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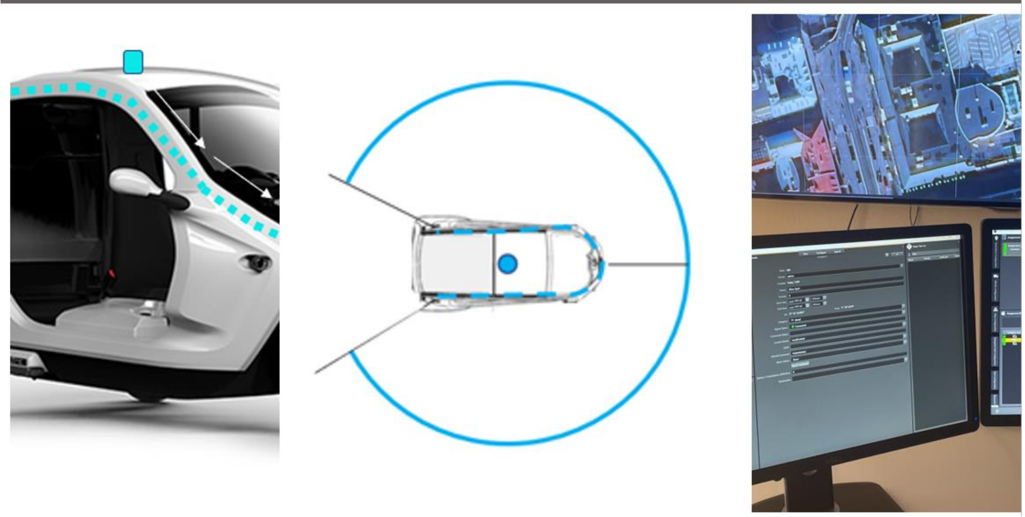

Development of self-driving and control room functions and of external HMI for automated delivery vehicles

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RISE Report : 2022:132

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Abstract

Road users may need additional information to a vehicle's speed and position in lane to understand the behavior and intentions of self-driving vehicles, such as external Human Machine Interface (eHMI), i.e. visual signals (lights) indicating the vehicle's status, behavior and intentions, especially in environments where self-driving vehicles are expected to drive at low speeds, for example, in urban environments. The study in this report developed and implemented self-driving functions and control room functions in an automated delivery vehicle (ADV), as well as developed an eHMI concept to communicate the vehicle's states, intentions, and behaviour to the surroundings.

The software stack and the development of the main features of the self-driving driving capabilities including the lateral controller are described in this report. Further, modules such as the *Representational State Transfer* (REST) for communication, the remote control of the ADV and the eHMI communication interface with the vehicle signals are presented. A lesson learned from the study is that further refinement in repeatability of the initial conditions of the system is essential.

Most of the individual parts of the chain from a command to the ADV were created via the user interface in the *Autonomous Transport Management System* (ATMS). However, the whole chain was hard to achieve, and the need of frequent testing and integration was evident and faults in the chain could result in cumbersome and long procedures to restart the integration test. The study also revealed issues with the stability of the entire system.

Several eHMI concepts have been developed in industry and in research. However, up to this date there are no standards or established frameworks for the design of eHMI. Nevertheless, guidelines and recommendations have been proposed in different studies, for example that eHMI should be consistent with existing eHMI, address road users in general and not tell or instruct other road users what to do. The eHMI-concept developed in this study conveyed the following messages: Automation mode, Acceleration, Deceleration and Delivery mode. A model for an eHMI-strategy is also proposed.

The eHMI prototype on the ADV in this study was composed of LED lights with multiple color options, an ECU with CAN hardware and software that controlled the eHMI. The initial idea was to use vehicle data from the CAN bus, such as speed and steering angle and the control algorithm worked technically, but the eHMI for acceleration and deceleration were activated/inactivated too fast (within 1-2 seconds) for an observer to perceive and grasp the meaning of the eHMI. A lesson learned was that the activation/inactivation of the eHMI should, therefore, be executed by the computer that manages the autonomous driving functions in the ADV.

Key words: Autonomous delivery vehicles, Self-driving functions, Control room functions, external HMI development

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Sammanfattning (Swedish)

Trafikanter och fotgängare kan behöva mer information utöver fordonets hastighet och position i körfältet för att förstå ett självkörande fordons körbeteende och avsikter, till exempel olika former av externt Human Machine Interface (eHMI), d.v.s. visuella signaler (lampor) som visar fordonets status, beteende och intentioner, framför allt i miljöer där självkörande fordon förväntas köra i låga hastigheter, till exempel i stadsmiljöer. I iteration 1 hade fordonet inga självkörande funktioner.

Studien i denna rapport fokuserade på att utveckla och implementera självkörande funktioner för mindre leveransfordon (eng. Automated delivery vehicle, ADV), samt att utveckla kontrollrumsfunktioner. I studien utvecklades även ett koncept för eHMI. Flera eHMI-koncept har utvecklats inom industri och forskning, men det finns inga standarder eller regler för eHMI. Det finns dock riktlinjer och rekommendationer från olika studier om eHMI, vilka har legat till grund för utvecklingen av eHMI-konceptet i denna studie, och som indikerar följande lägen: Automatiseringsläge, Acceleration, Deceleration och Leveransläge. En modell för en eHMI-strategi föreslås också.

