trafikplatsavstånd, kapacitetsproblem och mycket växlande trafik är det mycket svårt att hitta platser där AD-broar dels är möjliga med hänsyn till kostnader och intrång, och dels kan lösa kapacitetsproblem vid en blandning av AV och vanliga fordon.

Energieffektivitet för individuella fordon påverkas främst av bilens hastighet och hastighetsförändringar. Automatiserad körning öppnar upp för möjligheten att reglera bilens hastighet enligt principerna för energiekonomisk körning. Det är också möjligt att individuella automatiserade fordon som kör energieffektivt påverkar omgivande fordon så att hela trafiksystemet blir mer energieffektivt vid en viss andel av automatiserade fordon. ADFE-projektet fokuserar på hur introduktionen av individuella automatiserade fordon påverkar energieffektivitet, emissioner, och ljudnivåer, medan effekten av förändrad mobilitet, eller fordonsutformning (ex. dimension, vikt) ligger utanför projektets omfattning. En stor del av arbetet inom energieffektivitet ägnades åt att utveckla och kalibrera en simuleringsmiljö för hela trafiksystemet (trafikmiljö, fordon, förare) för Göteborgs ringled med fokus på energiförbrukning under rusningstrafik på vardagseftermiddagar. Trafikmiljön kalibrerades med trafikflödesmätningar på bestämda platser, och förarmodeller för manuell körning kalibrerades hjälp av naturalistisk kör-data. Analys av naturalistisk kör-data visar att automatiserad longitudinell kontroll (med adaptiv farthållare, ACC) är mer energieffektivt än manuell körning för individuella bilar, medan simuleringar visar att om ACC-liknande AVs orsakar ökade köer så kommer energieffektiviteten minska och utsläppen öka för trafiksystemet.

2 Executive summary

The aim of the ADEST and ADFE projects is to evaluate the impact of unsupervised automation on urban highways on safety, traffic efficiency, and energy efficiency. Four work packages were defined to meet this aim: 1) **test probes** (i.e., automated prototype vehicles with a data acquisition system), 2) **safety**, 3) **traffic flow** (i.e., capacity, travel time, punctuality and robustness of the traffic system), and 4) **energy efficiency** (i.e., energy consumption, emissions, noise).

Three generations of test probes were developed for an operation design domain (ODD) that includes good weather, light, and roadway conditions on roads with separated travel directions. The ODD is restricted to the Drive Me route consisting of the Gothenburg ring road where the posted speed is 70 or 80 km/h. The test probes include several types of sensors (e.g., cameras, radars, LIDARs) and a sensor fusion platform that enables a 360-degree object detection around the vehicle. The vehicle control is planned at the strategic, tactical, and operational level. Additionally, a conflict manager consists of a precautionary safety (PCS) module and a collision avoidance module. The precautionary safety module anticipates potential conflicts and increases the safety margin (e.g., reduces speed, increases lateral distance) to avoid ending up in a conflict, while the collision avoidance module is engaged in case of a critical situation. The initial ambition with the test probes was to develop unsupervised automation, and make it available to regular customers in a Field Operational Test (FOT). For safety reasons the test vehicle was launched with a supervised automated system that could only to be engaged in certain conditions. A few regular customers were involved in a naturalistic study where only on-market driver assistance functions were available, and they were also allowed to try the automation on separate occasions when accompanied by a safety driver.

The safety work package focused on determining the potential safety impact of autonomous vehicles. Four safety challenges were identified: (1) development of a safety impact assessment methodology, (2) development of a pre-crash scenario-based approach, (3) definition of target levels for safety performance, and (4) development of crash avoidance performance testing methods. After reviewing existing approaches, the *Holistic Safety Impact Assessment Framework for Automation* was developed and applied in a feasibility study. First, real-world data was used to define ODD-relevant conflict situations, and the conflicts were digitally reconstructed and clustered into time-history-data (THd) batches per test-scenario. Computer simulations were used to study an ideal automated vehicle model in comparison with an attentive, skilled experienced reference driver model and other references (manual driving and driving with ADAS). The formulation of the reference driver model as a valid, testable target to determine "what is safe enough?" can be seen as a major achievement. The feasibility study results show a great crash avoidance potential from automation.

Other safety analyses pointed out that the mileage-driven approach to safety is infeasible, and a scenario-based approach is necessary to estimate the impact of automation on safety. Furthermore, a series of experiments studied over reliance, and dramatically illustrated the limits of driver capabilities to act in a supervisory role as automation becomes more and more reliable but not perfect (an Irony-of-Automation) pointing out the need for crystal clear communication about the driver's role and responsibility. This insight led to a formulation of human-centric types of automation (Assistance, Passenger-only automation, and Role-switching automation) instead of unidimensional "levels of automation" (e.g. SAE J3016). These types of automation are focused on improving understanding and communicating the role the driver plays.

The effect of automated vehicles (AVs) on traffic has been evaluated using: (1) traffic simulations, (2) analytical-empirical methods, and (3) analysis of traffic and accident-incident data. Travel patterns, ride sharing and demand are assumed unchanged by AVs in this study. A new approach to automatically calibrate traffic simulation models towards measured traffic variations is proposed and partly implemented within the project period. The effects of AVs on traffic efficiency depend on the relative difference in behavior between AVs and normal traffic. Cautious AVs are expected to reduce vehicle capacity and cause traffic problems in bottlenecks regions in urban motorway road networks. On the other hand, their expected ability to avoid collisions will take away associated capacity drops and traffic disturbances. The traffic improvement potential by entirely avoiding accidents and incidents suggest daily travel time standard deviation to decrease by some 40-60% using data from a section of the Drive Me route.

Traffic simulation results show that 2014 afternoon workday rush hour traffic on most parts of the Drive Me route is only marginally affected by a 20% share of cautious AVs. These AVs behave like adaptive cruise-controlled vehicles but restricted to 70 km/h, obey speed limits, have lower low-speed acceleration in traffic, and change and choose lane as regular drivers. Here, traffic is near free flow conditions which is also where more than 95% of Swedish motorway mileage is carried out. However, on the eastern side these AVs amplify traffic problems after capacity breakdowns resulting in growing queues with 20-45% increase in average mean peak hour travel time. For the same reason, queues dissolve more slowly with these AVs after lane blockages. For example, a 30 minutes lane closure on the south part of the route resulted in a 200 m increase in max average queue length and 3 minutes increase in max average vehicle delay due to these AVs.

Part of the available road network capacity is used up by unnecessary human lane changes, poor lane choices and other traffic-inefficient human driving behaviors. Future AVs will hopefully act more efficiently to avoid the corresponding capacity degradation. Several AV-based concepts to improve traffic efficiency are explored in the ADEST project. Challenges with AV related changes in motorway infrastructure, as well as possibilities with digital infrastructure, are also addressed during the project.

The impact of automated vehicles on energy consumption, noise, and emissions were investigated using real world measurements and computer simulations. We have focused on driving conditions and traffic demand typical for afternoon rush hour on the Drive Me route, and evaluated the impact of early AVs on a traffic system mixed with human-driven vehicles. To this end, naturalistic driving data was analyzed by comparing automated longitudinal control (i.e., adaptive cruise control) and manual driving. Also, a traffic simulation environment was created using a microscopic simulation tool. Since no existing traffic simulation tool addressing energy efficiency issues was available at the beginning of this project to handle and configure driving dynamics of AVs in a larger traffic system, the development of one was crucial for the success of this project. Much effort was put into implementing, verifying and validating the traffic simulation tool consisting of three parts: the traffic environment, vehicle models, and driver models for manual and automated driving. A method to optimize the parameter settings of the manual driver models was developed and applied in order to tune them and verify compared to naturalistic driving data on the Drive Me route. In addition, traffic detectors were placed in the traffic simulation environment at the same locations as the real detectors on the Drive Me route in order to compare average flows and speeds. The results show that longitudinal automation (i.e., adaptive cruise control, ACC) is more energy efficient than manual driving for individual vehicles in naturalistic driving data. The major differences are that ACC generally keeps a longer average distance to the lead vehicle, and have lower levels of acceleration and deceleration than manual drivers. A share of AVs between 1% and 5% was introduced into the simulation environment. The results show a clear trend of increasing energy consumption due to increased congestion, while the noise levels decrease for the complete traffic system as the share of AVs increase. It should be noted that the AVs were set to be very prone to stay in the right lane, only making lane changes if absolutely necessary.

3 Background

During the past decades, road transport in urban areas in Sweden (as well as globally) has been dominated by an increased number of fossil fuel driven cars and has resulted in increasing levels of emissions, traffic congestion, and loss of time. As we approach 2020, there is much renewed interest in revitalizing the urban road transports as one way of combating the challenges in metropolitan areas. Future automated vehicles (AVs) may influence the way the road transportation system is designed, how vehicles are used (including car sharing), thereby providing benefits for the society and individual mobility.

The Drive Me research platform was initiated 2013. The Swedish Transportation Agency, the City of Gothenburg, Lindholmen Science Park, Volvo Car Group, Chalmers University of Technology and Autoliv are part of the Drive Me research platform. The platform encompasses several research collaboration projects to support the development of autonomous driving, and its role for modernizing the existing infrastructure for road transports.

Within the Drive Me research platform, two projects – *Autonomous Driving Effects on Sustainable Transportation (ADEST)* and *Autonomous Driving Fuel Economy (ADFE)* – are presented in this report. The projects started in 2014 and 2015, and this report presents their results at the end of the projects in January 2019.

4 Purpose

The purpose of the ADEST and ADFE projects is to define and evaluate the impact of automated vehicles on sustainable mobility on urban highways. The projects focus on three main research areas: **safety**, **traffic flow**, and **energy efficiency**. Traffic flow includes several properties (i.e., capacity, robustness, travel time and punctuality) and energy efficiency extends to noise and emissions. Additionally, the **test probe** research area was included with the purpose to develop and implement automated driving functionality in vehicles in order to evaluate the performance on real roads with regular customers. The test probes are restricted to an operational design domain (ODD) on urban highways on the Gothenburg ring road during daylight and good weather/roadway conditions.

The objectives and general methods are described in chapter 5, while more specific description on research questions, methods, and results are presented in chapter 6.

5 Objective

This section explains the objectives as stated in the ADEST and ADFE applications, how the objectives were addressed and/or modified, as well as how/if they were met during the projects.

1) *Develop and build test probes (i.e., AV prototypes) that allow ordinary Volvo customers to operate autonomous vehicles on public roads such that the overall effects of these vehicles on the road transportation system can be studied.*

Three generations of test fleets were developed and built according to the project plans, following the progress of the function development during the projects. The third generation of test probes were intended for validation in real traffic by regular customers using unsupervised automation on urban highways. The initial ambition to launch a large scale Field Operational Test (FOT) using test probes with unsupervised automation functionality available to regular customers was not feasible since the test probes did not reach the performance required for in-production functions. For safety reasons, the developed AV prototypes require supervision by trained professional test drivers, while regular drivers were allowed to try the automation if a trained test driver was present as a backup driver (also called safety driver). As a consequence, the focus has shifted during the projects. The FOT with regular customers was significantly reduced to include a few families and only in-production driver assistance systems. Instead, increased effort was put into the objectives below, such as the development of computer simulation tools, analysis of data form existing field operational tests (with/without driver assistance systems), human factors research using test track experiments, as well as a methodology on impact assessment for each of the research areas (i.e., safety, traffic flow, energy efficiency).

2) *To develop tools, methods for estimating safety impact of automated vehicles, as well as to apply these to estimate the potential safety impact of automated vehicles in the defined operational design domain.*

The tools, methods, and potential safety impact assessment was performed according to the project plan using field data analysis, reconstructions of pre-crash events, and computer simulations comparing non-AVs with AVs. As described above in (1), assessment of driver and vehicle performance in in real traffic (i.e., a FOT study) with unsupervised AD was not feasible. Instead, an additional research objective was defined to address safety challenges with automation that require driver supervision. A series of test track experiments and publications were added to the ADEST research scope to investigate driver performance and human limitations in supervised automation. In addition, a general framework for safety impact assessment was introduced, taking various types of automation into account (i.e., varying driver roles and function capabilities).

