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Transportation Research Procedia 00 (2022) 000–000

Transportation Research Procedia

www.elsevier.com/locate/procedia

Transport Research Arena (TRA) Conference

Trustworthy Automated Driving through Increased Predictability: A Field-Test for Integrating Road Infrastructure, Vehicle, and the Human Driver

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Abstract

Higher levels of Automated driving (AD) vehicles require new allocations of functions among drivers, vehicles, and road infrastructure. The European Horizon 2020 project HADRIAN investigates how such reallocations could be practically achieved as part of Collaborative Connected and Automated Mobility (CCAM) to meet the benefit expectations of drivers while increasing safety. In a field demonstration it is shown how road infrastructure can be used to expand the prediction horizon of AD vehicles and how multimodal, driver-state dependent human machine interactions (HMI) could help address European mobility needs with AD vehicles and increase operational acceptance and safety. Whereas performance results of the various innovations are reported elsewhere, in this paper the evaluation of the feasibility of the HADRIAN innovation in an open road field-demonstration is described.

Keywords: human-centered design; human-systems integration; automated driving; CCAM, fluid interactions

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1. Introduction

Highly automated driving (AD) vehicles promise to offer improved safety (Papadoulis et al., 2019; Ye & Yamamoto, 2019) together with a multitude of previously unimagined possibilities such as increased productivity and wellbeing (Singleton, 2019). AD vehicles also promise to reduce stress and lead drivers to experience less monotony. Different discrete levels of AD are defined (SAE International, 2021) and several of them may be available on a given vehicle on a single trip. The multitude of such AD levels increases the difficulties for human drivers correctly understanding their role and safely interacting with automation. Interaction problems with automation has been identified as a critical issue in previous research (Kyriakidis et al., 2019; Lu et al., 2016), along with appropriate trust-calibration (Hoff & Bashir, 2015; Körber et al., 2018; Payre et al., 2016), the difficulty of monitoring automation without active control responsibilities (Endsley, 2016; Merat et al., 2019), mutual understanding of intent (Bengler et al., 2012), as well as difficulties of maintain appropriate mode awareness (Eriksson & Stanton, 2016, 2017; Stapel et al., 2019). Specifically, the human role for conditional (SAE level 3) (SAE International, 2021) is substantially different from partial automated driving (SAE level 2) where in both levels the vehicle performs the necessary lateral and longitudinal manoeuvres. During SAE level 3, the driver may disengage from driving during periods of time while remaining fall-back ready to take over the driving task again when the vehicle informs the driver to do so. In contrast, during SAE level 2 the driver remains responsible to actively monitor the vehicle and intervene any time. While the driver’s tasks are quite different between these SAE levels, the vehicle performs pretty much the similar maneuvers so that drivers must be able to well differentiate these SAE levels to enable the expected overall safety benefits of AD. This can become challenging for normal, non-trained drivers, especially when the changes in level occur frequently and unpredictably on a single trip. This challenge also impacts the perceived usefulness of such AD and therefore the user perception of the overall benefits of AD vehicles.

The EU H2020 project HADRIAN (Holistic Approach for Driver Role Integration and Automation Allocation for European Mobility Needs, https://hadrianproject.eu/) investigates methods to resolve such challenges to achieve safe and acceptable AD from the human driver perspective. The project investigates holistic solutions that combine the vehicle, the driver, and the road infrastructure information to achieve safe solutions in a human-centered way. In the remainder of this paper the term automated driving level (ADL) is used instead of SAE level is used because slight but important modifications of the SAE definitions are investigated in the HADRIAN project. In this paper we briefly outline and motivate the innovations and refer to project deliverables and forthcoming publications for detailed results. The paper itself focuses on the evaluation of the feasibility of the developed innovations in a field-demonstration on public roads with a real vehicle. Overall, there are three field-demonstrations conducted in the HADRIAN project.

2. Description of the HADRIAN Innovations

The HADRIAN project started by identifying the expected mobility needs and benefit opportunities for AD in Europe in various EU mobility visions and roadmaps (ERTRAC, 2017; L’Hostis et al., 2016; National Association of City Transport Officials, 2019; Simpson, 2019). A set of three personas was identified that exemplify some of the variety of AD benefit cases for which the HADRIAN innovations should be designed: an elderly person who has lost some driving license privileges; a truck driver in a workplace that has become increasingly less attractive; and a business woman who wants to work during her drive to work. For these personas, twelve AD use scenarios were derived for different road environments from urban to rural and the drivers’ likely non-driving related activities that are enabled by AD. For these AD scenarios, three main types of HADRIAN innovations were identified to facilitate the human driver role, see Figure 1, left.