Den tekniska utvecklingen i studien omfattande bl.a. programvarustacken och de automatiserade körfunktionerna, inklusive sidokontrollen, *Representational State Transfer* (REST) för kommunikation med eHMI-signalerna och med fordonssignalerna. De flesta av de enskilda delarna av kedjan från ett kommando till ADV:n skapades via ett gränssnitt i det autonoma transporthanteringssystemet (eng. *Autonomous Traffic Management System*, ATMS). Hela kedjan var dock svår att uppnå, och vikten av testning och integration blev tydlig. Fel i kedjan kunde bl.a. resultera i besvärliga och långa procedurer för att starta om integrationstestet. Studien visade också att stabilitetsproblemen i systemet.

eHMI-prototypen på ADV:n bestod av LED-lampor med flera färgalternativ, en ECU med CAN-hårdvara och programvara som styrde eHMI. Till en början användes fordonsdata från CAN-bussen (hastighet och styrvinkel) som aktiverade de olika eHMI-signalerna. Kontrollalgoritmen fungerade tekniskt, men studien visade att eHMI för acceleration och deceleration aktiverades/inaktiverades för snabbt (inom 1-2 sekunder) för hinna uppfatta och förstå innebörden. En slutsats var att aktivering/inaktivering av eHMI i stället bör utföras av samma dator som hanterar de autonoma körfunktionerna.

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Preface

This report is from the GLAD project (GLAD: *Goods deliveries under the last mile with automated delivery vehicles*). GLAD was a research and development project with the overall aim to gain knowledge about user needs as well as about the technical, societal, business and policy related challenges with automated delivery vehicles (ADV). The GLAD project was conducted during June 2020 and September 2022 and was coordinated by RISE Research Institutes of Sweden. The project was partly financed by the Swedish Transport Administration (ref. no. TRV 2020/26017). The partners in the GLAD project were RISE Research Institutes of Sweden, Aptiv AB, Combitech AB, Clean Motion AB and Halmstad university. The studies in the GLAD project are summarized in the following report:

- Söderman, M., (2022), *GLAD, Goods deliveries under the last mile with automated delivery vehicles - Summaries of the studies in the GLAD project*, ISBN 978-91-89757-24-0, RISE report 2022:135

The full reports from the studies in GLAD are:

- Andersson, K. (2022), *Autonoma leveransfordon – vad är de för sorts fordon och har det någon betydelse? (Eng. Automated delivery vehicles - what kind of vehicles are they and does it matter?),* ISBN 978-91-89711-44-0, RISE report 2022:100
- Söderman, M. (2022), *Typical and critical traffic situations with small electric delivery vehicles – indications for future automated delivery vehicles*, ISBN 978-91-89757-19-6, RISE report 2022:130
- Söderman, M., Andersson, J., Habibovic, A., (2022), *Use cases and high-level requirements for safe interactions between Automated Delivery Vehicles and human operators in a terminal,* ISBN 978-91-89757-20-2, RISE report 2022:131
- Andersson, J., Habibovic, A., *How to convey the intent of an automated vehicle with its longitudinal and lateral movements - evaluating four communication concepts in two traffic situations involving pedestrians* (Report under construction, 2022)
- Söderman, M., Clasen, R., Bergström, G., Collings, W., (2022) *Development of self-driving and control room functions and of external HMI for Automated Delivery Vehicles,* ISBN 978-91-89757-21-9, RISE report 2022:132
- Söderman, M., Clasen, R., Bergström, G., Collings, W., (2022) *People's understanding of external HMI and their experiences of interacting with an Automated Delivery Vehicle in a terminal context,* ISBN 978-91-89757-22-6, RISE report 2022:133
- Gonzales, S., Sveder, C., Oscarsson, E., Jönsson, S., (2022) *Challenges and potential business applications of Automated Delivery Vehicle initiatives - a brief overview,* ISBN 978-91-89757-23-3

1 Background

In the GLAD project, there are three studies about automated delivery vehicle (ADV) development and Human interactions with ADV. The first study (Andersson & Habibovic, 202x)[1] explored how participants, as vulnerable road users (VRU), experienced an ADV's driving behaviour in terms of its positions in lane and its speed, as implicit communication of its actions and intentions towards VRUs. Two scenarios were studied: (i) a pedestrian (participant) standing at the side of a street ready to cross when an ADV was approaching; and (ii) a pedestrian facing an approaching ADV driving partly on the walking lane in order to pass an obstacle on the road. The results from the study indicated that the ADV's speed communicated its behaviour and intentions more clearly compared to its position in the lane. Moreover, the higher speed (28 km/h) seemed to have indicated the ADV's actions and intentions more clearly compared to the lower speed (15 km/h). For example, when the ADV maintained high speed, the participants thought the ADV would not stop for them to cross the street. Also, when the ADV decelerated from the high speed the participants thought it was clearer that it would yield for them. However, the results showed great deviations in the participants' ratings which suggest that they perceived the ADV's driving behaviour differently.

The findings indicated that additional means beyond the ADV's speed and positions in lane, for example different forms of external Human Machine Interface (eHMI), i.e., visual signals that communicate the vehicle's states, intentions and behaviour to the surrounding, could provide support for VRUs to better understand the ADVs' behaviour and intentions, especially in environments where ADVs are expected to drive in low speed, such as in urban environments. Today's vehicles (manually driven) are also communicating via eHMI, even though we usually do not call them "eHMI", for example brake lights, turning signals, general warnings (horn and hazard lights). In addition to these explicit "eHMI", vehicles also communicate via movements (speed, acceleration, deceleration etc.), position in lane and distance to other vehicles and to VRUs. This type of implicit communication conveys important information to people in the surroundings.

The vehicle in the study had no self-driving functions but was driven by a human driver hidden behind semi-transparent windshields, a so-called Wizard-of-Oz (WOz) vehicle. Therefore, as an advancement of the WOz-vehicle, the succeeding step in the technical development in the study presented in this report was to develop and implement self-driving functions and site control functions in the vehicle. Also, an eHMI-concept for the ADV was created. The site control functionalities were developed to control and monitor the ADV and to handle transport missions for one or several vehicles.

