Hi-Drive

Designing Automation

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Effects

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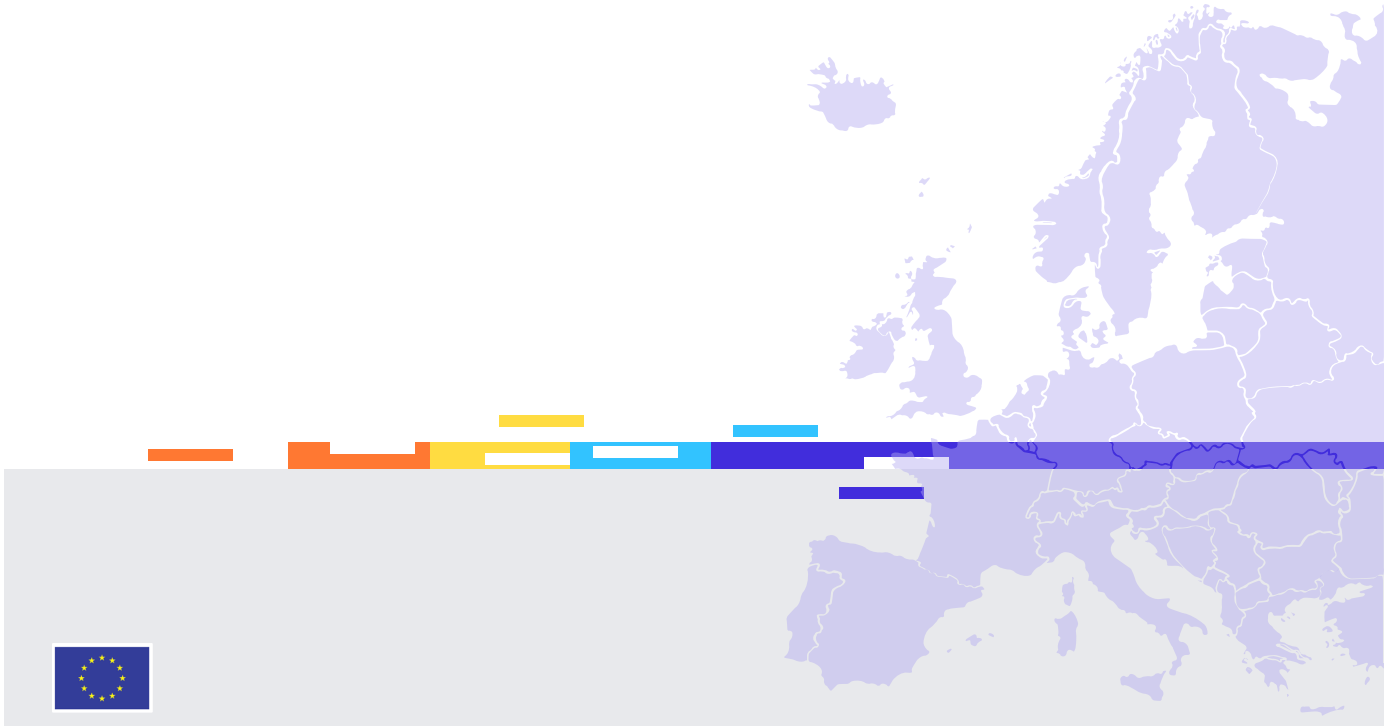

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Executive summary

This deliverable summarises and connects the results of the individual impact areas addressed in the Hi-Drive impact assessment, which are presented in Deliverables D7.3 (safety), D7.4 (mobility, efficiency, environment, and transport system), and D7.5 (socioeconomic). The aim of the impact assessment was to analyse the effects of automated driving (AD) incorporating Hi-Drive technology enablers such as connectivity and advanced positioning. These were compared with AD without enablers to determine the enabler effects, but also with manual driving to identify the overall effects of AD and its enablers. For manual driving, two different future baseline scenarios were considered: the traffic-today baseline, representing the current penetration of advanced driver assistance systems (ADAS), and the full-mandatory-ADAS baseline, representing an adjusted baseline that accounts for the increasing future ADAS penetration due to ADAS mandated by law.

The mobility impact assessment was performed based on extensive global surveys including more than 17,000 respondents from nine different countries within the EU and beyond. The effects for the impact areas safety, efficiency, environment, and transport system were calculated based on simulations. The impact assessments for safety, efficiency, and environment used harmonised modelling of the automated driving functions (ADFs) and the enablers, which was calibrated with real-world driving data gathered as part of the Hi-Drive project. The transport system impact assessment used macroscopic simulations incorporating results from the mobility and efficiency impact assessments. Finally, the socioeconomic impact assessment performed a cost-benefit analysis based on the estimated costs and effects across the different impact areas for AD.

Across impact areas, AD and its enablers deliver benefits beyond mandatory ADAS. At 30% penetration, 19.7% of motorway and 21.8% of urban fatal target accidents could be avoided compared to the traffic today baseline; while minimum-risk manoeuvres may introduce a small rise in motorway accidents (0.3%), the safety effect remains clearly positive. ADFs are likely to increase traffic by enabling non-driving-related activities that improve travel quality and may induce more frequent, longer trips. Efficiency and environmental impacts are modest: travel times rise slightly (0–3% at up to 50% penetration on the European network) due to desired speed changes, with enablers mitigating this; tractive energy per vehicle-kilometre travelled (VKT) decreases dependent on the scenario (0–15%), and CO_2 effects are small (−1% to +1%), with enablers able to offset increases.

System-level modelling shows negligible changes in modal split. Capacity reductions and route choices lead to increases in VKT and vehicle-hours-travelled, e.g. VKT +1.5% outside the ODD at 50% penetration of the automated driving function and enablers. Socioeconomic

benefits are dominated by safety (€22 to €40 bn) and user gains (€23 bn from comfort and the ability to work/relax), partly offset by higher travel time costs (€6.8 to €7.5 bn), and smaller benefits from reduced energy consumption and CO_2 emissions (€0.5 to €1.8 bn). Accounting for vehicle and infrastructure costs yields an average benefit–cost ratio of 1.2 for the full-mandatory-ADAS baseline and 1.8 for the traffic-today baseline, indicating that the benefits of AD and its enablers clearly outweigh the costs. The harmonised AD behaviour used in Hi-Drive produces robust system-level results, with strong safety gains accompanied by some efficiency trade-offs.

Glossary

Term	Definition
Automated driving function (ADF)	A common feature addressed by a group of automated driving systems
Automated driving system (ADS)	The hardware and software that are collectively capable of performing the entire DDT on a sustained basis, regardless of whether it is limited to a specific operational design domain (ODD); this term is used specifically to describe a Level 3, 4, or 5 driving automation system.
AD	Automated driving
ADAS	Advanced driver assistance systems
AV	Automated vehicle
BADF	Baseline ADF or ADF without enablers
Baseline	Set of data to which the performance and the effects of the technology under study are compared
Crash rate	The crash rate indicates the ratio of crashes resulting from the simulations to overall simulated driving scenarios
Driving scenario (DS)	A driving scenario is a short period of driving defined by its main driving task (e.g. car-following, lane change) or triggered by an event (e.g. an obstacle in the lane).
Driving scenario instance	A driving scenario instance represents a single segment in time that is assigned to a certain driving scenario.
Dynamic driving task (DDT)	All of the real-time operational and tactical functions required to operate a vehicle in on-road traffic, excluding the strategic functions such as trip scheduling and selection of destinations and waypoints. (From SAE J3016)
EADAS	Enhanced ADAS, available in BADF and EADF vehicles when driving manually outside their ODD. This enhanced ADAS stems from the better sensors of the BADF/EADF required for automated driving compared to the ADAS mandated by the EU (referred to hereinafter as mandatory ADAS).
EADF	Enabled ADF or ADF with enablers
Enabler	Technological tools (SW, HW, Methodology) that have the potential to enable new vehicle automated function/s and/or upgrade existing vehicle automated function/s.
ERiC	European Risk Calculation tool used for scaling up to European level.