3) *To estimate the effect of future automated vehicles on traffic in terms of capacity, travel time, punctuality and robustness of traffic systems for different shares of automated vehicles. To analyze and modify the automated vehicle behavior to optimize traffic efficiency. To establish and use traffic simulations based on VISSIM to answer research questions.*

The tools, methods, and AV traffic impact assessments were performed according to the project application using VISSIM traffic simulations. Estimates have been provided for the effect of AVs on capacity, travel time and robustness for an expected future AV behavior and share. In order to address effects on punctuality, a new calibration procedure targeting normal traffic variations was proposed and partly implemented with example impact results provided. This work was performed with new manning and a change to an open-source tool (i.e., SUMO) to be aligned with ADFE efforts. Since AV effects on traffic depend on the relative difference between AVs and regular vehicles, we decided to focus on calibrating normal traffic models to traffic variations rather than providing more impact results for other AV functionalities, more AV shares and traffic system optimization by AVs.

In addition to the traffic simulation approach included in the ADEST work packages, the research questions have also been addressed for different types of road networks and traffic situations using analytical/empirical models for assumed short- and long-term AD behaviors. Furthermore, the effects on traffic by avoiding accidents and incidents with AVs have been estimated quantitatively from travel time measurements for a road section along the Drive Me route.

4) *To analyze how the infrastructure should be modified to improve traffic efficiency when a large proportion of the vehicles in the traffic system are automated. To study concepts of future road infrastructure to verify the behavior and capability of autonomous vehicles.*

Possible measures to modify the existing physical infrastructure have been studied during the project in terms of dedicated AV lanes, reduced lane width and special AV bridges. Several challenges with these concepts have been identified, and physical infrastructure concepts have therefore not been built during the project.

On the other hand, the importance of establishing a well-functioning digital infrastructure for the introduction of automated vehicle related functions has grown throughout the project period. This project has contributed towards an increased understanding of the opportunities and challenges related to digitalization.

5) *To develop a scientific methodology for assessing the environmental impact of automated vehicles. This will then be used to design and carry out experiments (physical and/or virtual), and analyze the results of these with the goal of answering the research questions related to energy efficiency, as well as environment and health.*

A literature study was performed to conclude the state of art regarding the impact of automation on fuel efficiency. A scientific methodology was developed according to the defined objectives. A traffic simulation environment was developed in SUMO, and open source simulation tool. The simulation environment was calibrated using real life traffic flow measurements, and applied to answer the defined research questions within the ADFE project. Existing naturalistic driving data was used to investigate the effect of automated longitudinal control (i.e., Adaptive Cruise Control) on energy efficiency in real traffic, as well as to parametrize and select the most suitable type of driver model for manual driving. In parallel, NREL used the same pre-requisites and conducted research in order to be able to compare methods and results by the end of the project. The initial intention to perform physical experiments using the test probes was not feasible since the test probe functionality was developed until late in the project. Consequently, the emphasis on virtual experiments (i.e. simulation) and analysis of existing real world data was increased.

6 Results and deliverables

The results and deliverables including the four research areas test probes, safety, traffic flow, and energy efficiency are presented in this chapter.

6.1 Test probes

A brief overview of the test probes (or AV prototype vehicles) is presented here in the public project report.

Today there are several vehicle models on the market with advanced driver assistance systems capable of doing all actuation required to stay in lane most of the time. However, the difference between systems capable of driving in lane most of the time compared to a system proven to drive safely without driver supervision is huge. An unsupervised automated system has to have a proven effect on traffic safety as well as the ability to operate correctly, including solutions to handle potential failures. Simply put, unsupervised automation has to be designed to detect and respond to rare events without faults. These high requirements on the system solution influence all parts of the system, from sensors to actuators and from hardware to software.

The Operational design domain (ODD)

The ODD defines the specific conditions under which the automated vehicle is designed for including type of road environment and driving conditions (e.g., light, weather, road surface conditions).

The ODD for the test probes is defined by selected urban highway road segments that is part of the Gothenburg ring road, illustrated in Figure 6.1.1. The selected road is called the Drive Me route, and the outer circle in the figure is approximately 30 km long. This road is mainly dual carriageway with 2-3 lanes in each direction, and median barriers separates travel directions. The posted speed is 70 or 80 km/h. The Drive Me route is not designed for the presence of pedestrians, with a few exceptions (i.e., a bus stop close to the road). The ODD includes good light, weather, and road surface conditions. Poor driving conditions such as slippery road surface, dark light conditions and bad weather is not included.

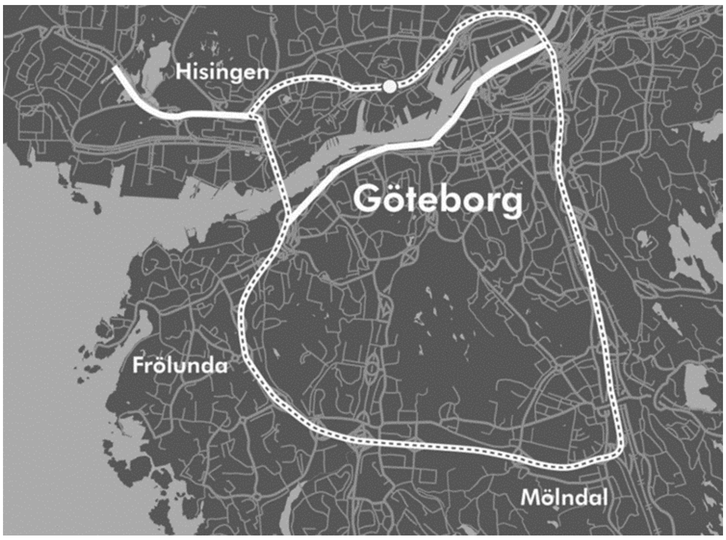

Figure 6.1.1. The Drive Me route defining the road segments within the ODD.

Development and build of test probes (i.e., AV prototype vehicles)

Three generations of test probes have been developed as an iterative process in parallel with the research activities within traffic safety, energy efficiency and traffic flow. The test probes were designed to achieve unsupervised automation for regular customers. When transferring responsibility from driver (as in driver assistance) to the vehicle (as in unsupervised automation), the vehicle has to be designed and proven to operate correctly within the ODD. In order to set functional safety requirements on the autonomous vehicle, each risk is systematically analyzed through a Hazard Analysis & Risk Assessment (HARA), and requirements are set in accordance to legal requirements, OEM requirements and applicable standards, such as ISO 26262. The Automotive Safety Integrity Level (ASIL) classifies safety critical hazards, and listing the most critical hazards will clarify the need for an extremely robust system architecture on both the hardware and software side. A high ASIL requirement imposes a need to implement redundant technical solutions to increase function availability and robustness.

The main task for the first generation of test vehicles was to define requirements on the sensor platform, and to provide an initial proposal for a sensor hardware platform. To measure detection performance, a roof-mounted sensor reference box was designed with high accuracy and resolution sensors.

The second generation test vehicles were designed to have similar hardware prototype solutions as in an unsupervised automated vehicle, but without meeting all the hardware and software specifications. A system solution similar to an unsupervised automated vehicle enabled the continued work on software structure and basic functionality.

The third generation of test probes were built in order to validate and analyze the overall impact of unsupervised automation on the road traffic system. The initial ambition to launch a large scale Field Operational Test (FOT) using test probes with automation functionality available to regular customers was not feasible since the test probes did not reach the performance required for in-production functions. For safety reasons the test vehicle was ultimately launched with a supervised automated system that was allowed to be engaged under certain conditions. A few regular customers were involved in a naturalistic study where only in-production driver assistance functions were available. They were also allowed to try the test probe automation on separate occasions when accompanied by a safety driver.

The sensor platform and the sensor fusion software for an unsupervised automated system shall secure robust detection of objects around the vehicle. To secure full detection in all driving conditions within the defined ODD, several sensor technologies are used. Cameras are primarily used for object detection, signs and lane recognition. Radars are primarily used to measure distance and velocities to structures with high density. Lidars are a perfect complement to cameras and radars to measure distance and angle to physical objects. Ultrasonic sensors are used to detect objects closer to the vehicle. By combining these sensor technologies, a redundant sensor platform can be established.

The sensor fusion platform includes a high definition (HD) map with multiple layers of information including road shape, lane boundaries, and landmarks (e.g. barriers, poles, signs, and other stationary objects) along the Drive Me route. The map is tailored to the sensors, and localization algorithms determine the position of the vehicle on the map. The platform combines raw data from multiple sensors to detect objects on the road. This provides a coherent and robust description of the complete 360 degree view including all surrounding objects and their current physical properties (direction of travel, speed, acceleration, object type, etc.).

The decision making and control functionality has been divided into different levels of planning: *Strategic route planning* (finding the route), *tactical planner* (decides desired speed and travel lane etc.), and *operational planner* (plans the geometrical trajectory for lane changes, and keep track of objects in the vehicles path, etc.). Additionally, a *conflict manager* consists of a precautionary safety (PCS) module and a collision avoidance module. The PCS increases the safety margin in case of a potential conflict, for instance by reducing speed and increasing lateral distance to a stationary vehicle on the shoulder. Collision avoidance acts as an extra safety layer and is only activated in critical situations. Actual safety margins, perceived safety, and user trust in automation all play an important role for these specifications which aim to mimic a skilled, attentive, and safety-conscious driver.

Another important aspect for a safe implementation of unsupervised automation is how to secure a clear responsibility in the hand-over between the automation and the driver, as well as avoid mode confusion. With all the involved complexity and the on-going safety research, two different HMI solutions were implemented for the third generation of test probes. One HMI for unsupervised automation, and one for supervised automated mode. Both solutions have similar control behavior to support research, but the supervised automation solution always requests and reminds the driver to monitor driving.

6.2 Safety

The potential of automation to revolutionize vehicle safety is widely recognized, given that as much as 94% of crashes have been attributed to driver-related critical reasons such as recognition errors, decision errors, and performance errors (NHTSA, 2015). It is assumed that automation, through advanced sensing, algorithms and crash avoidance systems, has the potential to significantly reduce crashes and thereby save lives. However, the level of human crash avoidance performance that must be surpassed by automation is very high if it is to improve upon human performance or achieve the vision of zero fatalities and serious injuries (Johansson, 2009; Eugensson et al., 2011).

In the last few years there has been an intense focus on how to determine and ensure the safety of automated vehicles at a number of organizations (e.g. NHTSA AD Guidelines, 2018; EuroNCAP 2018, ISO 26262-1:2018, ISO/PAS 21448:2019; Uber, 2018; Waymo, 2018; Shalev-Shwartz, et al., 2017; Fraade-Blanar et al, 2019; and Wood et al. 2019). The safety work package focused on determining the potential safety impact of autonomous vehicles using predictive methods which *estimate* real-life crash outcomes, whereas the test probe work package focused on how to develop safe technology. Four safety challenges were identified and addressed by developing a Holistic Safety Impact Assessment Framework for Automation, and thereafter applying it in a feasibility study in order to answer the formulated safety research questions (SRQ). The four main safety challenges *(SRQ 1. What are the main safety challenges with self-driving cars?)* were identified as:

(1) development of a safety impact assessment methodology,

(2) development of a pre-crash scenario-based approach,

(3) definition of target levels for safety performance, and

(4) development of crash avoidance performance testing methods.

After reviewing existing approaches, the Holistic Safety Impact Assessment Framework for Automation in Figure 6.2.1 was developed to answer *SRQ 2. How should the safety impact be quantified?*.