2 Objectives and goals

2.1 Objectives

The objectives for the study:

1. To develop and implement self-driving functions in the ADV limited to driving a pre-defined route from point A to point B.

[1] The report from this study is expected in 2023.

2. To develop integrated site control functions which can send commands and receive status from vehicle (Autonomous Traffic Management System, ATMS <-> Vehicle) and to develop functionalities for multiple route segments (A->B->C).
3. To develop and implement eHMI, i.e., visual indicators on the ADV which communicate the ADV's behavior and intentions to people in the vicinity.

2.2 Development of self-driving functions

The self-driving functionalities were limited to a pre-defined route. To achieve this, a controller algorithm was defined and developed, leveraging ego-position estimations from the ADV to enable path-following capabilities. Another goal was to implement the required communication capabilities specified by the site control functionality as well as the functionality to parse and use a route received through this interface. Also, a CAN interface with the eHMI system was defined where signals from the ADV were sent to enable corresponding light responses from the eHMI.

2.3 Site control functionality

The site control functionality is a set of programs that give an operator the possibility to monitor and control several automated vehicles and handle transport missions for the vehicles. The site control setup is shown in Figure 1. The site control functionalities included the following steps:

1. Vehicle starts and connects to Autonomous Traffic Management System (ATMS).
2. Vehicle appears as connected in ATMS.
3. ATMS sends command: "Go to autonomous mode"
4. Vehicle goes to autonomous mode.
5. Vehicle change mode in ATMS to autonomous.
6. ATMS sends assignment with at least two segments (A -> B -> C)
7. Vehicle starts assignment.
8. Vehicle stops at first point (B).
9. ATMS sends commands to vehicle to continue assignments (go to C).
10. Vehicle goes to C.

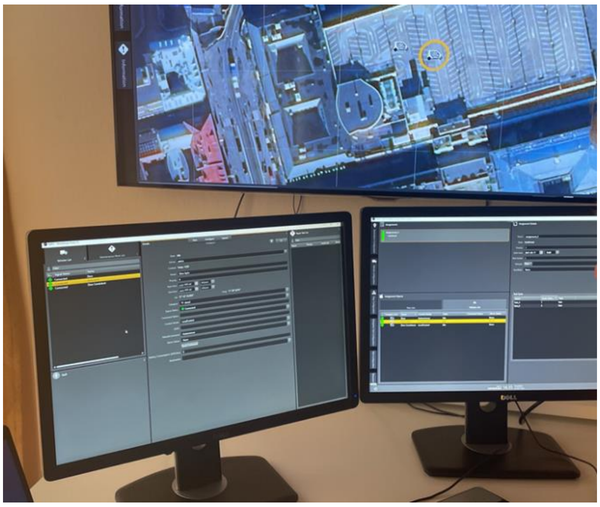


Figure 1. *The site control room setup.*

2.4 eHMI concept

The results from the first study (Andersson & Habibovic, 202x) indicated that some type of eHMI could be useful for people to understand the ADV's behaviour and intentions, especially for ADVs driving in slow speeds as they would do in urban environments, but also in terminals. An eHMI-concept was therefore developed for ADVs operating in goods terminals where they also interact with the personnel.

3 Method

3.1 Technical development

3.1.1 ADV controller

The development of the controller algorithm for path following by the ADV addressed the need to calculate and adjust the steering angle and the velocity to follow the pre-selected route at a desired speed of approximately seven kilometres per hour. For this purpose, a Pure Pursuit Controller (Coulter, 1990) was selected which is a path tracking algorithm that is quite popular in robotics because it has a low complexity in terms of parameters and high robustness of operation. The controller can be described as constantly chasing a selected point ahead of its current position.

The technical implementation of the controller leverages functionality from the Robot Operating System (ROS) navigation stack. The input used in this controller was defined and stored in Comma Separated Value (CSV) file types and contained information about the route structured so that each point had an order-ID, GPS-coordinates, reference heading and reference speed. The reference heading was calculated from the raw GPS-coordinates chosen and used cubic spline interpolation to create a route with one point per meter before saving in the specified CSV-format. This information was converted from geodetic to local cartesian coordinates and used as targets for the ADV while driving.

With the route defined and integrated in the system, the ADV utilized self-localization modules and feedback from the controller to determine if a point had been reached. To increase robustness, a point was deemed as reached if the ADV was within a threshold distance of it. While the goal point was not reached, the required steering angle for the next point was continuously calculated and used together with the reference speed as input for actuators and drivers of the ADV.

3.1.2 ADV communication interface

A representational state transfer (REST) module was implemented for communication with the site control application in the ADV software stack. The REST module enabled the ADV to send and receive information and data over a network connection. Thus, this feature was designed to enable remote monitoring, control and even command execution on the ADV without physical access to the on-board computer or privileged access such as a SSH connection.

To accommodate the different status modes ('Connected', 'Autonomous Mode', 'Assignment') specified by the site control application, the internal state machine of the

ADV was expanded so that sequential confirmation of each status was necessary before a state change was allowed during remote operation. Once a mission had been received the route of the mission was parsed internally to convert the received GPS-coordinates into the necessary data structure used in the controller. In this study the received route from the site control application was not used live during the mission but instead verified against a local copy of the route.