Vehicle: The prediction horizon of the AD vehicle is increased so that upcoming changes in ODD become more predictable to the driver. This should allow the driver to better prepare for the upcoming changes and reduce the likelihood of hasty and unsafe transitions back to manual driving. The increased AD predictability should also increase the experienced quality of non-driving related activities (NDRA) as drivers know how much time they have available to complete their tasks. Three different aspects of AD predictability are increased: First, the expected duration of ADL 3 on a trip is provided to help drivers to better plan and execute their non-driving related activities. Secondly, the remaining time in AD mode is displayed to the driver to help prepare for a takeover, similar to how an exit announcement on trains helps passengers prepare getting off the train. And thirdly, the amount of time available after a Takeover Request (TOR) from ADL 3 back to manual driving is displayed to the driver to help avoid premature and ill-prepared transitions. In an initial study, the AD predictability has been shown to be perceived highly beneficial by drivers as well as increase the likelihood of safe gaze behavior in driving simulation studies (Marx et al., 2022), in addition, the current paper describes the evaluation of feasibility of implementing such AD predictability through C-ITS messages in a field-demonstration. The increased AD predictability thereby forms the backbone of the other HADRIAN innovations.

HMI: The HADRIAN HMI enhances state-of-the-art AD driver controls and displays using multiple modalities to support the driver understanding of the current AD status and effectively transition to and from AD, see Figure 1, right. The HADRIAN HMI also translates the increased AD predictability to the driver. Thereby, a head-up display (1) provides time critical information to the driver concerning upcoming maneuvers and ADL transitions. An AD status display on a mounted electronic tablet (2) provides all information about the current ADL and upcoming changes of the ADL, including all AD predictability information. Haptic feedback via the steering wheel (3) aids the driver to perceive the transitions between ADL, specifically receiving direct feedback about the status. An LED panel under the wind-shield (4) indicates the currently active level of automation and warnings using different lighting patterns and colors if an inappropriate driver state is detected. All HMI components are connected to a Driver Monitoring System (DMS) system that observes the driver and triggers warnings or instructions as needed (5 and 6). The individual benefits of these innovations have been investigated separately as well as jointly in driving simulation studies and are reported elsewhere[†], also publications of these results are forthcoming. In this field-demonstration, the feasibility of these HMI innovations is demonstrated and tested in a test vehicle in an open-road environment.

Figure 1 Primary HADRIAN Types of Innovations (left) and AD Supporting HMI inside the vehicle including DMS (right)

Driver: The driver retains a critical role during ADL 2 and 3 and is supported by the increased AD predictability and the HADRIAN HMI. For this purpose, an interactive tutoring application helps the driver acquire and dynamically improve the needed competences and knowledge to successfully use the HMI. This tutoring application provides information before, during, and after certain driving segments to the driver and adaptively informs the drivers to improve critical behaviors such as sufficient monitoring of the environment and vehicle state during transitions back to manual driving to avoid hasty transitions. The benefits of the tutoring application have been investigated in driving simulator studies and are reported elsewhere[1], also publications of these results are forthcoming. In this field-

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[1] https://hadrianproject.eu/results-2/

demonstration, the feasibility of providing AD tutoring is demonstrated and tested in a test vehicle in an open-road environment.

The remainder of this paper describes the evaluation of the feasibility of the described innovations in a real vehicle in an open road environment.

3. Field-Demonstration

3.1. Objective

The objective of the field-test is to evaluate the feasibility of the HADRIAN innovations in a real vehicle and operate on an actual road. Participants experience the HADRIAN functionality and HMI in different driving scenarios and evaluate whether everything worked as expected and rate their experience and possible improvements. Specifically, the focus is on demonstrating that the increased AD predictability can be effectively translated to the driver with an appropriate HMI without overburdening the driver and therefore increase safety and acceptability.