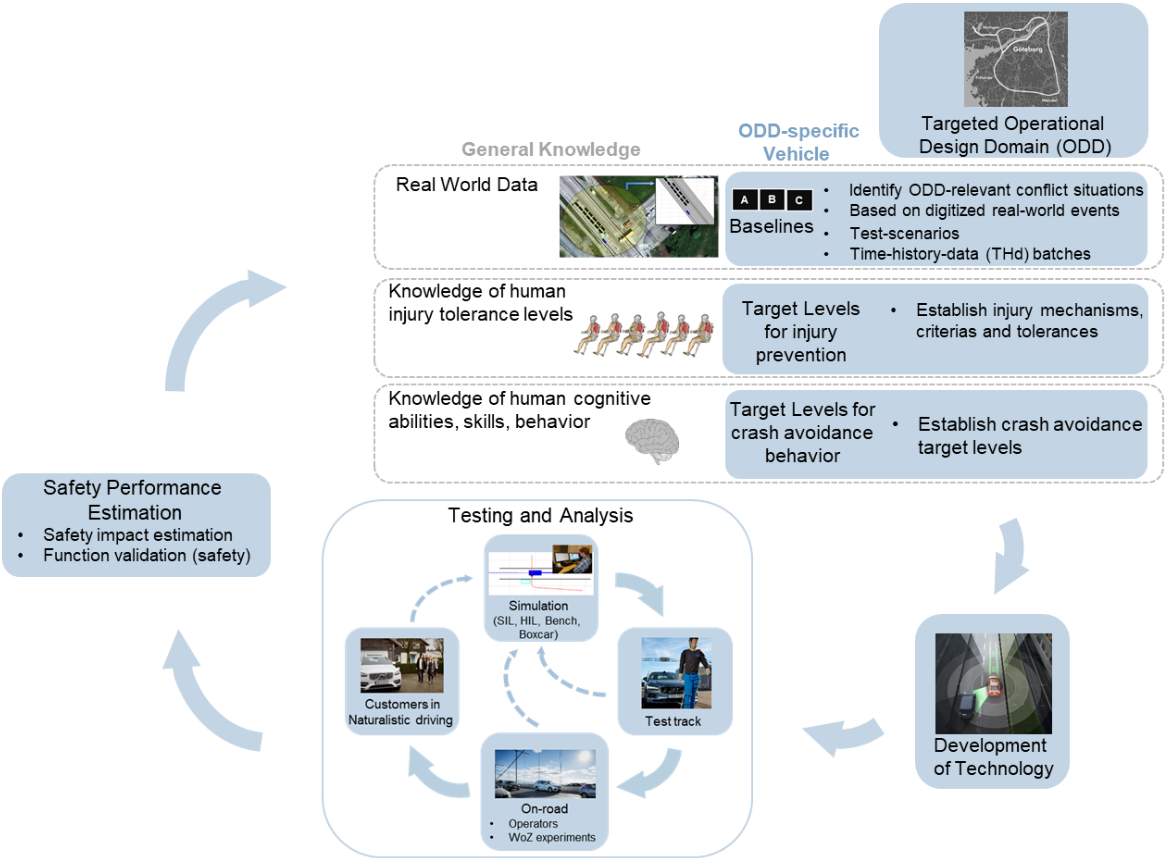

Figure 6.2.1. The holistic automation safety impact assessment framework.

The safety impact assessment is performed by rotating stepwise through each blue element in Figure 6.2.1, starting with formulation of the targeted operational design domain (ODD) (e.g. a divided highway in good weather conditions). The framework is depicted to emphasize its iterative and incremental nature, whereby the process iterates until an acceptable safety performance is achieved.

Baselines

After the targeted ODD is determined, valid real-world baselines for safety assessment are constructed. Baseline data are crashes, near-crashes (i.e., critical situations that human drivers manage), and non-dangerous events (see A, B, and C types of baselines in Figure 6.2.2). In addition, a large amount on normal non-eventful driving data are used for the overall development of AV functionalities, although not considered in the traffic safety evaluation specifically.

In this step, the relevant baselines within the ODD are determined. 22 ODD-relevant conflict situations were identified in real-world crash data to answer *SRQ 2.1 Which traffic conflict situations should be addressed for safety assessment?* (for more details see Lindman, et al., 2017). Thereafter various sets of real-world traffic event data were digitally reconstructed and clustered into time-history-data (THd) batches per test-scenario.

Different sets of baselines are needed to calculate the *intended positive effects*, *unintended negative effects,* and *residual crashes* as shown in Figure 6.2.2*.* The analysis of the AV performance regarding numbers of crashes-avoided and -mitigated, and non-dangerous situations where the AV performs a crash avoidance intervention that could potentially lead to a crash, forms the values for *intended positive effects* and *unintended negative effects* used in the final traffic safety impact assessment.

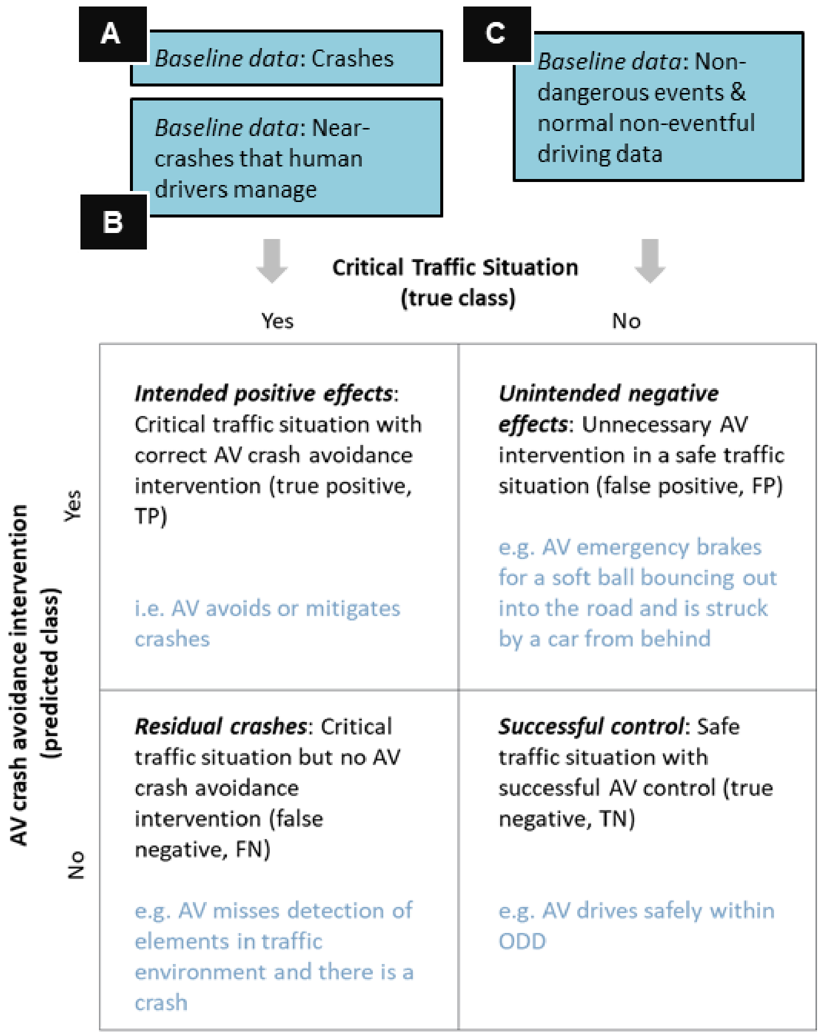

Figure 6.2.2. Contingency table illustrating data needed to determine intended positive effects, unintended negative effects, residual crashes, and successful control.

To study *SRQ 2.2 How do the automated vehicle and the driver react in safety-relevant situations?*, a feasibility study was conducted for three out of the 22 identified conflict situations (see Table 6.2.1).

Table 6.2.1 Conflict situations evaluated in the feasibility study.

Same direction, – same lane	
SDhvB (RE-F)	host and opponent vehicle travel in the Same Direction in the same lane, host vehicle is Behind the opponent vehicle (Rear-End Frontal)
SDhvF (RE-R)	host and opponent vehicle travel in the Same Direction in the same lane, host vehicle is in Front of the opponent vehicle (Rear-End Rear)
Opponent Vehicle Lane Change	
ovSD_lanechangeRT	host and opponent vehicle travel in the Same Direction in different lanes, opponent vehicle changes to the lane on its Right side (Lane Change)
ovSD_lanechangeLT	host and opponent vehicle travel in the Same Direction in different lanes, opponent vehicle changes to the lane on its Left side (Lane Change)
Car-to-Pedestrian SCP	
SCPpr, pedestrian from right	Straight Crossing Path, pedestrian from right

Safety target levels

The crash avoidance target is a mathematical model of an attentive, skilled and experienced Reference Driver as developed and implemented in the CAE simulation framework used for safety performance estimations of Automated Driving Mode. The crash avoidance target level (the reference driver model performance) is used in the safety performance assessment of whether an AV has reached an acceptable level for safety. The reference driver model can be applied to each individual baseline (i.e. a single case within a representative batch of digitized real-world traffic crashes and near-crashes for a specific conflict situation).

Figure 6.2.3 illustrates this principle with an example case for a Car-to-Pedestrian, Straight Crossing Path conflict. In the example, the reference driver exhibits defensive driving behavior (precautionary safety behavior) and reduces vehicle speed when approaching the stationary vehicle, and then has a fast reaction of 0.6s to when the pedestrian becomes visible. In comparison, the AV exhibits the similar precautionary behavior but reacts faster than the human. Reference driver reactions were implemented for each individual case per conflict situation in the feasibility study. The formulation of a valid, testable crash avoidance target to determine “what is safe enough?” can be seen as a major achievement in this project.

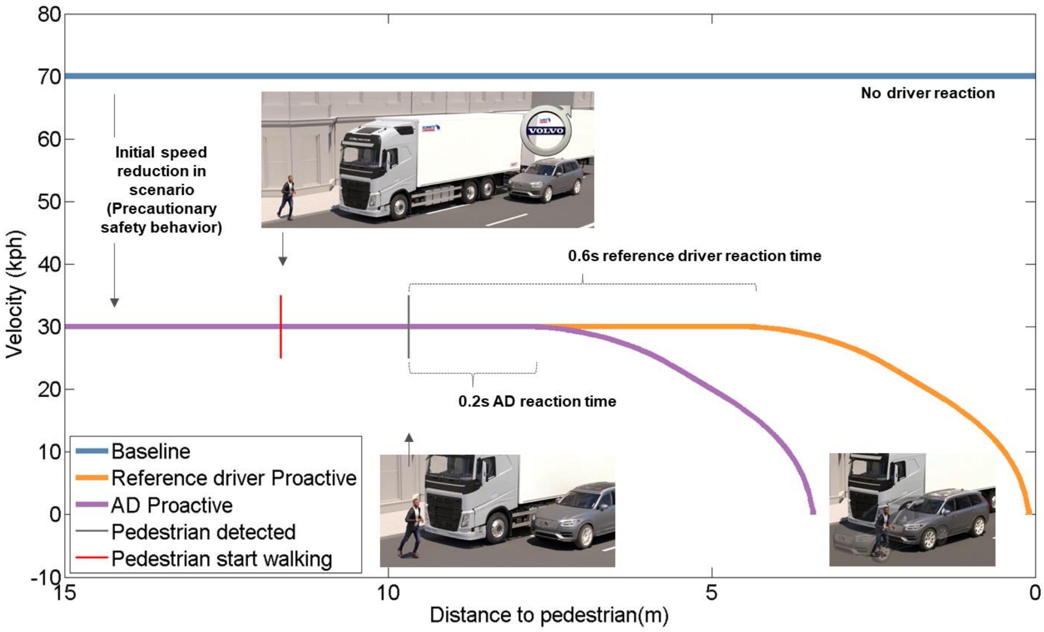

Figure 6.2.3. An example of the virtual Reference Driver Model behavior (yellow), in comparison to the original crash case where there was no driver reaction (blue), and the behavior of an automated vehicle (purple).

Knowledge of human injury tolerances and occupant protection principles has guided the development of protection inside and outside the car for many years (Jakobsson, et al., 2019). Although this injury prevention knowledge is relatively mature, groundbreaking work is needed on the new challenges associated with the crash safety verification of AD vehicles, e.g., new crash test configurations and a new variety of occupant seating positions. This work is currently ongoing in other projects addressing the residual crashes that an AV may be involved in.

Feasibility study

Results show a comparison to the crash avoidance target level in three conflict situations. Figure 6.2.4 illustrates an example of evaluation results. The baseline in the figure are all drivers that crashed (as they were actual real-life crashes). The *intended positive effects* in the treatment CAE simulation of an AD-model (crashes avoided and crashes mitigated) is compared to the performance of the reference driver model. In this example the target is indicated by the red dotted line, which is the estimate of what an attentive, skilled and experienced driver would have been able to avoid in the conflict situations. If the AD-model outperforms the reference driver model then the target is met. The AD-model performance should be viewed as the *crash avoidance potential* (max or ideal performance) of the AD vehicle, due to the fact that there may be a *potential reduction* of crashes in real-world traffic due to uncertainties in estimation (e.g., sensor performance variance, malfunctions, unintended negative effects). In addition, estimates of *actual outcome* will need to be based on estimates of potential unintended negative effects (see Figure 6.2.2), such as unnecessary AV interventions in safe traffic situations (false positive type I errors, e.g. the AV braking for a soft ball bouncing on the road) and critical traffic situations without AV intervention (false negative type II errors, e.g. residual crashes from sensor performance variance, malfunctions).

Thus, the crash avoidance *potential* needs to compensate for uncertainties in estimation of *actual* performance, providing an *assessment margin* to be on the safe side and ensure that the crash avoidance target level is met. The residual crash involvement should be assessed with regard to injury prevention to assist in making decisions regarding whether the total safety performance meets injury prevention targets.