3.1.3 ADV – eHMI function interface

The CAN interface for the eHMI-functions was initially designed so that signals (vehicle speed, reference speed, vehicle steering and vehicle state) were sent from the ADV to the eHMI controller for processing. The signals were transformed with an offset and a multiplier to reduce ambiguity. However, the movement and state processing were at a later stage of the development moved to the ADV. The CAN interface was then re-designed to send a flag value for acceleration, deceleration and stand-still from the ADV while vehicle steering processing was retained in the eHMI controller.

To calculate the acceleration/deceleration signals, the vehicle speed was continuously sampled over time and averaged with parameters determining the history length and sample frequency. These were then compared to the current speed to determine if the ADV was accelerating or decelerating with respect to the average speed of the sample history.

3.2 Overall system architecture

The system architecture diagram of the ADV-system is illustrated in Figure 2. The diagram shows the overall conceptual structure of the functions and components in the ADV-system and their relations, inputs and outputs within the boundaries formed by the environment (operational design domain, ODD), the vehicle (motion) and the human users of the ADV (interactions).

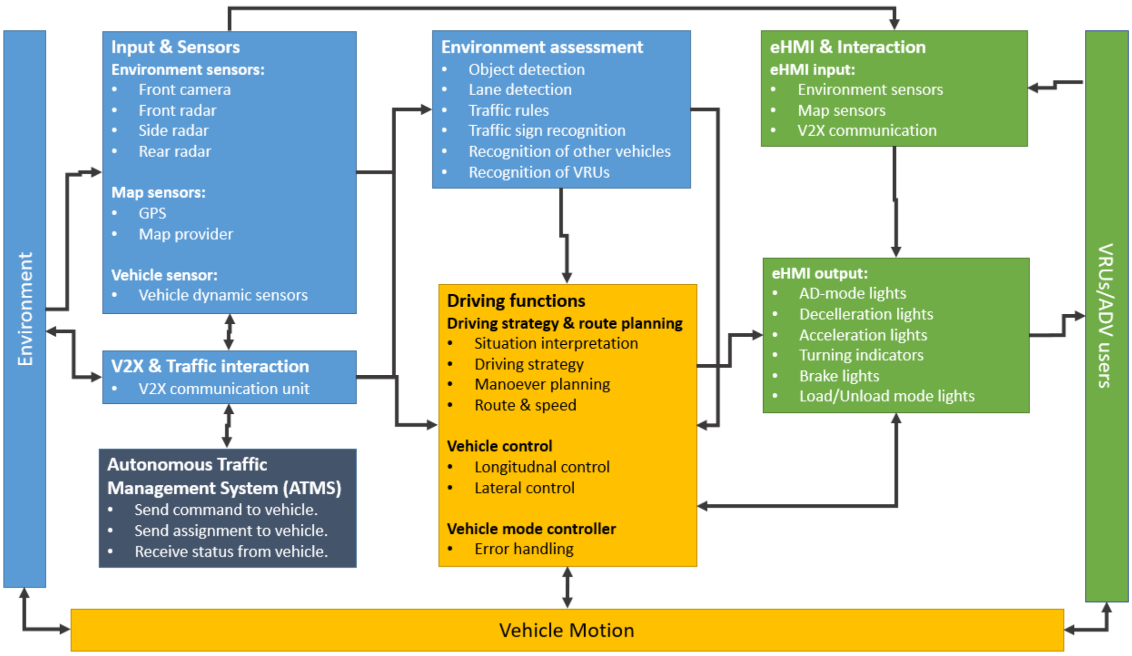


Figure 2. *The overall system architecture.*

3.3 Site control development

The focuses in the site control development were (i) to develop the integration with the vehicle from the ATMS, (ii) to send and receive information (send several route segments, and (iii) to send commands to the vehicle and to receive status from vehicle) ATMS <-> Vehicle. Functionality to send several route segments (A->B->C) was also developed.

A part of the integration was to streamline functionality to create missions based on pre-recorded routes via CSV-files. Here follows a description of how that was done:

- File(s) containing coordinates was read as input
- The coordinates were processed and added together in an array with dimensions dependent on the number of files and the number of coordinates in these files.
- The array of coordinates was then added to mission objects which contained additional information, such as:
    - The type of coordinate-system used,
    - A unique identifying number
    - Target and max speed for a given coordinate
- The mission objects were bundled together and assigned to an assignment. An assignment contains more properties that are added based on the mission in question, such as:
    - **Initial Mission**: Mission that contains instructions for the vehicle to get from its current position to the start position of the assignment (first coordinate in the coordinate list).
    - **Ending mission**: Same as Initial mission but the mission is from the last coordinate to a pre-defined parking spot.
    - **Start-/End time**: As the name suggests, this is an instruction that tells the vehicle when the mission is expected to start and/or finish.
    - **Task cycles**: The number of times the vehicle should perform an assignment, for example, drive from A-B, then B-A repeatedly.
    - **Type**: Type of assignment, Task/Maintenance/Alarm
    - **Priority**: If resources are limited, priority can be given to decide which assignment and in what order.
- A message Header was created alongside the assignment to indicate cursory information:
    - **Vehicle ID**: Which vehicle is this intended for
    - **Message Type**: What type of message it is
    - **Timestamp**: When is this message created
    - **Unique ID** for this message
- The Assignment was then serialized and together with a message header published for the specified vehicle to receive and perform.
- The site control application was expected to receive continuous information from the vehicle so that the current position and state could always be viewed.

Figure 3 shows a sequence diagram of this process.