Term	Definition
Experiment	An experiment consists of a series of test runs / trips to investigate a common aspect (ADF, Enabler, User) and is conducted under comparable circumstances. It is made up of several test runs / trips. Experiment types include open road, test track, driving simulator, simulation models, etc.
Full (mandatory) ADAS baseline	Baseline for impact assessment considering "full penetration of mandatory ADAS", reflecting the situation in which the full potential of the European Commission's 2022 decision to make certain ADAS mandatory for new passenger cars has been realised.
GLOSA	Green light optimal speed advisory
HDV	Heavy-duty vehicle
ISA	Intelligent speed assistance
Measure	The magnitude of a quantity such as length or mass relative to a unit of measurement, such as a metre or a kilogram.
MRM	Minimal risk manoeuvre
NDRA	Non-driving-related activities
OEM	Original equipment manufacturer
Operational design domain (ODD)	Operating conditions under which a given driving automation system or feature thereof is specifically designed to function, including, but not limited to, environmental, geographical, and time-of-day restrictions, and/or the requisite presence or absence of certain traffic or roadway characteristics.
Operation	An operation is the execution of experiment(s) in a defined place and time.
PCU	Passenger car unit
Research question	A general question to be answered by compiling and testing related specific hypotheses.
SIA	Safety impact assessment
Target accident	Accident which can be potentially affected by the technology under evaluation, i.e. in this case taking place within ODD of the ADF
Test scenario	Description of sequence of triggers, events and actions among use case entities (ego vehicle, other traffic participants, etc.) in order to reach a use case goal.
TOR	Take-over request
Traffic scenario	Traffic scenarios have a broader horizon than the driving scenarios and cover a specific road section with certain traffic characteristics.

Term	Definition
Traffic-today baseline	Baseline for impact assessment “as in traffic today”, reflecting the penetration of ADAS in the near future.
Use case	Abstract description of the interaction between an ADF and its environment in order to reach a particular goal (e.g. cooperative merging onto a motorway).
VKT	Vehicle-kilometres travelled
VRU	Vulnerable road user
VTT	Value of travel time

1 Introduction

1.1 The Hi-Drive project

Connected and automated driving (CAD) has become a megatrend in the digitalisation of society and in the economy. CAD has the potential to drastically change transportation and create far-reaching impacts. SAE level 3 (L3) automated functions were piloted in Europe by the L3Pilot project in 2017–2021 (L3Pilot consortium 2021). Hi-Drive builds on the L3Pilot results and advances the European state of the art from SAE L3 'Conditional Automation' further up towards 'High Automation'. This is done by demonstrating in large-scale trials the robustness and reliability of CAD functions under demanding and error-prone conditions with special focus on:

- connected and automated vehicles (CAV) travelling in challenging conditions covering variable weather and traffic scenarios and complex infrastructure,
- connected and secure automation providing vehicles / their operators with information beyond the line of sight and on-board sensor capabilities,
- complex interaction with other road users in normal traffic,
- factors influencing user preferences and reactions including comfort and trust—and eventually through a wide consumer acceptance of AD resulting in purchase and use, enabling viable business models for AD.

The project's ambition is to extend the AD's operational design domain (ODD) from the present situation, which frequently demands taking over control of the vehicle by a human driver. As experienced in the EU flagship pilot project L3Pilot, on the way from A to B, a prototype level 3 automated vehicle (AV) encountered a number of ODD boundaries, leading to fragmented availability of the AD function (ADF). Hi-Drive addresses these key challenges which are currently hindering the progress of driving automation. The concept builds on reaching a widespread and continuous ODD, where automation can operate for longer periods, and the interoperability is assured across borders and brands. Hi-Drive strives to extend the ODD and reduce the frequency of take-over requests (TORs) by selecting and implementing technology enablers leading to highly capable CAD functions, operating in diverse driving scenarios (DSs) including, but not limited to, urban traffic and motorways. The removal of fragmentation in the ODD is expected to give rise to a gradual transition from conditional automation towards higher levels of AD.