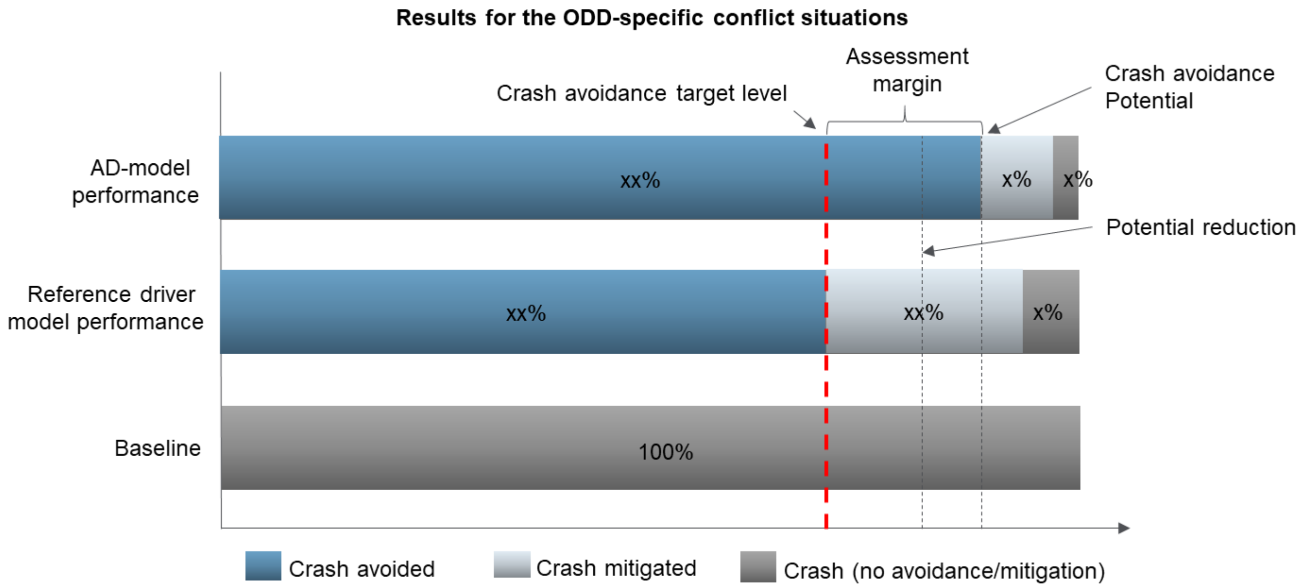

Figure 6.2.4. Example results illustrating the crash scenario performance of an AD-model compared to the reference driver model- and baseline performance.

As demonstrated by the feasibility study results *(SRQ 2.3 To what proportion and degree are different crashes avoided or mitigated?)*, there is a great crash avoidance potential from automation. Within the operational design domain (ODD), the automated vehicle outperformed the crash avoidance target level (the reference driver model performance which represents a maximum human performance level) in all conflict situations, and also outperformed ADAS performance. The results also illustrate that the impact on overall crash rates is tied to the definition of the ODD. That is, an AV can only affect the crashes within its ODD, the more an ODD covers where frequent and serious crashes occur, the more safety impact that AV will have. Avoidance and mitigation performance were affected positively by driving at posted speed, and that exclusion of adverse lighting and weather conditions from the ODD left those crashes to the ADAS or driver to avoid since the AV cannot be activated there. Within the ODD, one key insight is that there are still residual crashes which typically occur in congestion lane change situations or situations with visual obstructions where there is no room for avoidance maneuvers. How to reduce serious injuries and fatalities to zero in these residual crashes, through occupant and injury prevention, is the subject of ongoing research projects within crashworthiness.

Within the motorway ODD, the ideal, fictive AD-Model was estimated to give the following results:

- *Same direction, rear-end frontal*: 100% crash avoidance (compared to 100% for the reference driver model, and 88% crash avoidance plus 5% crash mitigation for ADAS).
- Results for *Rear end, Rear crash* were presented as probabilities of crash. The chance of being hit from behind – in the various real world Rear-End Frontal crash situations given that a vehicle is following at a constant time headway – does not vary much for different baseline and treatment settings, although a small trend of decreased rear crash probability can be noted with ADAS and the ideal AD model.
- *Car-to-pedestrian SCP, pedestrian from right*: 97% crash avoidance plus 3% crash mitigation (compared to 83% and 17% for the reference driver model, and 90% plus 9% for ADAS).
- *Opponent vehicle lane change*: 93% crash avoidance plus 6% crash mitigation (compared to 79% and 18% for the reference driver model).

Other safety analyses

Other analyses pointed out three safety myths:

(1) Myth of the mileage-driven approach,

(2) Myth of driver capabilities, and

(3) Myth of unidimensional automation.

Lindman et al (2017) identified that the mileage-driven approach to safety is infeasible, as the number of kilometers necessary to establish future differences in crash rates indicate that retrospective traffic safety evaluations will be far from realistic for many years to come. A series of experiments and papers (Victor et al, 2018; Gustavsson et al, 2018; and Tivesten et al, 2019) studied over reliance, and dramatically illustrated the limits of driver capabilities to act in a supervisory role as automation becomes more and more reliable but not perfect (an Irony-of-Automation). These results *(SRQ 2.2 How do the self-driving vehicle and the driver react in safety-relevant situations?)* point to the need for crystal clear communication about whether automation is assisting or replacing the driver in order to avoid driver-automation expectation mismatches. This insight led to a formulation of human-centric types of automation (Assistance, Passenger-only automation, and Role-switching automation) instead of unidimensional “levels of automation” (e.g. SAE J3016, 2016). These types of automation are focused on improving understanding and communicating the role the driver plays rather than the level or (unidimensional) amount of automation.

In summary, the performed research in this project addressed all safety research questions and contributed to the understanding of a range of issues in each element of the Holistic Safety Impact Assessment Framework for Automation (Figure 6.2.1). Results from application of this framework *(SRQ 3. How can traffic safety be improved? and SRQ 4. How can automation contribute to a crash-free road transport system?)* (1) show automation can surpass the crash avoidance target level, (2) show how large this improvement could be in comparison to manual driving and driving with ADAS, and (3) show how the degree of improvement depends on road type and operational design domain. Clearly, the potential is enormous.

6.3 Traffic flow

How can AVs influence traffic flow?

Autonomously driven (AD) cars with strong focus on cautious control and/or comfort can be expected to reduce traditional capacity and cause traffic disturbances if driven autonomously through bottleneck areas. On the other hand, their potential to avoid accidents and incidents would take away associated capacity drops and traffic disturbances.

Capacity in motorway road networks like the Drive Me route depends mostly on lane change areas and queues propagating back from exit bottlenecks. More effective automated lane change behavior than today's will probably appear, but it is not expected in the first AD versions. Initial very cautious AVs will most likely reduce high flow lane change efficiency why capacity is expected to decrease accordingly. Moreover, AVs with low low-speed acceleration, as compared to human drivers, will delay traffic recovery after capacity breakdown, during stop-and-go traffic, dissolve queues more slowly and increase traffic disturbances and travel times accordingly. If customer preferences and safety allow, these AD-induced traffic disturbances may be overcome.

More than 95 % of Swedish motorway mileage is carried out in free flow conditions. Legally driving AVs which respect the speed limits, in contrast to a large portion of human driven vehicles, will naturally have correspondingly longer travel times in free-flow conditions. AV users will probably not notice the time difference since travel time becomes value time when user is freed from the driving tasks. These AVs will probably have small effects on free-flowing traffic as long as other faster moving vehicles can overtake them easily when so desired.

Unnecessary lane changes, poor lane choices and other traffic-inefficient human driving behaviors use up part of the available capacity in present road networks. AVs will hopefully avoid these behaviors and the corresponding capacity degradation. Further work is needed to understand the magnitude of this problem/opportunity. Future AVs may also provide new ways to control traffic directly at a microscopic level in urban/motorway road networks and at signalized intersections which may have significant effects on the traffic system efficiency.

How can avoided crashes influence traffic flow?

Modern driver support and collision avoidance systems should already in the short term reduce accidents and incidents, and capacity drops of this kind. These effects will improve further when safe AVs are introduced at a larger scale. Two approaches have been used to estimate these potentials, as reported in Kronborg, Bergh, Svensk & Palm (2018). The first analyzed police reported accidents with Volvo cars involved using travel time and spot speed-flow data from the Swedish Transport Administration detector systems. The other compare travel time distribution data for days with and without accidents or incidents for a part of the Drive Me route.

Some efforts have been done to assess the traffic improvement potentials by entirely avoiding accidents and incidents using data from a section of the Drive Me route. These suggest daily travel time standard deviation to decrease by some 40-60% and percentiles to improve by for 85th: 1 to 12%, for 95th: 3 to 53%, for 99th: 18 to 37% and for 99.5th percentile: 33 to 61% due to road section.

Thus, there are substantial traffic improvement potentials in avoiding accidents and incidents with vehicles equipped with active safety and AD systems.

How may AVs impact traffic on the Drive Me route?

The impact of a 20% share of identical AD vehicles on the 2014 workday afternoon peak hour traffic on the Drive Me route around Gothenburg has been studied using VISSIM traffic simulations. AD effects on traffic have been evaluated for capacity, travel time, robustness and to some extent punctuality. Here, we assumed AD vehicles to behave similarly to a pre-2016 tuning of Volvo Cars' Adaptive Cruise Control at its shortest time gap but often with lower low-speed acceleration. Furthermore, these AVs are assumed to not introduce own unnecessary speed oscillations, to obey speed limits, and to choose and change lane with the same logic as the normal drivers in these calibrated simulations. In these simulations, AVs were not allowed to drive faster than 70 km/h, i.e. sometimes below the speed limit, which is likely an overly pessimistic assumption for the future situation when the AD share will be 20%.

These simulation results indicate that afternoon rush hour traffic on most parts of the Drive Me route (with no or minor capacity problems) is only marginally affected by these AD vehicles at this AD share at least when it comes to travel time averages. This should also hold during non-peak parts of the day when there is less traffic demand.

More seriously, the capacity breakdowns which occur already without AVs on the eastern side of the ring road (already with capacity problems), get amplified by these AVs in autonomous mode with a 20-45% increase in mean peak hour travel time on the eastern side on average, with 5% average increase eastbound on Söderleden and 15% for the entire Drive Me route. There are increasing delays with the growing queues on the eastern side throughout the rush hour probably due to slower flow breakdown recovery and a small average capacity reduction by 2% due to 20% of these AD vehicles. If capacity breakdowns cannot be foreseen, then punctuality would degrade accordingly.

The influence 20% of these AVs have on traffic system robustness at 30-minute lane blockages for 2014 afternoon workday rush hour traffic has been studied with VISSIM for 8 separate lane closures on the Drive Me route. The traffic system becomes less robust with these AVs in autonomous mode if the lane closure causes traffic disturbances without AVs, otherwise no effect. This is probably a result of the low acceleration at low speeds for these cautious comfort-oriented AVs. The lane closure on Söderleden resulted in 10 percentage points additional reduction in traffic flow during incident on average and 35-40 percentage points for the entire hour due to 20% of these AVs. Queues caused by the incident dissolved more slowly with 200 m increase in max average queue length and 3 min increase in max average vehicle delay. A lane closure near the traffic light on northern section yielded 15 percentage points additional reduction in traffic flow during incident and 20 percentage points for the entire peak hour. The average effect for all lane blockages is 6 percentage points additional reduction in traffic flow during incidents, and 15 percentage points for entire hour with 20% of these AVs on the Drive Me route during 2014 workday afternoon rush hour traffic.

In order to avoid the predicted traffic disturbances in rush hour bottlenecks of AVs with very cautious or comfort-oriented tuning, for example from low low-speed acceleration and/or less efficient high-flow lane changes as compared to human drivers, it might be more suitable with manual operation in these critical areas / situations.

Tactical and strategic lane choice are critical for capacity. This is even more the case for these slowly moving AVs. A more dedicated AV keep right function might have improved capacity.

For the simulations above, calibration is done towards measured averages why analysis focus is on average effects. To address punctuality, we are developing a new calibration procedure aimed to automatically capture normal traffic variations based on multi-objective optimization. Initial results have been presented. Model calibration without good pre-tuning requires good quality data, and an easier access to such data would be preferred.

How should motorway infrastructure be modified when AD vehicles become common?

The importance of establishing a well-functioning digital infrastructure for the introduction of automated vehicle related functions has grown throughout the project period. The analysis of how motorway infrastructure may change when AD vehicles become common are presented in Kronborg, Bergh, Svensk & Palm (2018). Harmonization/ standardization work, necessary investments in hardware, software, including responsibilities for such investments, and business models are examples of identified challenges for industry and authorities to address at both national and international level. Even though the ADEST project has not focused on digital infrastructure, it has contributed towards an increased understanding of the opportunities and challenges related to digitalization. Results from the project has been used as valuable inputs to start other demonstration projects such as; Nordic Way (EU funded project within Connecting Europe Facility) and AD Aware within the Strategic Innovation Platform (SIP), Drive Sweden.