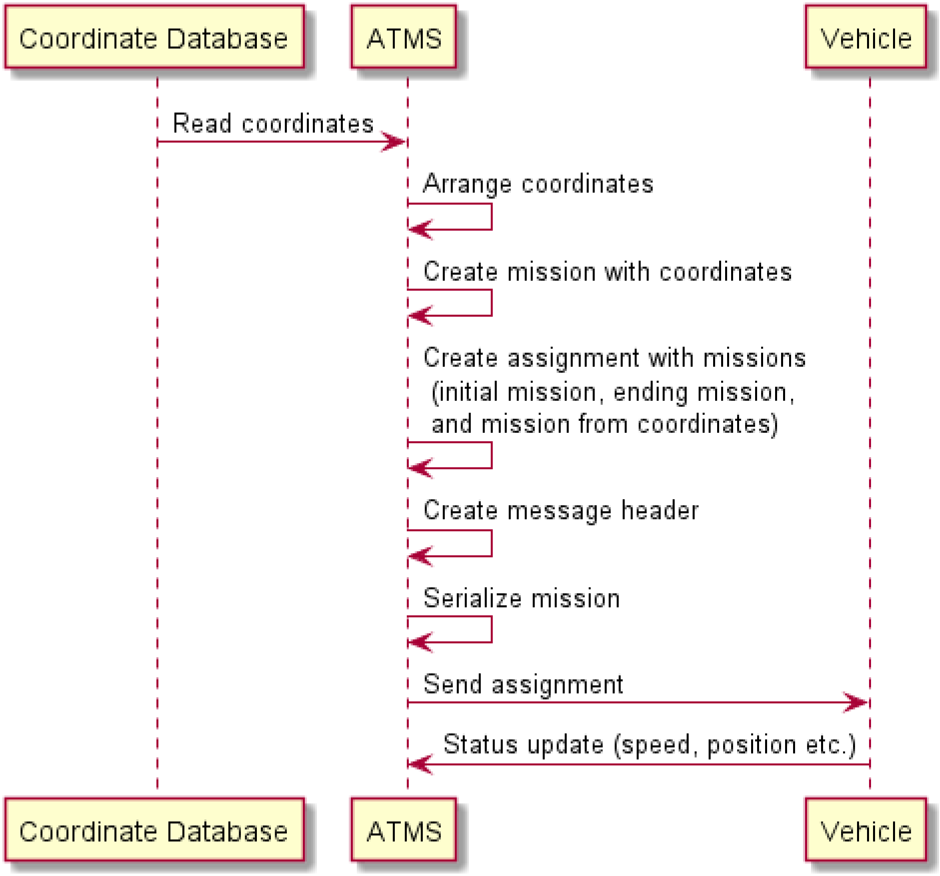


Figure 3: *Sequence diagram ATMS and Vehicle.*

3.4 eHMI development

The National Highway Traffic Safety Administration (NHTSA) in the USA has stated that automated vehicles must be capable of conveying information to humans regarding their intentions and performance (ISO/TR 23049:2018), often referred to as some sorts of external HMI (eHMI). ISO (ISO/TR 23049:2018), has also reasoned that since automated vehicles' behaviours will probably behave differently to circumstances compared with conventional vehicles' behaviour, new (or additional) ways of communication for automated vehicle (AV) - human interactions may be needed.

Different types of visual indicators on automated vehicles as means to communicate the automated vehicles' behaviours and intentions have been explored in several studies. Findings, for example from Faas et al. (2020), Métayer et al. (2019) and Wilbrink et al. (2021) indicate that people can feel safer and have more trust in AVs with eHMI and can help pedestrians to understand the AVs' intentions. However, the results from the studies are not completely consistent in whether eHMI does provide support to humans in decisions when to cross a street (or not) compared to AVs with no eHMI.

There is a great variety of eHMI concepts, but most of them are (i) based on visual modalities, (ii) designed for passenger cars, (iii) using abstract signals and (iv) addressing multiple recipients, mostly pedestrians, with the same message(s) at the same time. eHMI concepts are also typically one-way communication (from the vehicle to the surrounding) and limited to individual (1:1) interactions, i.e. no interactions between multiple humans and AVs (Dey et al., 2020, Carmona et al. 2021). Moreover, there is no common taxonomy or commonly accepted testing and validation procedures for eHMI (Dey et al. 2020). Moreover, most eHMI-concepts have been developed for passenger cars, less for heavy trucks, and only a few for light weight delivery vehicles (Dey et al., 2020), such as the ADV in the GLAD project.

AV – human interaction strategies were investigated in the EU project interACT (2019) and different eHMI concepts were developed and evaluated for as means for communication and cooperation between AVs and VRUs (Kaup et al. 2019). Yet, there is currently no established framework or standard for eHMI about *what* eHMI concepts should communicate (content) or *how* the eHMI concepts should be designed (texts, icons, projections, light signals, colours etc.) to communicate specific messages to people in the surrounding. Still, several high-level criteria, guidelines and principles have been suggested by different sources. In interACT (2019) criteria for visual eHMI were defined, for example:

- Perceivable in daylight and night
- Perceivable in various speeds (0-50 km/h)
- Compatibility with conventional external light units/functions (turning signals, brake lights etc.)
- Understanding the eHMI (simple, clear, learnable)
- Independent from language skills/reading skills (avoid the usage of text or symbols to reduce communication barriers based on language skills, age, or culture etc.)
- Potential to display different messages (If more than one message should be transferred via one single HMI, the signal design has to be adaptable, e.g. by changing luminous intensities and frequencies).