3.2. Test System

The test system combines components of the vehicle, road infrastructure, and the driver's HMI, see *Figure 2*: (1) Road infrastructure units (RSUs) send critical information from the road environment to the vehicle to expand its prediction horizon. Specifically, information about upcoming obstacles that either require termination of AD or allow the vehicle ADL 3 function to continue operations are communicated to the vehicle via C-ITS messages, see following subsection. (2) The vehicle's ADL 3 capabilities, specifically Adaptive Cruise Control (ACC), Lane-Keep Assist (LKA) and Trajectory Planning (TP) receives the information for its trajectory planning and displays the appropriate HMI information to the driver, specifically, the predicted duration of the ADL 3 portion of the driver and the duration of the transition. This information is displayed on the HADRIAN Fluid HMI (3) along with the other information that was briefly described above.

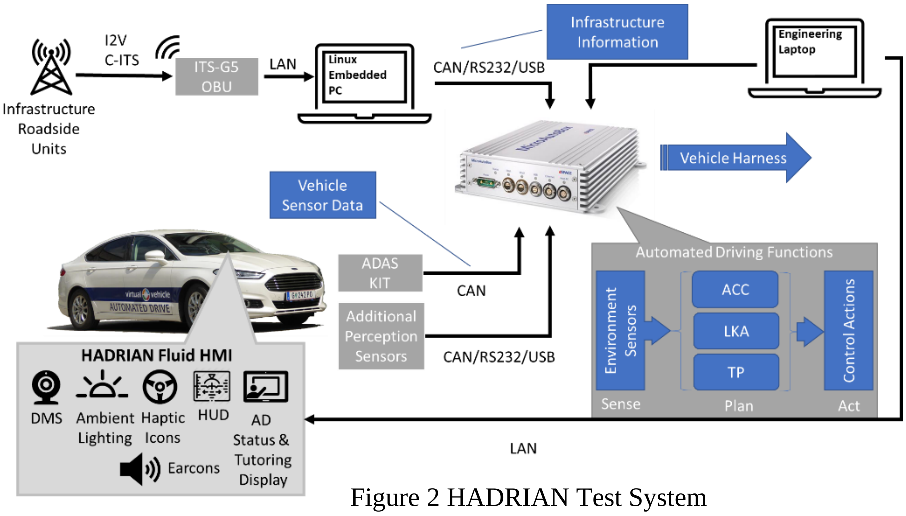

Figure 2 HADRIAN Test System

3.3. Demonstration Scenarios

The evaluation is structured in six demonstration scenarios that will be performed on the A2 motorway near Graz, between the consecutive exits "Graz Ost" and "Gleisdorf" where the necessary C-ITS infrastructure is available. The selected scenarios provide a representative sample of critical situations:

- **Scenario 1, Predicted transition back from ADL 2 to manual driving:** The driver has enabled ADL 2 on the motorway. A construction site is ahead requiring a lane change that the driver must perform manually. As the vehicle approaches the construction site, an RSU sends a C-ITS message about the construction site to the vehicle. The vehicle determines that a change to manual driving is needed and therefore displays the upcoming transition to manual driving to the driver with sufficient time for the driver to reengage in the manual driving. The HMI informs the driver that a lane change maneuver will be necessary. The driver uses this information to perform the necessary checks and takes back driving control and performs the lane change.

- **Scenario 2, Continue ADL 3 through an environmentally triggered lane closure** (construction zone versus obstacle on the road)**:** The driver has engaged ADL3 while driving on a motorway. As the vehicle comes closer to an upcoming construction area with a closed lane, an infrastructure roadside unit sends a message about the construction site to the vehicle. The vehicle's AD function uses this information to update its planned trajectory needed to execute the lane change maneuver. The AD function also triggers an HMI message to inform the driver that a lane change will be performed automatically so to not surprise or startle the driver who may be engaged in a non-driving related activity. The vehicle then completes the lane change maneuver. The two variations of this scenario reflect different lane change triggering events: for scenario 2.1, the lane is closed due to a construction zone, for scenario 2.2, the lane is temporarily not usable due to an obstacle (a tire) on the road.