Possible measures to modify the existing physical infrastructure have also been studied during the project in terms of dedicated AV lanes, reduced lane width and special AV bridges. The results indicate that special lanes for AVs would only improve capacity and travel time for AVs unless the total number of lanes increases. The overall capacity with also non-AVs would decrease unless AV-ratio is sufficiently high. The main reason for this is merge problems where AV-lane ceases if that also means a reduction in total number of lanes.

Effective lane widths on capacity problematic sections in Sweden are already around 3 m (including road markings) with effective truck and bus widths around 2.7 m. Narrow AD lanes could then not take trucks unless truck size is adjusted accordingly. A Swedish problem with narrower lanes is increased rutting partly due to studded tires. AVs might reduce this problem by choosing lateral position within a narrow lane with larger variation than “normal”. In addition, extensive monitoring and reporting of road condition status by all AVs to road network owners can help to identify and guide road maintenance to needed areas at appropriate times.

In urban motorway systems with short interchange distances, capacity problems, and very varying traffic, it is very difficult to find places where AV bridges can be located. These locations need to be considered with respect to investment costs, intrusion in the environment, and if they can solve capacity problems in a mixture of AVs and non-AVs. As a result, no such locations have been identified along the eastern side of the Drive Me route at expected reasonable costs and normal aesthetic quality values.

6.4 Energy efficiency

The Energy efficiency of an individual vehicle is primarily affected by the speed and speed changes. With AVs it is possible to take the driver out of the driving task, and therefore create new opportunities to increase the usage and precision of Eco-drive mechanisms. Moreover, and perhaps more importantly, AVs can also influence surrounding vehicles on the road to drive in a more energy efficient way, meaning it is not only the AV that is affected by introducing AV-functionality on the roads, but many manually driven vehicles will be affected by them as well. It is expected that several mechanisms in traffic will change when adopting to AD and this will affect traffic flow. This in turn will affect the energy efficiency, by changing vehicle speeds and acceleration, travel time, brake losses, and aerodynamic resistance. It is also expected that other types of emissions will be affected, such as noise and particle emissions.

In the selection of driving conditions in this project, we have focused on the ring route around Gothenburg in afternoon rush hour. This is a typical commuter route consisting of 70-80 km/h motorway, where congestion is common on some locations. The technology level of the AV regarding energy efficiency is what can be expected in the timeframe between 2020 and 2030.

There will also be changes in personal mobility (e.g., car sharing and ride sharing) when highly autonomous vehicles are available on public roads. The way we use cars will probably not be the same in the future and this affects energy efficiency, but perhaps not so much 'fuel consumption per vehicle kilometer' as 'total energy spent on personal mobility'. Due to the very high uncertainty to what extent this will occur in the future, the effects of this has not been included in this project. However, it is a very important field of research to know more about the effects on mobility and the instruments that are needed for AD to fit into a sustainable future.

A literature study conducted, shows that data on real-life effect of AV on energy efficiency and other environmental aspects has been lacking, and even now (2019), at the end of the project, real life experience with mature AV is still very limited. While the potential of single factors within AV are widely known and may provide significant improvements in energy efficiency there are currently no established methods to estimate the expected impact in entire traffic systems.

Automation facilitates the implementation of eco-driving, including optimized acceleration and deceleration, efficient engine use and gear shifting, and even more efficient routing and better optimized driving patterns. In addition, safer AV-cars enable the shift to smaller vehicle sizes and consequently lower fuel consumption. Also, AVs are the key to future autonomous taxis, and considering taxi size can be matched with the individual trip requirements, energy efficiency may hence be improved. Moreover, AVs can improve energy efficiency by having smaller engines with lesser requirements for acceleration.

On the other hand, AVs might increase travel demand and total fuel consumption by providing mobility for many groups that are currently unable to drive, such as children, older seniors, people with medical conditions that preclude driving, and those who are non-drivers by choice. The potentially reduced cost of travel as a result of removing the requirement of driving skills can also motivate more people to travel more and longer. Moreover, passengers who are freed from the driving task may request more energy-intensive features for leisure or productivity.

Due to the unpredictability of these considerations, the total impact on energy is not clear and tentative estimations from experts around the world span from -80% to +300%. Whether AV will have a positive or negative effect on traffic volume, urban life and energy efficiency depends highly on how prepared the society is, how it acts, and obviously how AD functionality will develop. It is important to consider that the system effects of AVs on energy efficiency depend also on the interaction of AVs with other vehicles in a traffic system. To evaluate the behavior of AVs on a large scale, traffic simulation is an alternative that has been shown to be effective.

We have addressed the questions about energy efficiency by evaluating the impact of early AVs on a traffic system mixed with human-driven vehicles. To this end, tens of thousands of log files from real driving was analyzed. Also, a traffic simulation environment was created using a microscopic simulation tool. Since no such existing traffic simulation tool was available at the beginning of this project, the development of one was crucial for the success of this project. Much effort was put into implementing, verifying and validating the simulation environment.

For an adequate simulation, three pieces are necessary: the environment, the driver model, and the vehicle. For our purposes, the simulation environment must not necessarily reflect all aspects of real traffic, but it must represent the aspects essential for estimating energy efficiency in real traffic.

The environment describes the road network, lanes, entry and exit ramps, road grades, posted speed, traffic origin-destinations matrix with individual route choices, and so on. In this project we have specifically focused on the ring road around Gothenburg, referred to as the Drive Me route (see section 2.1.1. for more information). We simulate this route at afternoon rush hour. For the simulation we have used SUMO, which is an open source microscopic traffic simulation suite created by DLR (Deutsches Zentrum für Luft- und Raumfahrt). Because of it being open source, it is possible to improve or in any other way further utilize the work made in this project.

All entrance and exit roads to the Drive Me route are included. In order to get a realistic inflow of cars to the route, parts of the connecting roads are also modelled. The traffic demand itself (i.e., traffic inflows and outflows) is derived from a VISUM traffic model, which was built and owned by the City of Gothenburg.

A screenshot from the program can be seen in figure 6.4.1.

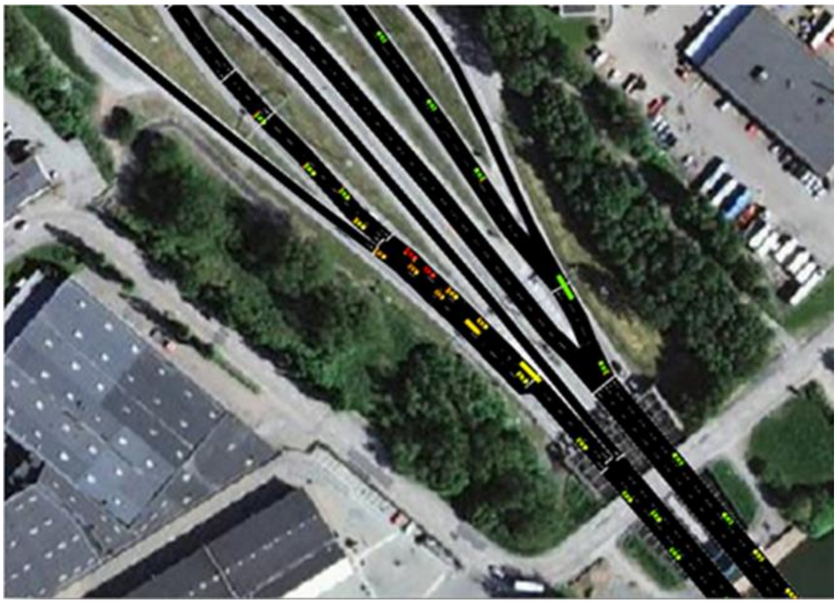

Figure 6.4.1. Bird's eye view of the SUMO simulation tool. Satellite picture source: Eniro.se

A method to optimize the driver models parameter settings has been developed and applied in order to tune them and verify compared to recorded data from vehicles on the Drive Me route. The main challenge to simulate traffic is not only to model cars following each other, but also the complexity in lane changing behavior. This has also been addressed in this research project.

AVs are assumed to maintain the speed at the speed limit when in free flow conditions. We assume that using a conservative cautious control model to simulate AVs is justified when simulating a low share of AVs, applicable for the near future. However, when the share of AVs increases together with the degree of autonomy, these models may no longer be valid. Furthermore, this model was limited to passenger vehicles, thus all heavy vehicles in the simulation have human drivers.

To calculate noise, The HARMONOISE model was used within SUMO. This model is widely accepted to give a representative level of noise along the roadside, given the input of vehicle mass, speed and acceleration.

In order to calibrate and validate the traffic simulation we use two different sets of measured data from the Drive Me route: traffic detector data and detailed driving data from several individual cars provided by Volvo Cars.

This data was compared to speed traces from vehicles in the simulation in order to evaluate how accurately the driver models represent human driving behavior.

Results

By analyzing several thousands of trips on the Drive Me route from the dataset provided by Volvo Cars, instantaneous comparisons have been made between cars driving with and without Adaptive Cruise Control activated. It was shown that diesel cars with ACC activated have a lower fuel consumption on average compared to manually driven cars, for comparable speeds (see fig 6.4.2).

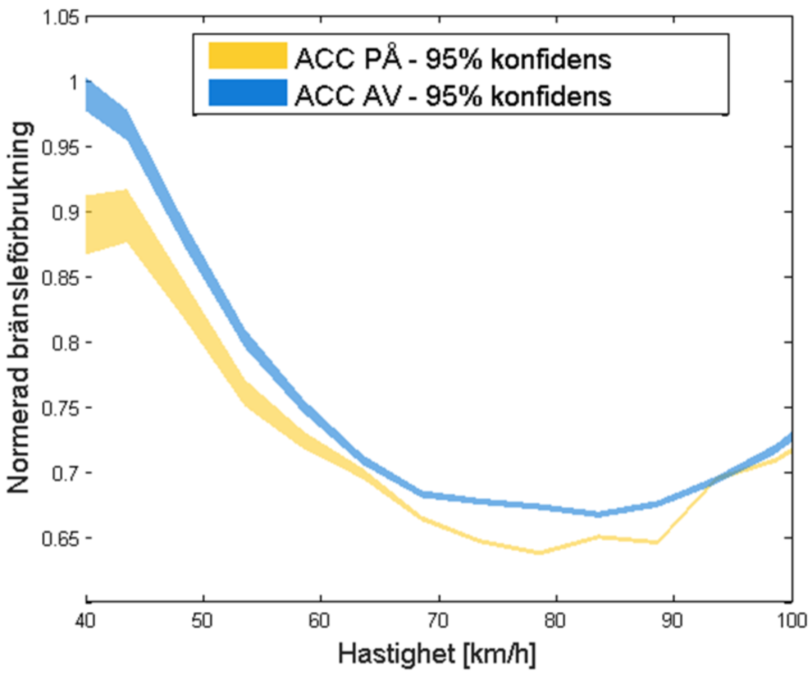

Figure 6.4.2. Normalized Fuel consumption [volume/distance] for diesel cars when driven with ACC on or off respectively.

This result indicates that longitudinal automation is more energy efficient than manual driving. The reasons behind this is that cars with ACC activated tend to keep a longer average distance to the lead vehicle than manually driven cars, at least in non-congested situations.

Partly, ACC also induces lower acceleration and deceleration, which have been observed in the data (see Figure 6.4.3).