Wilbrink et al. (2019) have suggested four categories of information that should be provided by eHMI:

- Vehicle driving mode
- Vehicle's next maneuvers
- Perception of environment
- Cooperation capabilities

Habibovic et al. (2018) have presented five principles for eHMI:

- Pedestrians should be able to easily distinguish if a vehicle is in manual or automated driving mode.
- Pedestrians need to obtain information about AVs future state (i.e., their intent and plans) rather than their current state.
- Pedestrians should be provided with information that eliminates the need to seek eye contact in encounters with AVs.
- Pedestrians should not be told explicitly when/where to cross the street in encounters with AVs.
- Pedestrians should experience encounters with AVs as calm and not stressful.

Carmona et al. (2021) have suggested a set of high-level guidelines:

- The meaning of the eHMI should be clear, coherent and unambiguous and easy for people to understand.
- The eHMI should be visually easy to see/observe by people in the vicinity of the ADV
- Consistency between behavior of the ADV and the eHMI
- The ADV should continuously inform its state (active in automated mode, inactive) and behavior (longitudinal and lateral movements).
- Changes in mode and behavior should be clearly communicated.
- Commonly accepted or standardized symbols, icons and signals should be used
- Colors that specifically indicate autonomous features should not interfere with colors already implemented or reserved for other purposes in vehicles.
- Color blindness should be regarded in the design of eHMI.

There is also ongoing work within ISO about eHMI for AVs. Up to this date ISO has not published a final version, but according to ISO/DTR 23049 (January 2018)[2] there are some aspects that should be considered about eHMI are, for example:

- Abide by existing and forthcoming laws, regulations, and policies
- Be unique and distinct
- Co-exist and not interfere with existing communication schemes
- Consider mixed traffic situations and scenarios with multiple automated vehicles
- Few, perceptible, learnable, easily understood
- Similar to existing signals used vehicles
- Noticeable by various road users
- Noticeable under almost all environmental conditions.
- If possible, rely on similar approaches as done for existing visual communication signals, e.g. current indicator lights.

ISO/DTR 23049 (2018) also highlights that the format and style of communication signals to other road users should be harmonious and consistent regardless of the brand of the automated vehicle. If not, they could create confusion and contribute to people not accepting or trusting automated vehicles. In sum, external visual communication systems (eHMI) should be:

- Standardized
- Limited in the number of signals
- Distinct and salient
- Not distractive

[2] Disclaimer by ISO: “This document is not an ISO International Standard. It is distributed for review and comment. It is subject to change without notice and may not be referred to as an International Standard.”

- Provide a positive impact on traffic safety and societal acceptance.

Based on the premises mentioned above, the following directions were the basis for the development of the eHMI in this study:

- The eHMI should be consistent with existing eHMI (turning signals, brake lights, hazard lights etc.) in terms of colours, format and meaning (content)
- The eHMI should address road users in general (i.e. not addressing specific individuals)
- The eHMI should be abstract eHMI (no figures/characters, texts or icons)
- The eHMI should have unique eHMI features for ADVs (automated, no driver etc.)
- The eHMI should communicate a limited number of messages: the ADV's state, behavior and intent
- The eHMI should be non-instructive (not telling road users what to do)
- The eHMI should be consistent with the vehicles' implicit communication, i.e. the vehicles' movements (longitudinal and lateral movements, speed etc.)

Figure 4 illustrates a proposed model about the order of what type of information AVs should be conveyed to the surrounding. The model asserts that the primary message (base layer) is that the vehicle is an automated vehicle (AV). The next layer is about communicating the AV's behaviour/actions and intent, i.e. lateral and longitudinal movements and standstill. Lateral movements, for example when changing directions in intersections and changing lanes, are explicitly communicated via conventional turning signals. AVs may also need to communicate longitudinal changes in specific situations, for example when approaching a zebra crossing and when starting to drive when people have crossed. In a goods terminal it could be useful to communicate the ADV is about to stop for loading/unloading. The top layer of the model refers to messages about the AV's perception of objects in the surrounding, for example obstacles that obstruct the ADV's path. This model could serve as a guidance in what type of eHMI and what messages should be communicated to the surrounding depending on the context.

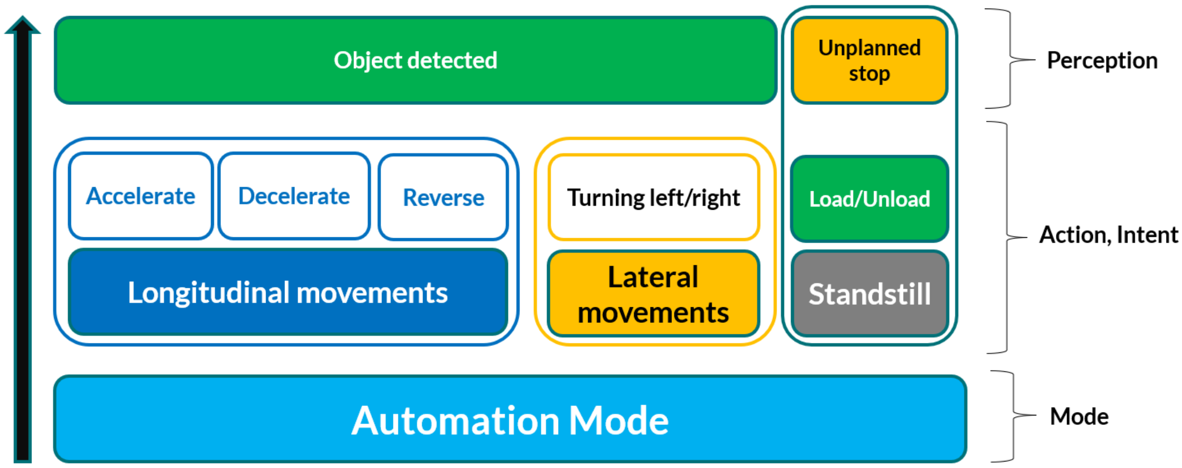


Figure 4. *A proposed model of the order (from bottom to top) of the type of information ADVs should communicate to the surrounding.*

3.5 eHMI hardware

The eHMI hardware consisted of two main parts:

1. Top light mounted on the ADV's roof. A small 360-degree LED strip that could be either be On or Off.
2. Side lights mounted on the ADV's front to sides. Four LED strips (two on each side of the ADV) controlled by a micro controller that communicated with the ADV.