- **Scenario 3, Planned termination of ADL3 driving:** In this scenario, the driver sits in the stopped vehicle and plans the trip. The vehicle tells the driver the expected stretches of the road where ADL 3 will be available. Upon starting the trip, the vehicle informs the driver when ADL 3 can be engaged and for how long it will be available. After enabling ADL 3, the vehicle HMI continuously displays the remaining duration of the automated drive. Upon coming close to the end of the automated driving period, the vehicle informs the driver to initiate a take-over, allowing the driver 15 sec for transition back to manual driving.

- **Scenario 4: Unplanned termination of ADL 3 driving:** This scenario is similar to the previous scenario until ADL 3 is engaged. Once engaged, the road infrastructure site reports an unexpected construction on the road, requiring the termination of ADL 3. The vehicles HMI informs the driver about the unexpected transition back to manual driving, allowing the driver 15 sec for the take-over back to manual driving.

- **Scenario 5: Switching between ADL 2 and 3 during the drive:** The driver has engaged ADL 2 while driving on a motorway. After driving for a few minutes in ADL 2, the infrastructure roadside unit sends a message to the vehicle that ADL 2 is not available anymore on an upcoming stretch of the road (e.g. due to damaged lane markings). The vehicle's HMI displays to the driver a message to start manual driving, providing the driver at least 5 sec response time. After driving for a few minutes in manual mode, the vehicle displays the availability of ADL 3. The driver engages ADL 3 and drives in ADL 3 for a few minutes. The infrastructure roadside unit subsequently sends a message that ADL 3 is not available anymore on the upcoming stretch of the road but ADL 2 is available. Therefore, the driver receives a message on the HMI that ADL 2 is becoming available soon, providing 15 sec time for the TOR. Upon changing the mode to ADL 2, the driver drives in ADL 2 for some minutes until the end of the scenario.

3.4. Demonstration Conduct

During all drives the vehicle is operated by a safety driver who is responsible for the safety of the vehicle along with an engineering observer who ensures that the automated driving function is working properly, see Table 1. The engineering observer sits behind the safety driver. Because a safety driver is actually operating the vehicle this person is not available to evaluate the system. Therefore, the demonstration participant who will evaluate the HADRIAN functionality is referred to as a "demonstration pseudo driver" (DPD) and is seated on the right front seat. The DPD evaluates the HADRIAN system during the scenarios and also communicates verbally as needed with the safety driver. The DPD receives specific instructions prior to the demonstration to take an “as-if” perspective and view the happenings as much as possible from a real driver’s perspective. The Driver Monitoring System (DMS) engineer is seated behind the DPD and ensures appropriate data collection of the DMS.

Table 1 Demonstration Participant Positions in the Vehicle

Role	**Seat**	**Tasks**
Safety Driver	Driver Seat	Responsible for the safety of the drive, transitions to and from ADL
Engineering Monitor	Left rear seat	Monitors vehicle functions for safe performance, monitors traffic during lane change maneuvers and informs the safety driver as appropriate
Demonstration Pseudo Driver (DPD)	Right front seat	Evaluates the system, initiates ADL via voice to the safety driver
DMS Engineer	Right rear seat	Monitors the DMS and adjusts as appropriate to ensure appropriate data collection

Prior to the first drive, the DPD driver is familiarized with the vehicle and the upcoming demonstration. Then the DPD watches a tutorial on the tutoring app, explaining the automated driving functionality and needed interactions. When the DPD is ready to start driving, the safety driver drives the vehicle onto the motorway and the DPD decides when the safety driver should initiate automated driving.
Close to the end of the scenario, the safety driver drives the car to a parking lot and stops there. The DPD completes a short survey and provides impressions about the drive. Then the next scenario starts. Each drive on the motorway is about 12 km long.

The road infrastructure represents a critical enabler of the demonstration scenarios, especially to increase the predictability of the AD operations for the driver. The following subsections describe that such road infrastructure is technically within the realms of possibility, and even already at the current level of implementation useful for the purpose at hand.