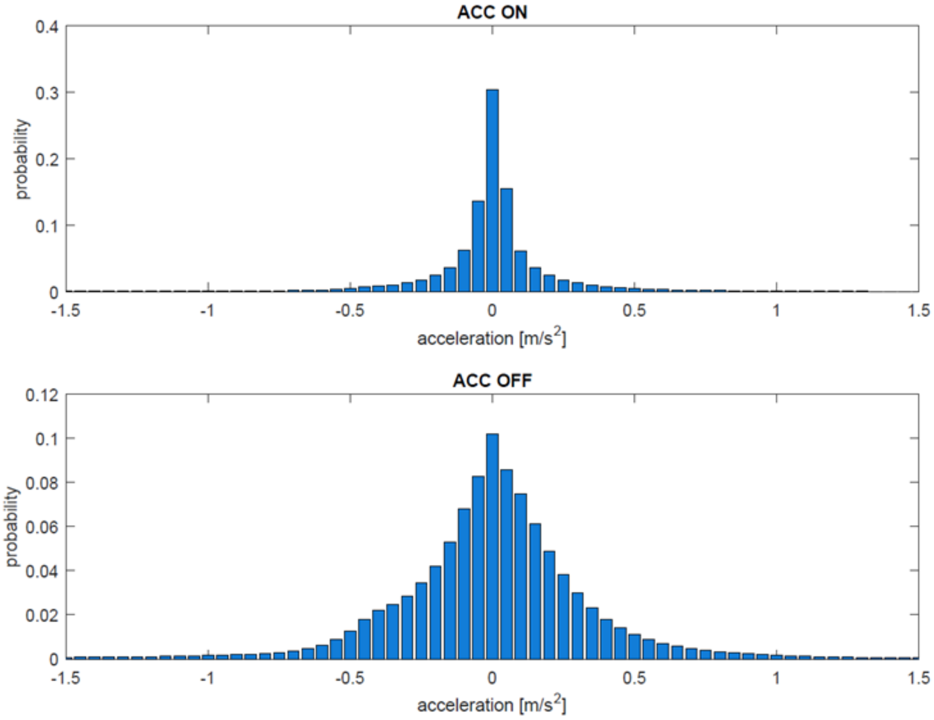

Figure 6.4.3. Histogram of different accelerations with ACC on or off respectively.

However, when driving on roads where traffic is congested, AVs, at least with the conservative behavior implemented in our simulation, increases congestion and hence increases the total fuel consumption in the traffic system. This is partly due to the longer distance to the lead vehicle (AVs may take up more “space” on the road, allowing for a lower throughput).

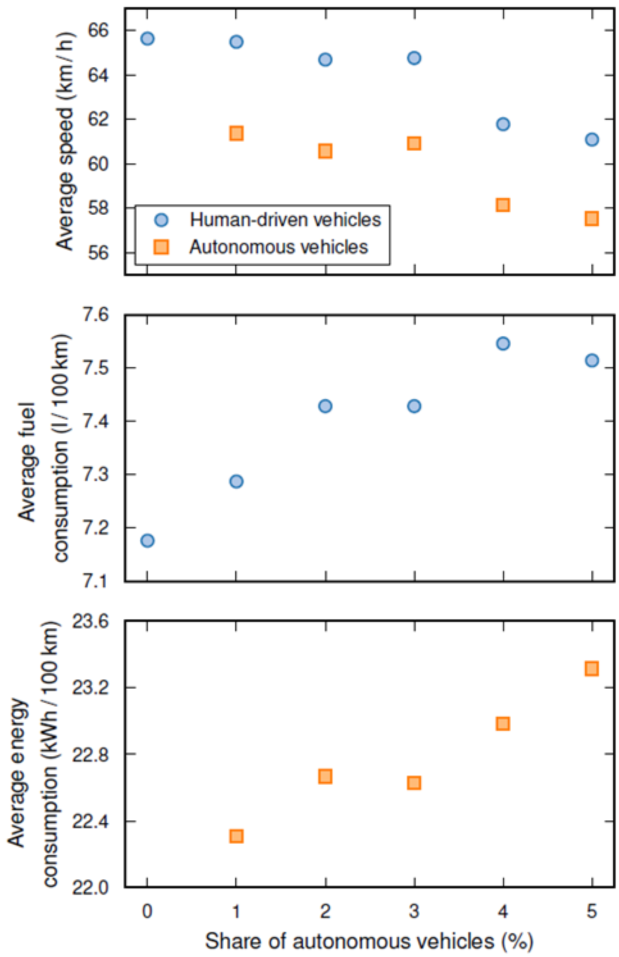

Figure 6.4.4. Some system effects when increasing the share of simulated autonomous cars in traffic on the route. AVs are assumed electrified, while human driven cars are conventional.

AVs was seeded in randomly at all entries, at a fixed statistical share of between 1% and 5%, see Figure 6.4.4. At higher shares of AVs, traffic flow was affected to such an extent that the absolute values of energy efficiency were no longer reliable. Nevertheless, the trend is clear. It should be noted that the AVs where set to be very prone to stay in the right lane, only making lane changes if absolutely necessary.

The sound model HARMONOISE was implemented into SUMO, providing the estimated noise levels at the roadside. A simulation was run on a two-lane motorway stretch of road, see figure 6.4.5 for results. It should be noted that there were trailer trucks going 80 km/h on the stretch of road. Given the assumption that the AVs are not inclined to overtake, they will soon also be limited to 80 km/h, regardless of their desired speed. This probably explains the capped noise for higher desired set speeds. It should also be noted that the model does not take into consideration which type of engine there is (electrified/diesel/petrol etc.).

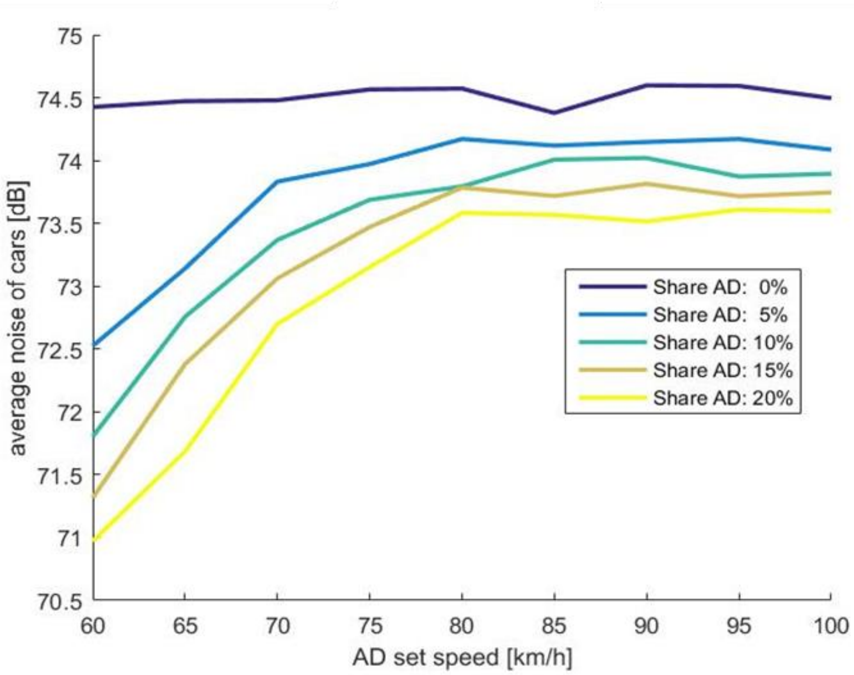

Figure 6.4.5. Average noise dependent on vehicle set speed and different shares of automated vehicles on the Drive Me route.

Conclusions

Due to a very high focus on safety, it has not been a realistic option to experiment with vehicle control algorithms on physical cars. One conclusion from this project is that autonomous control algorithms should evolve from existing driver support systems (which our conservative, cautious, AV models tried to mimic), to minimize the gap to the lead vehicle, at least when driving in a congested situation. This is to maintain performance in congested, or near congested, situations, or even improving performance in the complete traffic system, causing a decrease in total energy efficiency.

6.5 Project results and contributions to FFI goals

The ADEST/ADFE objectives, how they were addressed and/or modified, as well as to what extent the objectives were met are described in chapter 5.

This section describes lists the main project results and how they have contributed to the FFI goals that are most relevant for ADEST/ADFE:

- Overarching FFI objectives are: (https://www.vinnova.se/globalassets/mikrosajter/ffi/dokument/ffi-fardplan-2019.pdf),
  - To reduce the environmental impact of road transports
  - To reduce the number of people injured and killed in traffic accidents
  - To strengthen international competitiveness by stimulating research and innovation
- FFI sub-program *Traffic Safety and automated vehicles* (TSA) goals (in ADEST) (https://www.vinnova.se/contentassets/315fa102a839416486a70bcc4bf7b5d9/tsaf_augusti_2018_slutlig_version.pdf)
  - Program area A – Analysis, knowledge, and enabling technique for enhanced traffic safety.
  - Program area D – Driver support and interaction with different degrees of automation (i.e., driver assistance, and autonomous drive).
- FFI sub-program *Efficient and Connected Transport Systems* (with the Swedish abbreviation EUTS) goals (in ADFE) (https://www.vinnova.se/globalassets/mikrosajter/ffi/dokument/fardplan-euts-2018-10-11.docx).
  - EUTS focus on the benefits of a connected and cooperating traffic system with respect to the impact on transport efficiency (e.g., travel time), quality of life, and the environment (e.g., fuel consumptions, emissions, noise).
  - Program area 2 – Vehicle and mobility services, and specifically how automation can be used to create a benefit in the transportation system.
  - Program area 3 – Efficient use of infrastructure, and specifically how to use the infrastructure more efficient when automation increases.

The ADEST/ADFE projects sparked the development towards highly automated vehicles in Swedish vehicle industry due to the **development and building of test probes**. The resources for product development within this area steadily increased during the projects, resulting in a new joint venture company between Volvo Cars and Veoneer launched in 2017. This company, named Zenuity, now employs more than 600 people developing software for advanced driver assistance systems and autonomous drive. Although the very ambitious aim to enable regular customers to use unsupervised automation on the Drive Me route was not met during the project, it is still a clearly present and prioritized area for product development within the Swedish vehicle industry. The test probe work package enhanced our understanding on the design principles and challenges with developing unsupervised automation, and this knowledge has been used as a valuable input to ongoing work and development strategies for vehicles and infrastructure. This taps directly into the overarching **FFI goal** to increase the competiveness of the Swedish vehicle industry, as well as the TSA goal with respect to enabling techniques for automated drive (sub-program area A).

The **test probe vehicles** currently serve as a useful platform for product development and research since they are equipped with sensors and a data logger that is not available in production vehicles. Additional test probes were built outside the scope of the projects and are currently: 1) Used as prototypes and further modified for the development of highly automated vehicles. 2) Are driven by professional test drivers for technical evaluation including the behavior of surrounding traffic in the EU-funded project L3pilot. 3) A few test probes have been rebuilt to so called Wizard of Oz (an experimental platform), and are currently being utilized in various research project. These spin-off effects relate to the overarching **FFI goal** to increase the competiveness, since the vehicles facilitate product development and research. Additionally, the sub-program TSA (area A) goals is addressed since the vehicles are used as tools for research on real-world data on automated vehicle interactions with surrounding vehicles, and the Wizard of Oz is a tool for research on the corporation between human and automation.

The **safety** work package has delivered a general framework for impact assessment including different degrees of automation, a methodology for estimating the safety effect of autonomous driving (including analysis, reconstructions, and simulations based on real world crashes), an analysis of potential safety impact within the defined ODD, and internationally recognized human factors research on automation. This work package has a clear focus on the overarching **FFI goal** to reduce the number of people injured and killed in traffic accidents towards Vision Zero, as well as the goal to strengthen international competitiveness by providing leading safety research. Furthermore, the impact assessment framework and methodology is a clear deliverable to the TSA program area A. The human factors research on supervised automation provides an enhanced understanding on the balance between human and automation (TSA program area A), as well as how to support the driver (e.g., by attention reminders) in supervised automation (TSA program area D), resulting in revised design principles for supervised automation as well as one patent (overarching FFI goal on competitiveness).

A common **open source computer simulation platform** to study the impact of automated vehicles on the complete traffic system was initially developed and calibrated within the work package **energy efficiency**, and it was further developed for studying traffic efficiency with particular focus on traffic variations within the **traffic flow** work package. The advantage of open source tools, as compared to black-box commercial ones is transparency. The underlying equations are “visible” and can be modified in accordance with research needs. In addition, commercial traffic simulation tool VISSIM was also used during first phase of the traffic flow work package. This work has therefore made important contributions in the tools and methods needed to enable research within these areas. In addition, the open source platform may be shared and further developed together with other partners in ongoing and future research projects. This result is an important contribution to the **FFI goal** to increase the competitiveness by providing tools and methods that enable further research and collaborations. Furthermore, it has provided tools to study the environmental impact of road transports (overarching goal 1), and to investigate the effects of automation on transport efficiency and the environment within the traffic system (EUTS, program area 2 and 3). These simulation tools are now being further developed and used for Volvo Cars product development purposes to strengthen the competitiveness.

A **scientific methodology for assessing the environmental impact** of automated vehicles is partly addressed in the previous paragraph. However, the methodology consists of several parts using both analysis of real world data and virtual simulations with additional modules to estimate the energy consumption, emissions, and noise. The energy efficiency work has taken several important steps in developing the methodology and consequently strengthening our position in this field of research. This methodology is already further utilized by other partners in the research community, which will benefit ongoing and future research in this area. The methodology is an important contributions to the **FFI goal** to increase the competitiveness, and strengthening the research area of the environmental impact of road transports (overarching goal 1 and 3), and to investigate the effects of automation on the environment within the traffic system (EUTS, program area 2 and 3).