The side lights were built with addressable LEDs where each individual LED was controlled by the micro controller. The micro controller communicated with the self-driving system via the vehicle CAN bus (Figure 5).

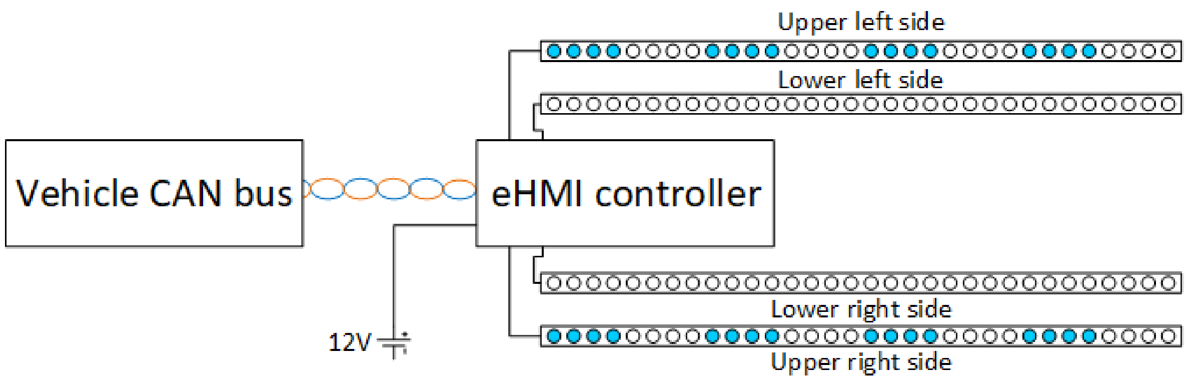


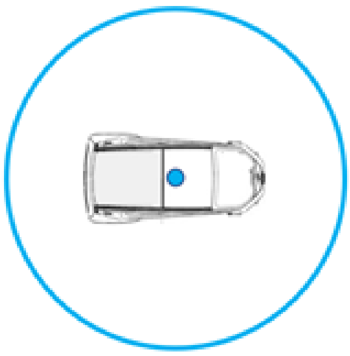
Figure 5: *Overall description for the eHMI hardware.*

4 Results and lessons learned

4.1 eHMI development and design

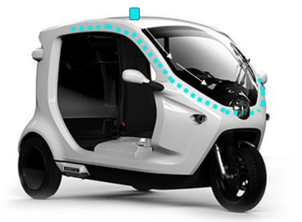
The eHMI-concepts that were developed in this study, described below.

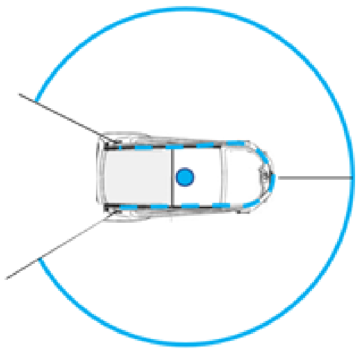
1. **eHMI Autonomous mode:**



Steady light mounted on the roof on the ADV indicating automated mode On. Visible 360 degrees. Colour: cyan.

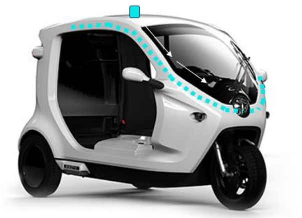
2. **eHMI Deceleration:**

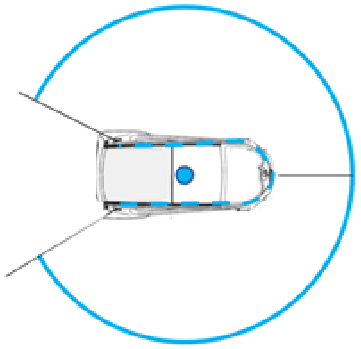




LED-stripes mounted on the sides of the roof, along the A-pillars to the front lamp. During deceleration the lights wander forward, from the roof's sides and the A-pillar towards the front lamp. Colour: cyan.

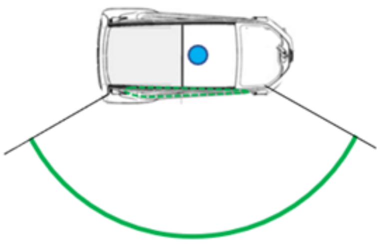
3. **eHMI Acceleration:**





LED-stripes mounted on the sides of the roof, along the A-pillars to the front lamp (same as the deceleration). During acceleration the lights wander backward, from the front lamp and the A-pillar towards the roof's sides. Colour: cyan.

4. **eHMI Load/Unload:**



LED-stripes mounted around the area for loading/unloading goods. The Load/Unload mode was activated when the ADV had stopped at a designated location for loading/unloading goods indicating that goods personnel can approach the ADV to load/unload goods.

4.2 eHMI implementation

The LED strips were implemented to constantly read the vehicle speed and turning angle from the CAN bus. With this information the vehicle acceleration was calculated. If the acceleration, or deceleration, was higher than the set threshold the LED strips were activated for the specific eHMI.