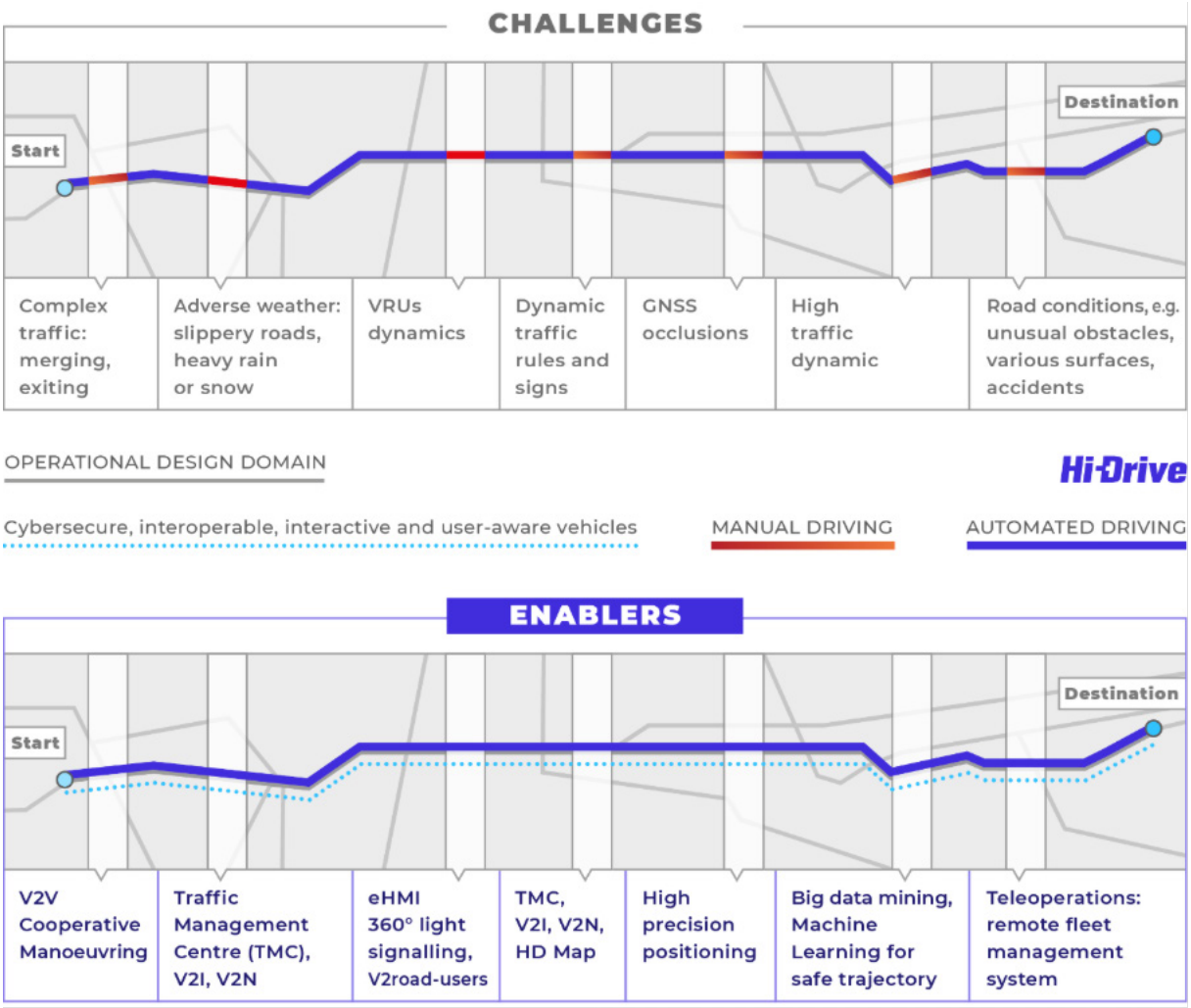


Figure 1.1: Defragmentation of the ODD in Hi-Drive.

The work in Hi-Drive started in July 2021 with the collection and description of the different ADFs, their ODDs and limitations (D3.1 *Use cases definition and description* by Bolovinou et al., 2023), and the enabler technologies that help overcome these limitations. When testable functions and use cases of driving automation were defined, research questions were formulated (D4.1 *Research questions* by Metz et al., 2023), leading to specification of data needed for evaluation and recording of vehicle and driver behaviour (D4.2 *Data for evaluation* by Fahrenkrog et al., 2022) and finding solutions for the experimental procedure (D4.3 *Experimental procedure* by Sintonen et al., 2023). Subsequently, evaluation plans were set for Users (D4.4 *User evaluation methods* by Madigan et al., 2023) and Effects (D4.5 *Effects evaluation methods* by Vater et al., 2023) evaluation.

The evaluation in Hi-Drive focuses on three areas: 1) users; 2) AD performance and availability; and 3) assessment of impacts (on safety, efficiency, environment, mobility, and

transport system). Furthermore, these assessments serve as input to determine whether the benefits of higher driving automation for the society outweigh its social costs. The project also engages in a broad dialogue with the stakeholders and the general public to promote the Hi-Drive results. Dissemination and communication are boosted by demonstration campaigns to show project achievements.

Overall, Hi-Drive strives to create a deployment ecosystem by providing a platform for strategic collaboration. Accordingly, the work includes an EU-wide user education and driver training campaign and series of Codes of Practice (CoP) for the development of ADFs and road-testing procedures, while also leading the outreach activities on standardisation, business innovation, extended networking with interested stakeholders, and coordinating parallel activities in Europe and overseas.

1.2 Overall implementation plan for Hi-Drive

The implementation plan for Hi-Drive follows the FESTA methodology. The FESTA Handbook (FOT-Net, CARTRE & ARCADE, 2021) compiles the knowhow gained since 2007 on the testing and evaluation of driver support systems and functions. The FESTA methodology was designed for field-operational tests (FOTs) with market-ready products. Therefore, it does not fully apply to studies with prototypical AD functions[1] (ADFs). Thus, some adjustments to the FESTA implementation plan, described as the "FESTA-V" structure, were required to accommodate the testing of AD.

Figure 1.2 illustrates the FESTA implementation plan adapted for Hi-Drive. The plan is divided into three phases: (I) prepare, (II) operate, and (III) evaluate. At the beginning of the preparation phase (I), ADFs, the technology enablers, and their use cases and associated test scenarios across multiple test environments (test track, open road, simulation) are selected and described in detail. Then, an initial list of research questions is set up and organised as high-, medium-, and low-level questions. The state of the art is summarised for topics covered by these research questions. The feasibility of each research question is checked next in terms of data availability, suitability of the experimental design and procedures, availability of research tools, methods and external data sources, and availability of resources (e.g. project duration and human resources) required.

[1] According to the Hi-Drive glossary: Automated Driving Function (ADF) is a common feature addressed by a group of automated driving systems, for example: Motorway ADF, Urban ADF.

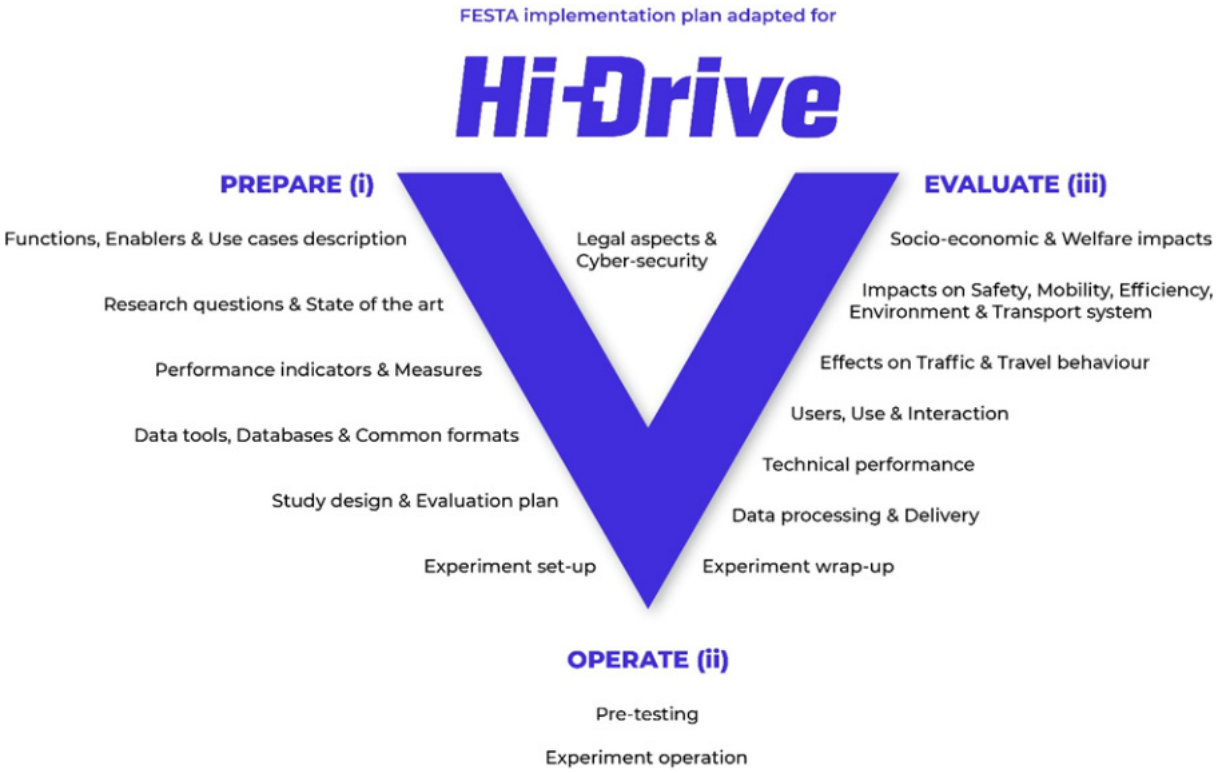


Figure 1.2: FESTA implementation plan adapted for Hi-Drive.