The **effect AV will have on traffic efficiency**, using simulations in VISSIM, couples directly to primary transportation needs by addressing transport efficiency and transport quality in line with the **FFI goals** for the sub-program *Efficient and Connected Transport Systems*. The underlying traffic, influenced by AVs, impacts societal targets on environment, safety and resource usage corresponds to the overarching **FFI goals**. Throughout this project period, Volvo Cars has gained important knowledge about available traffic data, resources and expertise in Sweden, driver and traffic modelling, and practical viewpoints relevant for the entire road network operations. Trafikverket has developed an increased understanding of autonomous vehicles in terms of their development process and what they really are to better understand implications of future AVs on road networks and traffic. This is relevant for infrastructure planning at Trafikverket. The collaboration between industry and authorities developed through this project gives a competitive edge to a small country like Sweden. The results of this traffic research have given important steps towards tools and guidance for: 1) to identify ODDs where a given AV will have positive or negative impact on traffic efficiency, 2) to put requirements on AV behavior and 3) to tune AV function parameters to be in balance with local traffic on selected ODD. In addition, the traffic improvement potential by avoiding accidents was shown to be significant during Gothenburg rush hour traffic. The project results also outline several future research directions for AVs and normal traffic in order to enable improved traffic system efficiency. All these aspects are important contribution to meet all overarching **FFI goals** on competitiveness, the **EUTS goals** on resource and energy efficiency, as well as the **TSA goal** on safety.

The project has also contributed towards a better understanding of the challenges related AV specific road infrastructure changes that would have to be solved in order to have positive impact on all **FFI overarching goals**. The ADEST/ADFE projects have also contributed towards a better understanding of the importance of establishing a well-functioning digital **infrastructure** for the introduction of automated vehicle related functions (EUTS goals, Program area 2-3).

7 Dissemination and publications

7.1 Dissemination of knowledge and results

How has the project results been (or plan to be) used and disseminated?	Mark with X	Comments
Enhanced knowledge within the research area	x	Yes, within all four research areas.
Implementation in other advanced technical development projects	x	Yes, see below.
Implementation in other advanced product development projects	x	Yes, it has been implemented in ongoing product development for future vehicles aiming for highly automated driving in production vehicles. In addition, the findings also serves as an input to further development of ADAS such as pilot assist and adaptive cruise control.
Introduction on market	x	See above, within the next couple of years.
Used in investigations / regulations / permit cases / political decisions	x	Yes, an AV driving permit for specially trained professional test driver has been issued by Transportsyrelsen in November 2018, at the very end of the projects. Continuous dialogue has been ongoing in relation to legal and rating requirements.

The results from these projects has been presented in the following papers and reports:

- Eight published scientific papers (Bjärkvik, Fürer, Pourabdollah & Lindenberg, 2017; Gustavsson, Victor, Johansson, Tivesten, Johansson & Ljung Aust, 2018; Lindman, Isaksson-Hellman, & Strandroth, 2017; Pourabdollah, Bjärkvik, Fürer, Lindenberg & Burgdorf, 2017a & 2017b; Tivesten, Victor, Gustavsson, Johansson & Ljung Aust, 2019; Victor, Tivesten, Gustavsson, Johansson, Sangberg & Ljung Aust, 2018, Zhu, Gonder, Bjärkvik, Pourabdollah & Lindenberg, 2019).
- Additionally Victor et al. (2019) received the Human Factors and Ergonomics Society's 2019 Jerome H. Ely Human Factors Article Award, since the paper was judged as the best article in the 2018 volume of the *Human Factors* journal.
- One public report (Kronborg, Bergh, Svensk, Nordqvist & Palm, 2018)
- Three internal non-public reports (Lind, 2017; Sukennik, Varhulík & Braný, 2016; Thuresson & Forsman, 2019).
- One manuscript (Larsson, Ljung Aust, & Victor (unpublished manuscript))

- Two book chapters (Seppelt & Victor, 2016; Victor, Rothoff, Coelingh, Ödblom, & Burgdorf, 2017).

Additionally, a more extensive non-public version of the ADEST/ADFE final report were presented to VINNOVA.

Several project presentations were also made at international conferences including SUMO User Conference 2017, IRCOBI 2017, the 2017 IEEE Transportation Electrification Conference and Expo, the IEEE 20th International Conference on Intelligent Transportation Systems 2017, the Driver Distraction and Inattention conference in 2018, and the Automated Vehicles symposium 2019. There were also presentations at two Swedish conferences including FFI conference for sub-program Traffic Safety and automated vehicles 2018, and Transportforum 2019.

The projects have also strengthened the **research collaboration** for the partners within the project (Swedish transport administration, Volvo cars), as well as with other collaboration partners. The work package energy efficiency has a close cooperation with the National Renewable Energy Laboratory (NREL) in Denver, US which has led to a joint paper on the effects of ACC. There has also been a number of workshops and contacts with key players within traffic simulation (e.g., NREL, VTI, Linköping Traffic System group, Automatic Control group at Chalmers Technical University). Several experiments for evaluating the technology and human performance has been performed at the ASTA Zero test tracks with valuable support from the staff at ASTA Zero. A number of projects and collaborations related to real world crash reconstruction, analysis, and computer simulations is also ongoing (e.g., iGLAD, GIDAS, VIRTUAL, OSCCAR, PEARS, Prospect, Propose). In an effort to enhance the THd datasets for the identified conflict situations, a research project has been carried out as a collaboration between the Drive Me research platform and Volpe (a US DOT federal agency).

Additionally, the ADEST/ADFE deliverables in forms of knowledge, methods, tools, and prototype vehicles has been further utilized in the product development and further research (see section 6.5 for details). For instance, the test probe vehicles have provided a useful tool in L3-pilot, an EU-funded project where Volvo cars has a close collaboration with Chalmers.

Even though Drive Me as a project has not focused on digital infrastructure, it has contributed towards an increased understanding of the opportunities and challenges related to digitalization. Results from the project has been used as valuable inputs to start other demonstration projects such as; Nordic Way (EU funded project within Connecting Europe Facility) and AD Aware within the Strategic Innovation Platform (SIP), Drive Sweden.

7.2 List of publications within ADEST/ADFE

Bjärkvik, E., Fürer, F., Pourabdollah, M. , and Lindenberg, B. (2017) “Simulation and Characterisation of Traffic on Drive Me Route around Gothenburg using SUMO,” in SUMO User Conference 2017 - Towards Simulation for Autonomous Mobility, 2017, no. July. Available at: https://www.dlr.de/fs/Portaldata/16/Resources/projekte/sumo/Proceedings_SUMO2017.pdf

Gustavsson, P., Victor, T.W., Johansson, J., Tivesten, E., Johansson, R., and Ljung Aust, M. “What were they thinking? Subjective experiences associated with automation expectation mismatch” Proceedings of Driver Distraction and Inattention DDI 2018, 2018. Available at: https://www.researchgate.net/publication/328388914_What_were_they_thinking_Subjective_experiences_associated_with_automation_expectation_mismatch

Kronborg, P., Bergh, T., Svensk, P.-O., & Palm, M. (2018). Trafikflöden och självkörande fordon Drive Me försökssträcka. Report 2018:165. Retrieved from https://trafikverket.ineko.se/Files/sv-SE/48313/Ineko.Product.RelatedFiles/2018_165_trafikfloden_och_sjalvkorande_fordon_drive_ me_forsoksstracka.pdf

Larsson, A., Ljung Aust, M., Victor, T. (unpublished manuscript) Using countdowns to facilitate planned take-over requests in highly automated driving.

Lind, G., Bergh T., & Strömberg, P. (2018). *Kapacitetseffekter av AD/AV-fordon Litterturstudie med kommentarer. Version 180212.*

Lindman, M., Isaksson-Hellman, I., & Strandroth, J., Basic numbers needed to understand the traffic safety effect of Automated Cars. In *IRC-17-40 IRCOBI Conference 2017,* 2017 (pp. 244–256). Retrieved from http://www.ircobi.org/wordpress/downloads/irc17/pdf-files/10.pdf

Pourabdollah, M., Bjarkvik, E., Fürer, F. , Lindenberg, B., and Burgdorf, K., "Fuel economy assessment of semi-autonomous vehicles using measured data," in 2017 IEEE Transportation Electrification Conference and Expo (ITEC), 2017a, pp. 761–766. Available at: https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7993365

Pourabdollah, M., Bjarkvik, E., Fürer, F. , Lindenberg, B., and Burgdorf, K., "Calibration and Evaluation of Car Following Models Using Real-World Driving Data" in IEEE 20th International Conference on Intelligent Transportation Systems, 2017b. Page 1-6, Available at: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8317836

Seppelt, B. D., & Victor, T. W. (2016). Potential Solutions to Human Factors Challenges in Road Vehicle Automation. In G. Meyer & S. Beiker (Eds.), *Road Vehicle Automation 3* (pp. 131–148). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-40503-2_11

Sukennik, P., Varhulík, M., & Braný, D. (2016). Autonomous cars' impact on traffic flow.

Thuresson, D., & Forsman, J. (2019). SUMO traffic simulations and measurements for the Drive Me route.

Tivesten, E., Ljung Aust, M., Victor, T., "SYSTEM AND METHOD FOR DETECTING AND/OR PREVENTING AUTOMATION EXPECTATION MISMATCH IN VEHICLE" European patent, Application number EP18200909.2, October 2018.

Tivesten, E., Victor, T.W., Gustavsson, P., Johansson, J., and Ljung Aust, M. "Out-of-the-loop crash prediction: The Automation Expectation Mismatch (AEM) algorithm", IET journal, DDI special issue (Submitted in Nov. 2018).

Victor, T., Rothoff, M., Coelingh, E., Ödblom, A., Burgdorf, K. (2017) When Autonomous Vehicles Are Introduced on a Larger Scale in the Road Transport System: The Drive Me Project. In: *Automated Driving. Springer International Publishing*, Switzerland, pp.541–6.

Victor, T.W., Tivesten, E., Gustavsson, P., Johansson, J., Sangberg, F., and Ljung Aust, M. "Automation Expectation Mismatch: Incorrect Prediction Despite Eyes on Threat and Hands on Wheel" Human Factors, 2018, Vol. 60, No. 8, pp. 1095–1116, DOI: 10.1177/0018720818788164, Available at: https://journals.sagepub.com/doi/pdf/10.1177/0018720818788164

Zhu, L., Gonder, J., Bjärkvik, E., Pourabdollah, M., Lindenberg, B. (2019). An Automated Vehicle Fuel Economy Benefits Evaluation Framework Using Real-World Travel and Traffic Data. IEEE Intelligent Transportation Systems Magazine. PP. 1-1. 10.1109/MITS.2019.2919537.

8 Conclusions and future research

The ADEST and ADFE projects have provided significant contributions in how to design and evaluate the potential impact of unsupervised automation on safety, traffic efficiency, and the environment within the operational design domain (ODD) defined by urban highways up to 70 km/h on the Drive Me route, and in good driving conditions. The tools and methods used in ADEST/ADFE will be further refined as part of partner in-house work and in ongoing/future research and collaboration projects.

A series of test probes were designed, developed, and built for unsupervised automation, a type of automation where the vehicle takes full responsibility for the driving task within the ODD. Consequently, the automation needs to achieve a sufficient level of safety on its own without the driver, for example implement redundant technical solutions as part of an extremely high and robust performance. For safety reasons, the test probes built by the end of the project were allowed to be activated in real traffic when supervised by a specially trained professional test driver since the automation did not reach the required performance for unsupervised automation for in-production vehicles.

An important test probe safety design characteristic, in addition to conventional collision avoidance, is precautionary safety. Precautionary safety adapts to *potential* conflicts by increasing safety margins to a location where a threat *may* appear (e.g., a pedestrian visually obstructed by a stationary vehicle).

Several tools and methods are needed to estimate the potential safety performance of unsupervised automation. These methods estimate both *intended positive effects* (i.e. crash avoidance and mitigation), *unintended negative effects*, and *residual crashes*. Real-world data analyses show that it is not possible to evaluate the safety impact of unsupervised automation based on a mileage-driven approach alone. Instead a scenario-based approach is needed. Therefore, a predictive method to *estimate* real-life crash outcomes based on reconstruction of real-world traffic situations and computer pre-crash simulations was developed and applied, revealing a great crash avoidance potential. A safety target for the crash avoidance performance was defined as an attentive, skilled, and experienced reference driver model. Future research should validate and improve the accuracy of the estimations provided from these methods.