3.5. Road Infrastructure to Vehicle Communications to Enable Extended AD Prediction Horizons

In 2016 the EU adopted a strategy toward Cooperative Connected Intelligent Transport Systems (C-ITS) toward Cooperative, Connected, and Automated Mobility (https://www.ccam.eu/). Since then, several EU projects are investigating how road infrastructure information can be made available to automated driving vehicles. The INFRAMIX (www.inframix.eu) project investigated the advancements in the digital road infrastructure and the upgrades in the physical infrastructure to support the transition period and the coexistence of conventional and automated vehicles. The INFRAMIX project focused on scenarios of dynamic lane assignments, construction sites / roadworks zones, and traffic bottlenecks (on-ramps, off-ramps, lane drops, tunnels, sags). The TransAID project (https://www.transaid.eu) focuses on transition areas in which automated vehicles will change their level of automation. The Mantra project (https://www.mantra-research.eu) investigates influences of automation on the core business of road operators and the ICT4CART project (www.ict4cart.eu) designs, implements and tests a versatile ICT infrastructure in real-life conditions. Finally, the ESRIUM project (https://esrium.eu/) investigates benefits of a high precision–GNSS assisted-digital map of road surface damage and road wear, see Table 2. While the communication of road infrastructure information to the vehicle has been thoroughly demonstrated, the HADRIAN field-demonstration shows the feasibility of using this information to increase the safety and acceptability of automated driving. The next subsection therefore reviews the used message types.

Table 2 I2V Information used in Related EU Projects

Information	Purpose	EU Project

Upcoming transition areas	Prepare to transition from automated to manual driving	Transaid, INFRAMIX (S.2)
Updated vehicle path	Continue automated driving through ODD disruptions or transitions	Transaid, INFRAMIX (S.3)
Updated vehicle speed / lane / headway advice	Optimize traffic flow	Transaid, INFRAMIX (S.1)
Guidance to safety spot	Manage minimum risk manoeuvre	Transaid
Toll lane information	Selecting a less congested toll station	ICT3CART (SCN 2.2)
Urban intersection monitoring information	Avoid danger and possible collisions for urban automated driving	ICT3CART (SCN 2.3)
360° traffic awareness	To avoid collisions for urban automated driving	ICT3CART (SCN 3.1., SCN 3.2.)
Lane merging	Automated vehicle merges lanes	ICT3CART (SCN 3.3.)
Enhanced position information	Enhanced positioning of own-vehicle in urban areas	ICT3CART (SCN 3.4.)

3.5.1. Communication protocols

Based on the standardized DATEX II format (www.datex2.eu), the cooperative intelligent transport systems (C-ITS) forms the cornerstones for connected driving and are defined among others in the C-ROADS specifications (https://www.c-roads.eu). Different C-Roads pilots services are currently available whereas others are planned for the near future. The specific message content and C-ITS messages that are used in the HADRIAN demonstration are currently available and listed in Table 3. Future versions of the C-ITS messages will be even more targeted to support the AD operations as performed in the HADRIAN project:

Table 3 C-ITS Messages used in the Field-Demonstrations

Communicated Information	Scenario	C-ITS Message Format
Terminate ADL 2 due to blocked lane ahead	1	DENM Road Works Warning (4.2.1[*])
Continue ADL 3 through upcoming lane closure	2.a	DENM Road Works Warning (4.2.1)
Continue ADL 3 through detected obstacle on lane ahead	2.b	DENM Hazardous Location Notification (3.2.7)
ADL 3 portions on planned trip	3	IVIM Automated Vehicle Guidance (5.2)
Unexpected termination of ADL 3	4	DENM Road Works Warning (4.2.1)
Multiple transitions between ADL 2 and 3	5	IVIM Automated Vehicle Guidance (5.2)

[*] Section number in the C-Roads specification (C-Roads, 2021)

Conclusions

The described HADRIAN demonstration evaluates the feasibility of increasing the predictability of AD and translate these benefits to the driver via a holistic HMI and DMS to improve the human driver role concerning AD safety and acceptability. This effectively brings together road infrastructure, the vehicle, and the driver and therefore may serve as example for future CCAM activities. The demonstration is intended to be conducted in September – October 2022 and results are presented at the TRA conference.

Acknowledgements

HADRIAN has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 875597. This document reflects only the author's view, the Climate Innovation and Networks Executive Agency (CINEA) is not responsible for any use that may be made of the information it contains. The publication was written at VIRTUAL VEHICLE Research Center in Graz and partially funded by the COMET K2 – Competence Centers for Excellent Technologies Programme of the Federal Ministry for Transport, Innovation and Technology (bmvit), the Federal Ministry for Digital, Business and Enterprise (bmdw), the Austrian Research Promotion Agency (FFG), the Province of Styria and the Styrian Business Promotion Agency (SFG).

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