Thereafter, the performance indicators and other data used to answer the research questions are defined, and the relevant evaluation tools are calibrated. Based on these evaluation requirements, five lists – one for each data category[2] – with the required information are defined. In the following step, the five lists are merged into one signal list, which specifies all the signals needed. Alongside the signal list, a Common Data Format (CDF) applicable to the project evaluation is specified for collecting, storing, and sharing the signals. The data to be shared for evaluation is agreed upon with the data providers. Various databases and data tools are defined for data processing and storage.

The experimental design and procedures are part of the study design. They enable the testing of highly automated driving and its technology enablers and provide data for evaluation. The plans for all operation sites are approved by the site owners and those setting the evaluation methodology.

[2] The data categories are closely linked to the different databases which have become the tool for making the data available for evaluation: experiment metadata, questionnaire data, performance indicator data, time series data, and aggregated time series data. Details in D4.2 *Data for Evaluation* by Fahrenkrog et al. (2023).

An evaluation plan is developed for all research questions to specify the methods, tools, and data to be used, scenarios to be addressed, and to plan the dependencies, i.e. linking the inputs and outputs as well as their timelines.

The experimental setup includes preparation of test vehicles, testing of selected parts of the technology and use cases, obtaining permissions (e.g. for test drives on public roads), selecting participants, and implementing data logging.

The operation phase (II) starts with the pre-testing step. It involves running all the phases of the project on a small scale to ensure that all the processes and tool chains function as intended. Once everything is confirmed to work as intended, the experimental operation begins. This phase involves the actual data collection.

The evaluation phase (III) starts with data delivery as part of the experiment wrap-up. In this phase, it is also important to report all deviations from the plan and any system updates made during the data collection phase. The data are converted into CDF, processed, and delivered to the evaluation team. There, the plans are implemented and the evaluations carried out. The final step is the documentation and publication of the results.

Within SP7 *Effects*, one deliverable presents the evaluation of the technical performance of the Hi-Drive enablers and CAD functions based on the gathered driving data (D7.1 *Technical evaluation results*). Three deliverables address the different impact areas considered within the impact assessment (D7.3 *Effects on Safety*, D7.4 *Effects on Mobility, Efficiency and Environment* and D7.5 *Socioeconomic Effects*). The results of the different impact areas are summarised in one deliverable to provide an overview of the main findings of the impact assessment (D7.2 *Effects*).

1.3 Objective overview and structure of the deliverable

This deliverable summarises the overall impact assessment results of the Hi-Drive project. Therefore, it condenses Deliverables D7.3, D7.4, and D7.5 mentioned above to provide an overview of the impact assessments performed. Chapter 2 introduces the impact assessment design as well as the joint fundamentals for the considered impact areas. Chapters 3 to 7 present the impact area-specific approaches and results for safety, mobility, efficiency and environment, transport system, and socioeconomic impacts. Chapter 8 concludes and discusses the results. For detailed results, approaches, and limitations, please refer to the impact area-specific deliverables.

2 Overall design of the Hi-Drive impact assessment

Hi-Drive aimed to extend the ODD and enhance AD performance within it through the use of technology enablers which affect the behaviour of the AD system within certain use cases. The Hi-Drive impact assessment was designed around the research questions on the estimated effects of highly automated driving, supported by technology enablers, both in specific driving scenarios and at the European level following market introduction, and the contribution of these enablers to these impacts (Vater et al. 2024). The objective was to investigate both direct and indirect impacts, including broader effects and impact chains often shaped by complex interactions and external factors (Innamaa et al., 2018; Vater et al., 2023).

The Hi-Drive impact assessment covered the effects of AD systems on safety, efficiency, environment, mobility, and the overall transport system. These were addressed through the following six high-level research questions:

- What is the impact of AD and its enablers on safety?
- What is the impact of AD and its enablers on energy demand?
- What is the impact of AD and its enablers on emissions?
- What is the impact of AD and its enablers on traffic efficiency?
- What is the impact of AD and its enablers on personal mobility?
- What is the impact of AD and its enablers on the transport system?

Within the assessment, the project focused on two different environments: motorways and urban areas. The two environments were selected in alignment with the project's developments and conducted operations, as they focused on these two environments.

For these evaluations, the following configurations of ADFs were defined:

- **EADF** ("Enabled ADF" or "ADF with enablers") refers to a market-ready ADF which includes the technology enablers investigated in Hi-Drive. The focus is on the extended functionality of the EADF rather than on which enablers are needed to realise these functionalities, as multiple enablers can support the same use case.
- **BADF** ("Baseline ADF" or "ADF without enablers") is the baseline for comparison with the envisioned EADF to investigate the contribution of the enablers. BADF cannot realise the extended functionalities of EADF. Still, it is a market-ready system that can be operated in traffic but may have a lower performance in certain driving scenarios (e.g. reduced speed in complex interactions) and a more limited ODD.

Various enablers were considered as part of the EADF. While some of them (especially connectivity enablers) were directly simulated within different impact areas, others contributed as part of the scaling-up to the EU level, as they extend the ODD (e.g. improved positioning). Details on the enablers considered in the impact assessment are provided in Hi-Drive Deliverable D4.5 (Vater et al., 2023):

The ODDs of the ADFs were defined as follows:

- **Motorways:**

  BADF: All speed limits (incl. no speed limit), allowed speed range 0 to 130 km/h. Lane width at least 3.2 m. All short (<2.5 km) tunnels, long tunnels with separation of directions inside the tunnel, and no intersections within the tunnel. Light and moderate rain, no snowfall. Snow on the side of the road when lane markings are mostly visible.

  Extension of ODD due to EADF: Driving on motorway ramps, merging lanes, and exit lanes. Roadwork sites, also including lanes narrower than 3.2 m. Long tunnels without separation of directions, tunnels with intersections inside the tunnel. Areas with incomplete lane markings. Snow on the road.

- **Urban:**

  BADF: Urban streets with speed limit up to 50 km/h. Lane width at least 3.0 m. Lane markings or curb needed at least on one side. Signalised and unsignalised intersections. All short (<2.5 km) tunnels, long tunnels with separation of directions inside the tunnel and no intersections within the tunnel. Streets with and without bicycle lanes, bus lanes, bus stops, tram tracks, on-street parking or speed bumps. Light and moderate rain, no snowfall. Snow on the side of the road when lane markings are (mostly) visible.

  Extension of ODD due to EADF: Lane width at least 2.5 m. Streets without lane markings or curbs. Roadwork sites. Long tunnels without separation of directions, tunnels with intersections within the tunnel. Heavy rain. Snow on the road.

Both BADF and EADF vehicles were expected also to be equipped with:

- EADAS ("Enhanced ADAS"), which refers to the advanced driver assistance systems (ADAS) available in BADF and EADF vehicles *when driving manually* outside their ODD. This enhanced ADAS results from the better sensors of the BADF/EADF, needed for automated driving compared to the ADAS mandated in the EU (called mandatory ADAS hereinafter).