Test track experiments confirmed the "Irony of automation" for drivers experiencing supervised automation for an extended driving period, resulting in some drivers failing to intervene during a conflict where the automation had known limitations. This highlights the need to have a crystal clear and continuous vehicle-driver communication about the driver role, as well as to ensure that the driver remains in-the-loop when supervised automation is engaged. Driver behavior research is essential for future development, both for supervised automation, and in unsupervised automation to be sure that the driver is capable of resuming manual control when reaching the end of the ODD. Experimental platforms, such as the Wizard of Oz, makes it possible to study the human interaction with automation and countermeasure concepts that are not yet developed. Future research should be aimed at clearly determining the limits of human capabilities while using different types of automation in different driver states (e.g., sleepy, intoxicated, daydreaming, etc.).

The safety research contributed to the understanding of a range of issues in each element of the Holistic Safety Impact Assessment Framework for Automation (Figure 6.2.1). Results from application of this framework (1) show automation can surpass the crash avoidance target level, (2) show how large this improvement could be in comparison to manual driving and driving with ADAS, and (3) show how the degree of improvement depends on road type and operational design domain. Clearly, the potential is enormous.

The effects of AVs on traffic efficiency depend on the relative difference in behavior between AVs and normal traffic. Cautious AVs are expected to reduce vehicle capacity and cause traffic problems in bottlenecks regions in urban motorway road networks. On the other hand, their expected ability to avoid collisions will take away associated capacity drops and traffic disturbances. The traffic improvement potential by entirely avoiding accidents and incidents suggest daily travel time standard deviation to decrease by some 40-60% using data from a section of the Drive Me route.

Traffic simulation results show that 2014 afternoon workday rush hour traffic on most parts of the Drive Me route is only marginally affected by a 20% share of cautious AVs. These AVs behave like adaptive cruise-controlled vehicles but restricted to 70 km/h, obey speed limits, have lower low-speed acceleration in traffic, and change and choose lane as regular drivers. Here, traffic is near free flow conditions which is also where more than 95% of Swedish motorway mileage is carried out. However, on the eastern side these AVs amplify existing traffic problems after capacity breakdowns resulting in growing queues with 20-45% increase in average mean peak hour travel time. For the same reason, queues dissolve more slowly with these AVs after lane blockages. For example, a 30 minutes lane closure on the south part of the route resulted in a 200 m increase in max average queue length and 3 minutes increase in max average vehicle delay with these AVs.

Part of the available road network capacity is used up by unnecessary human lane changes, poor lane choices and other traffic-inefficient human driving behaviors. Future AVs will hopefully act more efficiently to avoid the corresponding capacity degradation. Several AV-based concepts to improve traffic efficiency are proposed in the ADEST project. Challenges with AV related changes in motorway infrastructure, as well as possibilities with digital infrastructure, are also addressed during the project.

Analysis of naturalistic driving data show that diesel cars using ACC have a lower fuel consumption on average compared to manually driven cars. ACC keeps a longer distance to the lead vehicle, and induces lower acceleration and deceleration than manual driving. However, traffic simulations show that in already congested traffic, AVs with similar longitudinal control as ACC increase congestion and the total energy consumption of the complete traffic system. Furthermore, motorway simulations show that the vehicle speed and noise levels drop when introducing AVs.

An open source traffic simulation environment was developed and calibrated using traffic flow measurements and naturalistic driving data. This simulation was used for both energy efficiency and traffic flow simulations by the end of the project. Important methodological steps were taken in selection and parametrization of the different parts of the model: the environment, the driver (manual or automation), and the vehicle. The open source platform enables full control of the underlying equations needed for controlled experiments, and allows further development in future research.

The traffic simulations performed to study the impact of automated vehicles on traffic flow and energy efficiency, were mainly based on an assumption that the automated vehicles will drive similar to adaptive cruise control (with or without modified characteristics) and change lanes similar to human drivers. However, different types of control characteristics including lane change behavior needs to be investigated in future work, including their potential impact on all relevant areas such as traffic flow, energy consumption, safety, and user experience (e.g., comfort, perceived safety).

The initial ambition to launch a large scale Field Operational Test (FOT) using test probes with automation functionality available to regular customers was not feasible since the test probes did not reach the performance required for in-production functions. However, as the technology matures and reaches in-production status, a FOT could provide valuable insights into how end-users experience and interact with the automation, and provide useful data on vehicle interactions with the surrounding traffic environment. Development of unsupervised automation requires large amounts of data on road environments, as well as interactions with surrounding road users and objects. This data is needed for both normal driving as well as critical situations, including near-crashes, minor crashes, and high severity crashes. As concluded by the analysis in these projects, this data needs to come from different sources including probe-sourced data collection, naturalistic driving data, and extensive crash investigations with detailed understanding of the pre-crash phase. Additionally, HD maps need to be continuously updated to keep an accurate description of the road environment, in order to take changes such as road works into account.

Further, establishing a well-functioning digital infrastructure is necessary for the introduction of automated vehicles and requires standardization and clear responsibilities for investments in hardware and software. The physical infrastructure could be modified (e.g., dedicated AV lanes, reduced lane width) when a large proportion of the vehicles are AVs, but these changes may not be beneficial as long as there is a limited share of AVs and a mix of different vehicle sizes (e.g., restricting the minimum required lane width). In addition, it is difficult to locate AV-bridges in urban motorways such as the Drive Me route at expected reasonable costs and normal aesthetic quality values.

9 Participating partners and contact persons

This project was funded by FFI/VINNOVA and the project partners are Volvo Car Corporation (VCC) and the Swedish Transport Administration (Trafikverket (TrV)).

Contact persons:

Marcus Rothoff (tel +46 733 331746)

Hamid Zarghampour (tel +46 703 236911)

10 References

Bjärkvik, E., Fürer, F., Pourabdollah, M. , and Lindenberg, B. (2017) “Simulation and Characterisation of Traffic on Drive Me Route around Gothenburg using SUMO,” in SUMO User Conference 2017 - Towards Simulation for Autonomous Mobility, 2017, no. July. Available at: https://www.dlr.de/fs/Portaldata/16/Resources/projekte/sumo/Proceedings_SUMO2017.pdf

Eugensson, A., Ivarsson, J., Lie A. and Tingvall, C. (2011). “Cars are driven on roads, joint visions and modern technologies stress the need for co-operation”. International Technical Conference on the Enhanced Safety of Vehicles (ESV), 11-0352, Washington DC, USA.

EuroNCAP. (2018). 2018 Automated driving tests. https://www.euroncap.com/en/vehicle-safety/safety-campaigns/2018-automated-driving-tests/ Accessed June 13, 2019.

Fraade-Blanar, L., Blumenthal, M.S., Anderson, J.M. & Kalra, N. (2019). Measuring Automated Vehicle Safety. Santa Monica, CA: RAND Corporation. Available: https://www.rand.org/pubs/research_reports/RR2662.html

Gustavsson, P., Victor, T., Johansson, J., Tivesten, E., Johansson, R., Ljung Aust, M. (2018). What were they thinking? Subjective experiences associated with automation expectation mismatch. Proceedings of the 6th Driver Distraction and Inattention conference. Gothenburg, Sweden

Kronborg, P., Bergh, T., Svensk, P.-O., & Palm, M. (2018). Trafikflöden och självkörande fordon Drive Me försökssträcka. Report 2018:165. Retrieved from https://trafikverket.ineko.se/Files/sv-SE/48313/Ineko.Product.RelatedFiles/2018_165_trafikfloden_och_sjalvkorande_fordon_drive_me_forsoksstracka.pdf

ISO. (2018). Road Vehicles – Functional Safety – Part 1: Vocabulary. ISO 26262-1:2018

ISO. (2019). Road Safety – Safety of the Intended Functionality. ISO/PAS 21448:2019

Jakobsson, L., Bohman, K., Svanberg, B., Victor, T. (2019). Occupant protection for AD cars – The paradigm shift in crash safety? ESV 2019 conference, 2019: 19-0281

Johansson, J. (2009). “Vision Zero - Implementing a policy for traffic safety”. Safety Science, 47(6), 826-831. doi:http://dx.doi.org/10.1016/j.ssci.2008.10.023.

Larsson, A., Ljung Aust, M., Victor, T. (unpublished manuscript) Using countdowns to facilitate planned take-over requests in highly automated driving.

Lind, G., Bergh T., & Strömberg, P. (2018). *Kapacitetseffekter av AD/AV-fordon Litterturstudie med kommentarer. Version 180212.*

Lindman, M., Isaksson-Hellman, I., & Strandroth, J. (2017). Basic numbers needed to understand the traffic safety effect of Automated Cars. In *IRC-17-40 IRCOBI Conference 2017.* (pp. 244–256). Retrieved from http://www.ircobi.org/wordpress/downloads/irc17/pdf-files/10.pdf

NHTSA. (2015). *Critical reasons for crashes investigated in the National Motor Vehicle Crash Causation Survey, DOT HS 812115*. Retrieved from https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/812115

NHTSA. (2018). Preparing for the Future of Transportation: Automated Vehicles 3.0. ISBN 978-0-16-094944-9

Pourabdollah, M., Bjarkvik, E., Fürer, F. , Lindenberg, B., and Burgdorf, K., “Fuel economy assessment of semi-autonomous vehicles using measured data,” in 2017 IEEE Transportation Electrification

Conference and Expo (ITEC), 2017a, pp. 761–766. Available at: https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7993365

Pourabdollah, M., Bjarkvik, E., Fürer, F. , Lindenberg, B., and Burgdorf, K., "Calibration and Evaluation of Car Following Models Using Real-World Driving Data" in IEEE 20th International Conference on Intelligent Transportation Systems, 2017b. Page 1-6, Available at: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8317836

SAE. (2016). *SAE J3016 Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicle*. Retrieved from https://saemobilus.sae.org/content/j3016_201609

Seppelt, B. D., & Victor, T. W. (2016). Potential Solutions to Human Factors Challenges in Road Vehicle Automation. In G. Meyer & S. Beiker (Eds.), *Road Vehicle Automation 3* (pp. 131–148). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-40503-2_11

Shalev-Shwartz, S., Shammah, S. & Shashua, A. (2017). On a Formal Model of Safe and Scalable Self-driving Cars. arXiv:1708.06374v6

Sukennik, P., Varhulík, M., & Braný, D. (2016). Autonomous cars' impact on traffic flow.

Thuresson, D., & Forsman, J. (2019). SUMO traffic simulations and measurements for the Drive Me route.

Tivesten, E., Ljung Aust, M., Victor, T., "SYSTEM AND METHOD FOR DETECTING AND/OR PREVENTING AUTOMATION EXPECTATION MISMATCH IN VEHICLE" European patent, Application number EP18200909.2, October 2018

Tivesten, E., Victor, T., Gustavsson, P., Johansson, J., Ljung-Aust, M. (2019). Out-of-the-loop crash prediction: The Automation Expectation Mismatch (AEM) algorithm. IET Intelligent Transport Systems, DOI: 10.1049/iet-its.2018.5555

Uber. (2018). Uber Advanced Technologies Group A Principled Approach To Safety. Available: https://uber.app.box.com/v/UberATGSafetyReport

Victor, T., Rothoff, M., Coelingh, E., Ödblom, A., Burgdorf, K. (2017) When Autonomous Vehicles Are Introduced on a Larger Scale in the Road Transport System: The Drive Me Project. In: *Automated Driving. Springer International Publishing*, Switzerland, pp.541–6.

Victor, T., Tivesten, E., Gustavsson, P., Johansson, J., Sangberg, F., Ljung Aust, M. (2018). Automation Expectation Mismatch: Incorrect Prediction Despite Eyes on Threat and Hands on Wheel. Human Factors The Journal of the Human Factors and Ergonomics Society 60(8):001872081878816, DOI: 10.1177/0018720818788164

Waymo. (2018). Waymo Safety Report. On the Road to Fully Self-Driving. https://storage.googleapis.com/sdc-prod/v1/safety-report/Safety%20Report%202018.pdf

Wood et al. (2019). Safety first for automated driving. Available: https://www.daimler.com/documents/innovation/other/safety-first-for-automated-driving.pdf

Zhu, L., Gonder, J., Bjärkvik, E., Pourabdollah, M., Lindenberg, B. (2019). An Automated Vehicle Fuel Economy Benefits Evaluation Framework Using Real-World Travel and Traffic Data. IEEE Intelligent Transportation Systems Magazine. PP. 1-1. 10.1109/MITS.2019.2919537.