However, during the tests it was observed that due to the low vehicle speed (< 6 km/h) the calculated acceleration value was above the threshold value for very short periods of time. There was also a hysteresis to avoid unwanted animations on the LED strips. This decreased the time the LED stripes were activated during the acceleration and deceleration phases. As a consequence, the eHMI for acceleration and deceleration were visible during a very short period (less than 2 sec.) and it was assumed that it would be difficult for people to observe and understand the eHMI in such a short time. Therefore, the ADV's changes in speed may not be functional signals to trigger the LED stripes accordingly to communicate the ADV's behaviour to the surrounding. Further development and testing are necessary to create more stable light patterns that are timely activated and inactivated to communicate the ADV's behaviour (deceleration/acceleration). One way of doing this is to add acceleration and deceleration values to the route planning tool. The route planning tool will then send signals to the eHMI prior deceleration and acceleration are about to happen.

Other or additional sources might be needed to activate and inactivate the eHMI for deceleration and acceleration, for example (i) vehicle-to-infrastructure (V2I) information, e.g. traffic-lights and geofencing information, (ii) map data, e.g. approaching a crossing and (iii) AI-based sensors that can detect and predict other road users' behaviour.

4.3 Route

There were several successful attempts for the ADV to complete the test route. However, the starting conditions created complications, as the proximity of the starting position of the ADV and the end point of the test route were within the threshold of completion. To mitigate this, the distance between the ADV's starting position and its end point on the test route was increased. This required a manual repositioning of the ADV for each completed cycle and, thus, the time required to complete each cycle.

The lessons learned emphasizes the importance of robust implementation of storing and loading routes. During the tests there were several bugs related to the CSV-file format used to store and load route information. Consequently, there was a great need to use a systematic approach to specify and store routes in more suitable data formats. The approach used during the tests with local CSV-file did not scale well regarding using multiple routes and receiving routes over the REST interface. It was also important to ensure that there are tools for inspection, debugging and verification of a route readily available.

4.4 Site control application

The functionality to send several route segments, send commands to the vehicle and to receive status from the vehicle in a correct way was successfully tested with the vehicle. A lesson learned is that integration and tests *of the whole system* often requires more time than expected. Each part in the chain site control application -> vehicle worked well in the specific tests, but when put together issues occurred:

- Communication between the site control application and the vehicle could be established early on.
  - Site control application could find and establish a connection with the vehicle.
  - The vehicle was in "local control" state as default. When site control sent a request for state change the vehicle could change state. For example, a site control application tells the vehicle to enter "autonomous state", so it is ready to receive an assignment.
  - The vehicle had trouble accepting assignments at the start. This problem was identified to be due to a rogue negation in an if-statement in the vehicle state-machine.

4.5 ADV functions

The testing showed that the ADV had the capabilities to perform a series of tasks (drive the route, decelerate, stop, park, accelerate etc.), but the overall system instability meant that continuous reproducibility during the tests was not possible.

During the development, modules were mostly developed and tested separately or in smaller sub-systems of functions. This is a convenient procedure when working together with different partners in order to reduce complexity, but at the same time made it difficult to observe and track bugs related to the different sub-systems. For example, debugging of sub-systems was reduced because of ongoing debugging of a different sub-system. In general, there was a need for further testing of the complete system on-site, but due to circumstances such as home-office restrictions (due to Covid-19 pandemic) and poor weather conditions during the tests made it difficult to organize such tests.

The lessons learned from the development of ADV functions and communication capabilities highlighted the need for further documentation and consolidation of features. Although working with small iterations and good testing capabilities, many milestone capabilities implemented and tested were subject to bugs from underlying system conditions and of development of new features.

4.6 Battery

During the tests it was discovered that the vehicle battery was a limiting factor. Too low a voltage level affected the systems that controlled the ADV functions negatively and, therefore, charging was often required. A lesson learned was that the battery needs to have the capacity to maintain the required voltage for the ADV systems for at least 4 hours of testing.

5 Conclusions

The objectives for this study were: (i) to develop self-driving functions in the ADV, limited to driving a pre-recorded route from points A to B; (ii) to develop and integrate site control functions which can send commands and receive status from vehicle, and (iii) to develop and implement eHMI to communicate the ADV's behaviour and intention to the surrounding.

The objectives were partly reached. The ADV had the capability to perform specific tasks (drive the route, decelerate, stop, park, accelerate etc.), but the overall system instability made it not possible to continuously reproduce the planned driving cycles.

The site control functionality and the self-driving functions in the ADV worked independently, but the whole chain from site control application to the ADV's driving was hard to achieve. Future work will therefore focus on stabilizing the whole system. Additional functions will also be developed for the site control system, for example using an actual map/route to the ADV instead of using the locally stored map on the ADV.

The guidelines from previous studies about eHMI were useful in the development and design of the eHMI in this study, even though there are no standards or established framework for the content as well as for the design of eHMI[3].

An important matter is what triggers the eHMI, i.e. the timing when they are activated/inactivated. This study indicated that changes in the ADV's speed as triggers for activating/inactivating the eHMI did not give enough time for people in the surroundings to observe and process their meanings. Therefore, other signals should trigger the activation/inactivation the eHMI in a timely manner, for example adding acceleration and deceleration values to the route planning tool, which could trigger the eHMI *prior* the acceleration and deceleration. Adding acceleration and deceleration values to the route planning tool could also provide more stable and clear light movements in the LED-stripes.

Finally, a lesson learned is that integration and testing of the *whole system* (site control, self-driving functions, routes and eHMI triggers), and not of separate functions, are essential in order to make the ADV system work as intended.

[3] How people perceived and understood the eHMI developed in this study has been evaluated in Söderman et al. (2022), see list of references.

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