The **impacts** were evaluated in two pairings of systems:

- Treatment scenario with EADF vs. Baseline scenario of human-driven vehicles: for the full impact of automated driving

- Treatment scenario with EADF vs. the corresponding scenario with BADF: for assessing the contribution of enablers within this impact.

For **manual driving**, two different future baseline scenarios were investigated, each considering different ADAS penetration rates:

- "As in traffic today", reflecting the penetration of ADAS in the near future and assuming a very fast ramp-up of AVs (also referred to as the "traffic-today baseline" in the text),
- "Full penetration of mandatory ADAS", reflecting the situation in which the full potential of the decision to make certain ADAS mandatory for new passenger cars (European Commission, 2022) has been realised (also referred to as the "full (mandatory) ADAS baseline" in the text).

As the comparison with traffic today is most meaningful for smaller ADF penetration rates, the impact assessment addressed penetration rates of 10% and 30% of EADF and BADF in use among passenger cars. However, once full penetration of mandatory ADAS is reached, higher penetration of ADF can be expected. Therefore, for the comparison with full penetration of mandatory ADAS, larger penetrations of ADFs of 30% and 50% were selected. Note that "full penetration" of mandatory ADAS is likely less than 100% due to older vehicle models remaining on the road; thus 90% penetration was used. Impact area-specific evaluations were also free to include other penetration rates if resources allowed, in order to identify the specific conditions under which impacts can be expected.

3 Safety impact assessment results

3.1 Approach

The safety impact assessment (SIA) centres on the high-level research question: "What is the impact of AD and its enablers on safety?" (Metz et al., 2023). This is refined into three medium-level research questions:

1. What is the impact of AD and its enablers on safety in different driving scenarios?
2. What are the indirect impacts of AD and its enablers on safety?
3. What is the impact of AD and its enablers on safety at European level?

To answer these questions, the ADF with enablers (EADF) was compared to manual driving (including ADAS) and the ADF without enablers (BADF). The comparisons were conducted for two ADAS penetration scenarios: "as in traffic today" and "full penetration of mandatory ADAS" (cf. Chapter 2). The assessment methodology is outlined in Hi-Drive Deliverable D4.5 (Vater et al., 2023) and summarised in Figure 3.1.

Figure 3.1: High-level approach for the safety impact assessment.

Direct effects in terms of changes in crash probability and crash severity were derived via simulations of various driving scenarios using different input data, such as crash data and real driving parameters derived from Hi-Drive operations data. The simulation approach for the driving scenarios followed either the crash re-simulation approach or a stochastic scenario-generation approach based on certain crash mechanisms. Injury risk functions were applied to determine crash severities. The outcomes of the driving scenario simulation were then combined with changes in the frequencies of related driving scenarios, which were determined in dedicated traffic simulations.

To address the European level, the direct effects in the driving and traffic scenarios were scaled up using European accident databases (CARE) and the ERiC tool (Rämä and Innamaa,

2021) to estimate absolute changes in accident numbers and severities at different market penetration rates.

The SIA focused primarily on motorways and urban roads, since Hi-Drive has developed the AD systems for these roads. However, indirect effects due to EADAS (enhanced ADAS of ADFs outside their ODD) on rural roads were also investigated. Overall, 59 driving scenarios have been considered from which 40 driving scenarios were developed and simulated. The selection of the 40 driving scenarios was done based on their relevance in terms of accident numbers and simulations feasibility. For the simulations, four different simulation tools (openPASS, esmini, and two in-house simulation solutions) were applied. The simulated ADAS (e.g. AEB, ACC, ISA.) and ADFs are OEM-neutral systems, developed jointly with the other impact areas based on the information available to the impact assessment partners.

In addition, a qualitative assessment of indirect effects (e.g. changes in travel volume or modal choice) was conducted. More details can be found in Hi-Drive Deliverables D4.5 (Vater et al., 2023) and D7.3 (Sonntag et al., 2025)

3.2 Results

The results of the SIA address the three medium-level research questions. They include individual results for individual driving and traffic scenarios, as well as the overall scaled-up results at the European level. In addition, qualitative indirect impact assessments are provided.

3.2.1 Driving scenarios

To provide exemplary driving scenario results, two driving scenarios were selected: a typical rear-end conflict, which is common for both manually driven vehicles and ADFs, and a minimal risk manoeuvre (MRM), which is specific to ADFs. The extended list of all 59 driving scenarios is given in Hi-Drive Deliverable D7.3, Annex 2 (Sonntag et al., 2025). The driving scenarios were structured and indexed based on the top-level categories “Driving in Lane” (01|xx), “Changing Lane” (02|xx), “Crossing” (03|xx), “Turning Left” (04|xx), and “Turning Right” (05|xx).

3.2.1.1 Driving scenario example 1: Rear end conflict, cut-out

This scenario 01|06 (Rear end conflict, cut-out) was designed as a two-lane road with three vehicles (see Figure 3.2). Initially, all vehicles drove in the left lane. The ego vehicle was positioned at the rear with two other vehicles in front of it: the “middle vehicle” moving at the same speed as the ego vehicle, and the “lead vehicle” travelling at a lower speed. After a set time, the middle vehicle performed a lane change to the right while maintaining its speed to avoid colliding with the lead vehicle. This exposed the lead vehicle to the ego vehicle.

This scenario was simulated on three different road types: motorway (M), urban (U), and rural (R). The ego vehicle was tested under the following conditions: manual driving, three different ADAS systems, BADF, and EADF. BADF and EADF were not simulated for rural roads, leading to 16 different configurations for the scenario.

Initial ego speeds were varied in 10 km/h increments within the limits of the road type, while the middle vehicle always matched the ego vehicle's speed, as a following situation was assumed. The speed limits on the different road types were: motorway 60–130 km/h, urban 10–50 km/h, and rural 40–100 km/h. Other varied parameters included time headway (THW) values and lane change durations. These were sampled from distributions derived using the highD drone dataset (Krajewski et al., 2018), with outliers discarded. Scenarios in which collisions occurred between the lead and middle vehicles were excluded, because both were not equipped with the considered ADFs. A total of 106,796 valid scenarios were generated through the combination of initial speeds, THW, and lane-change times.

The simulation was implemented using a C2P approach (stochastic simulation of synthetic cases with pre-calculated trajectories, as defined in V4SAFETY project by Fahrenkrog et al., 2024), as no accident data for cut-out scenarios were available. The described scenario design followed the definition from UNECE R157 (UNECE, 2021), in which the cut-out scenario is explicitly defined.

No manual driving behaviour data were available from accident records; therefore, manual driving was simulated according to the human reference model described in UNECE R157 (UNECE, 2021). The BADF applied the common BADF model in this scenario, while the EADF additionally utilised V2X communication.

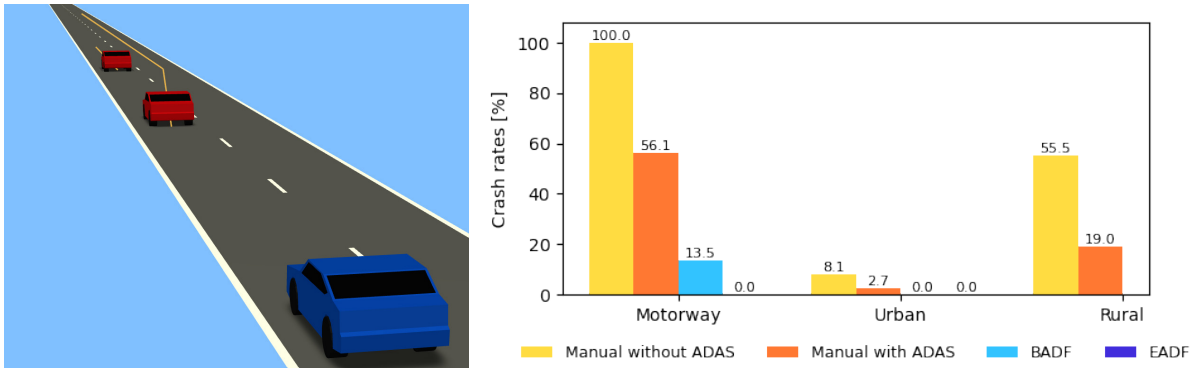


Figure 3.2: Driving scenario 01|06 visualisation (left) and simulation results (right).

The crash rates, i.e. the ratio of crashes resulting from the simulations to overall simulated driving scenarios are presented in Figure 3.2. The crash rate indicates the ratio of accidents resulting from the simulations to overall simulated cases. The ADAS crash rates for the three

different ADAS systems were averaged into a single value. Crash rates for manual driving are not 100% across all road types, as simulation parameters were sampled and not derived from accidents.
ADAS and ADF reduce the crash rates, owing to earlier and harsher reactions compared to human drivers. The BADF further benefits from the combination of ACC and AEB behaviours, while the EADF's V2X capabilities allow early detection of leading vehicles, effectively preventing all crashes.

In the urban scenarios, the crash rate of 8.1% for manual drivers indicates that this situation is not very challenging. The low driving speeds enable a quick standstill, reflected in the 2.7% crash rate for ADAS, which is further reduced to 0% for BADF and EADF.

3.2.1.2 Driving scenario example 2: Minimal risk manoeuvre

This driving scenario 01|19 (Minimal risk manoeuvre) was designed to show the outcomes of executing an MRM. The MRM was triggered once the ADF reached the limits of its ODD, either planned or unplanned due to technical issues, and the driver did not respond in time to a take-over request (TOR). Not every TOR results in an MRM; more typically, the driver is expected to react in time and regain control before the MRM is activated. Even when an MRM is activated, it remains possible for the driver to retake control of the vehicle.

The objective of this scenario was not to contribute to safety gains, but rather to analyse the risks introduced by an MRM, especially for surrounding traffic. Together with the MRM itself, the driver's behaviour was a critical factor in this scenario.

The scenario design involved the ego vehicle driving on a road with surrounding traffic, similar to a traffic simulation. The road layout depended on the road type: for this scenario, motorway and urban conditions were simulated. The motorway had two lanes with speed limits of 100, 120, and 130 km/h and an unlimited speed setting. The urban configuration had one lane with a speed limit of 30 km/h and two lanes with a speed limit of 50 km/h. For both road types, the parametrisation was 250, 500, 750, 1,000, and 1,500 veh/h for traffic volume, and 25% and 90% for the AEB penetration rate.

In the baseline condition, the ego vehicle was controlled by the Stochastic Cognitive Model (SCM) driver model. According to V4SAFETY (Fahrenkrog et al., 2024), this corresponds to a C2I classification (stochastic simulation of synthetic cases with human behaviour in simulation models).

The treatment condition comprised three sequential stages:

1. The ego vehicle is controlled by the Hi-Drive ADF, which is also active during the TOR. The driver never takes over during a TOR; therefore, the next stage, the MRM, is triggered.
2. The MRM is triggered at simulation time t = 20 s, following the manoeuvre described below until the driver takes over after a stochastically determined time.
3. After the driver take-over, the ego vehicle is controlled by the SCM driver model.

The MRM was modelled with a constant deceleration of 2 m/s^2. The deceleration increased to 5 m/s^2 in critical situations where the time-to-collision (TTC) with the preceding vehicle was less than 3 s. On the lateral axis, the vehicle remained in the middle of the lane during MRM execution, and no lane changes were triggered.

The take-over time of the driver was sampled from a gamma distribution derived from the BMW Hi-Drive experiment (see Engel et al., 2024) on public roads. However, it should be noted that no MRMs occurred during the experiment, as the manoeuvre was not active at the time. Instead, reaction times to the issued TOR were used, with the time between the TOR and the MRM subtracted.

Regarding the results, this scenario focused on quantifying the additional risk caused by MRM braking in lane. Depending on the initial velocity and take-over time, the MRM did not always end in a full stop within the lane. The results are shown in Figure 3.3. Crash rates increased by MRM as expected, although the maximum crash risk remained low, with BADF at 0.9%. The results for BADF were similar to those for EADF, as both ADFs did not differ in this scenario. The increase in crash rates due to the MRM was lower in the urban scenario than in the motorway scenario. This can be attributed to the smaller speed differences in urban scenarios, which make it easier for the surrounding traffic to react.

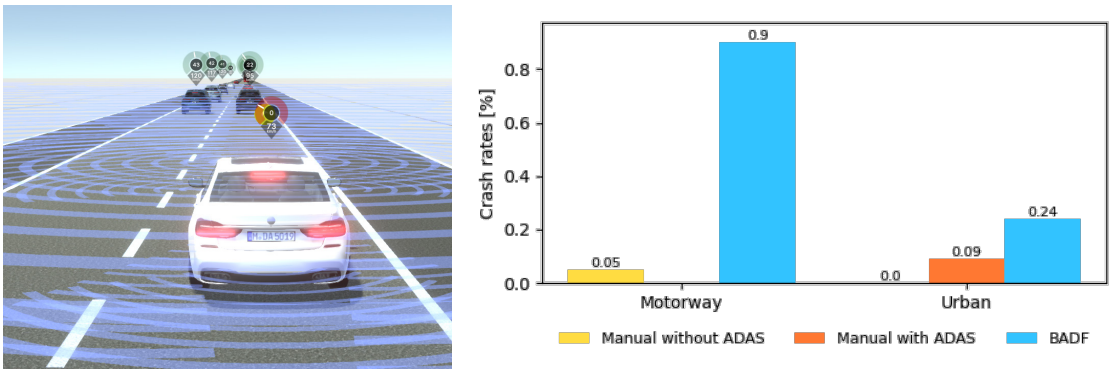


Figure 3.3: Driving scenario 01|19 visualisation (left) and simulation results (right).

The negative effect of the ADF in this scenario was expected. However, it should be noted that an MRM is a rare and short-lived event. Frequency of MRMs was assumed to be once every 30 hours for BADF and once every 45 hours for EADF, while the duration was assumed to be 0.05h for both. This greatly limits the negative consequences of this driving scenario.

3.2.1.3 Overall results

The results from all driving scenarios are presented in Figure 3.5. For each crash, in addition to the crash risk, the likelihood of fatal, serious, or slight injury was calculated. In the following, only the crash rates per scenario are shown. Limitations and assumptions are not discussed here, but they do exist (see also Deliverable D7.3, Sonntag et al., 2025), and the results should not be taken out of context. The results are unweighted as they represent average outcomes across the simulated traffic conditions, such as speed limits and traffic volumes.

Figure 3.5 summarises the relative change in crash risk per driving scenario achieved by the EADF. This represents the relative change compared to manual driving (outer ring), ADAS (intermediate ring), and BADF (inner ring), which are displayed in Figure 3.4. The colour mapping of the relative change is also described in Figure 3.4.

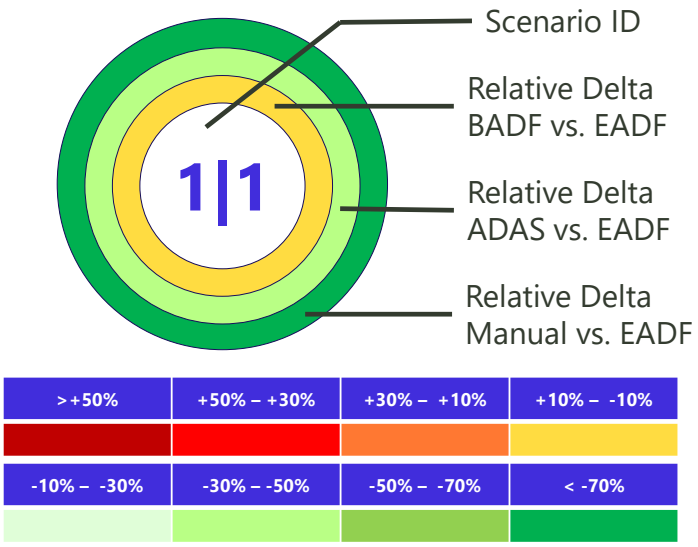


Figure 3.4: Structure of results plot per driving scenario.

At the driving-scenario level, it can be concluded that AD has the potential to enhance traffic safety across nearly all scenarios, though the actual impact depends on the AD design. Despite substantial effort and a large number of simulations (approximately 900,000 runs and more than 4.5 million manoeuvres), there were still scenarios where even more simulations could have been performed (e.g. lane-change conflicts because of a small ratio of

occurrence). Safety effects arising from extending the ODD were not captured at the driving-scenario level and only come into play during the scaling up.

Furthermore, ADAS already provides a substantial safety benefit in certain driving scenarios compared to manual driving, which limits the potential improvement achievable by both ADFs in these scenarios. A notable difference between EADF and BADF is not observable in all scenarios. The driving scenarios in which the EADF outperforms the BADF are listed in Table 3.1. The number of these scenarios already indicates greater safety gains associated with the enabler in urban environments. The only driving scenario with a negative impact is the MRM (01|19) discussed in the previous section (see Section 3.2.1.2.).

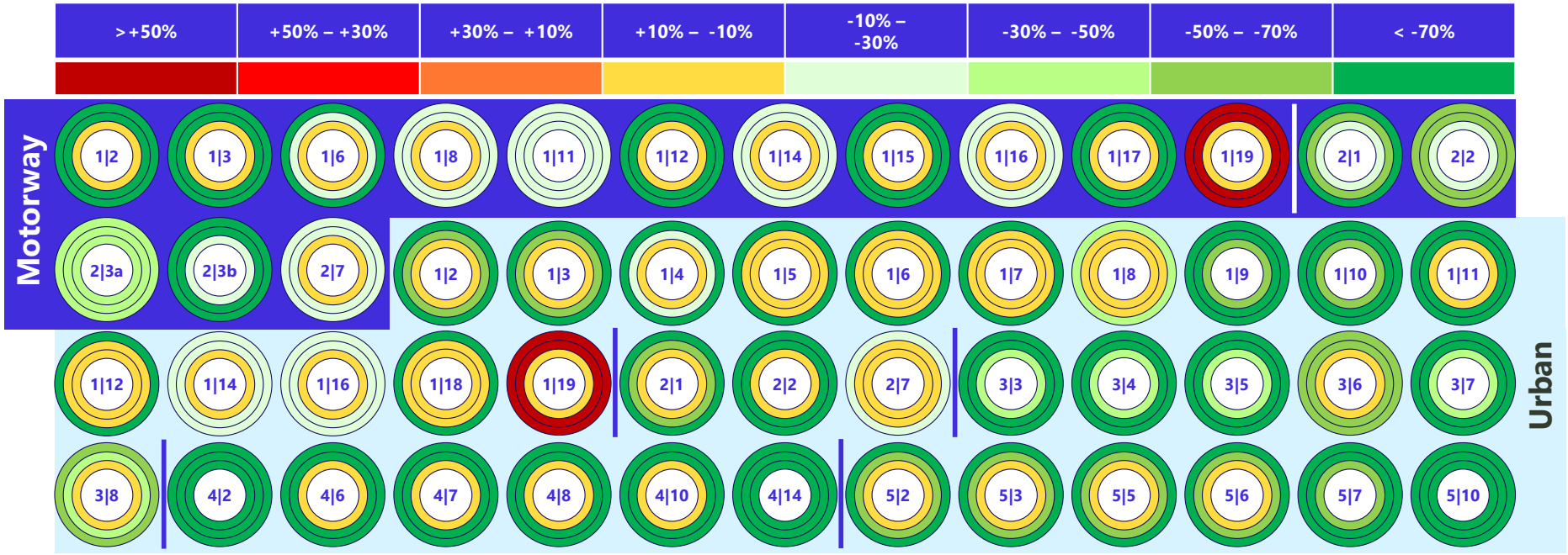


Figure 3.5: Driving scenario SIA simulation results (crash rate). Plots explained in Figure 3.4. Indexing: "Driving in Lane" (1|xx), "Changing Lane" (2|xx), "Crossing" (3|xx), "Turning Left" (4|xx), and "Turning Right" (5|xx).

Table 3.1: Scenarios in which the EADF outperforms the BADF in terms of crash rate.

Motorway	Urban
01|11 rear-end conflict (standing still)	01|09 moving from private garage/alley
02|01 & 02|02 discretionary lane change	01|10 entering/exit conflict (private lane/garage close to curve)
02|03 motorway entrance	03|03, 03|04, 03|05, 03|07 crossing intersection straight with traffic from left or right
	04|02 turn left + conflict with standing vehicle
	04|14 turn left with crossing traffic from right
	05|07 turn right with crossing traffic from left
	05|10 turn right with straight going VRU

3.2.2 Traffic scenarios

This section briefly discusses the simulated traffic scenarios. The goal of the traffic scenario simulations was to provide insight into how the BADF and EDAF affect traffic flow and the occurrence of relevant safety-related driving scenarios. Thus, the scope of the simulations was to investigate scenario frequencies rather than crash rates.

In traffic scenarios, there are no predefined manoeuvres; instead, the continuous effects of the models and systems in operation are observed. The focus is not on an ego vehicle and its conflict participants, but rather on all simulated vehicles. The vehicles are simulated with various systems within the same scenario.

In Hi-Drive, the traffic simulation was performed only for motorways and with a longer simulation time than in the driving scenarios. There was also a difference in the simulated vehicle composition: all vehicle types (manual driving, ADAS low, ADAS high, BADF, and EADF) were simulated according to their respective penetration rates, which depended on the current condition (baseline or treatment) and the overall baseline scenario (traffic today or full mandatory ADAS). Approximately 3 million agents were simulated in total, covering over 9 million kilometres.

Figure 3.6 shows the unweighted results for driving time in both traffic scenarios. The effects were similar for both ADFs: driving time in free-flow traffic increased for the BADF and EADF compared to manual and ADAS-driven vehicles. At the same time, driving time with time gaps shorter than 1.5 s decreased to ~0% for both BADF and EADF, which can be explained by the system settings and the legal requirements of the ALKS regulation (UNECE, 2021).

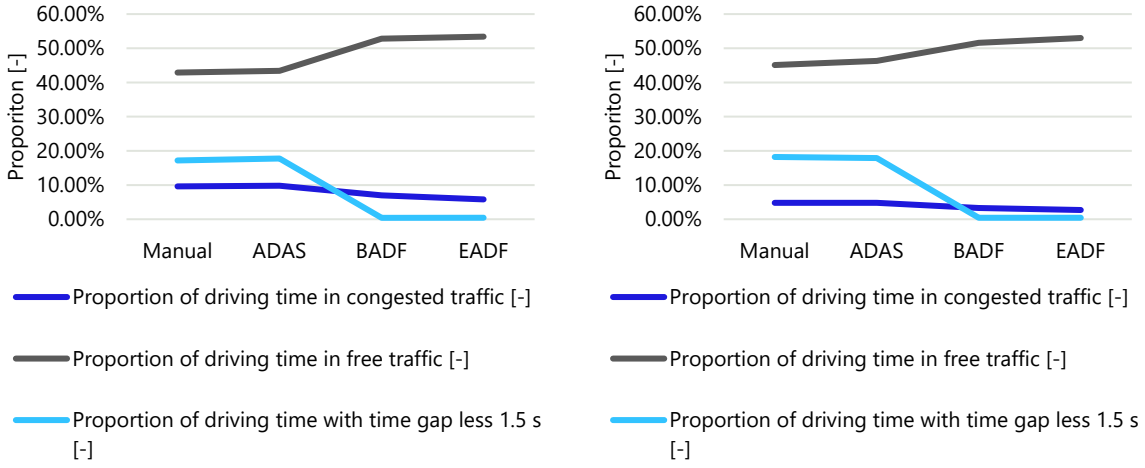


Figure 3.6: Results of traffic simulation – proportion of driving conditions (unweighted).

This also resulted in a shorter driving time in congested traffic for these two systems. The reduction of time in congested traffic for the ADF contributed to a smoother traffic flow.

Frequencies of driving scenarios within the traffic simulations are displayed in Figure 3.7. Vehicles equipped with ADFs showed fewer lane changes, fewer critical events (TTC smaller 1.0 s), and fewer passive cut-in manoeuvres. In terms of critical situations, all traffic participants – including ADAS and manual driving – benefitted from a larger fraction of AD traffic.

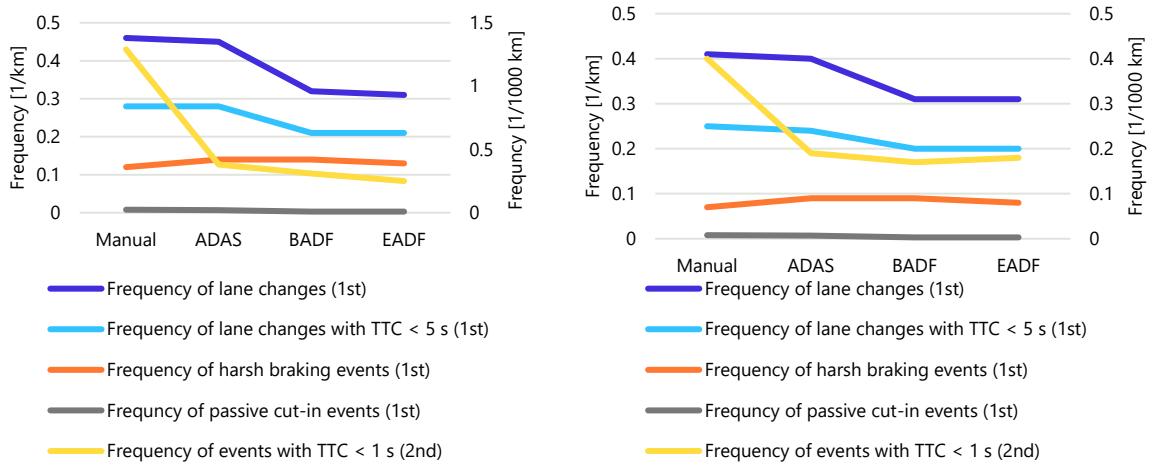


Figure 3.7: Results of traffic simulation – frequencies of driving scenarios (unweighted).

3.2.3 Scaling up

Based on the driving and traffic scenario simulation results, the scaling up to annual European level was performed.

3.2.3.1 Method

The scaling up used three main inputs: external accident databases, Hi-Drive inputs such as ODD descriptions, penetration rates, treatments, and baseline conditions, and the safety-simulation results at driving scenario level. All inputs fed into the ERiC scaling-up tool, whose output addressed the medium-level research question on the direct safety impact of EADF at the European level and the contribution of enabling technologies.

The process began by identifying target accidents, i.e. those accidents that took place within the ODDs of the BADF and EADF and can be potentially affected by this technology and assigning them to the simulated scenarios. To do this, Europe-wide CARE data were processed, considering whether accidents occurred on motorways or in urban areas, in tunnels or at intersections, in work zones, as well as weather, accident type, road surface, lane marking quality, and speed limits (the latter for urban ADF only). Although CARE contains many relevant attributes, some fields were missing or marked as unknown. Therefore, a data-imputation approach developed in L3Pilot filled these gaps to estimate the frequency of all relevant accident characteristics and to define target accidents that could potentially be prevented by the ADFs. In addition, national accident data supplemented CARE, helping to resolve missing information and to weight effect sizes when several simulations addressed the same accident type.

Unknown severities in CARE were adjusted using EU averages and allocated into fatal, serious, or slight categories. Accident types with missing information were reassigned to other categories based on observed frequencies. The allocation process used all available variables, including country, severity, road type, whether the accident occurred at a junction, and whether it happened inside or outside the ODD. Accident types marked as “Not specified” or “Unknown” were mapped to more specific counterparts using the distributions of these known counterparts. If weather, road markings, surface conditions, or speed limits were unknown for a given ODD, they were allocated to inside or outside ODD according to EU-wide distributions for each accident type. For target accident types lacking simulations, effect sizes were estimated from expert knowledge about the capabilities of the technologies, with explicit assumptions such as the ADF not causing unintended lane departures except under extreme conditions, not operating in an unsafe opposite lane, adhering to traffic rules, and no changes in conflicts with pedestrians or other vulnerable road users for routine driving, nor sudden changes in risk due to obstacles unless specifically triggered.

The scaled-up safety impact assessment follows the ERiC principles, drawing on the L3Pilot approach (Bjorvatn et al., 2021) and the work of Rösener et al. (2018). The core formula combines the number of target accidents by severity with changes in scenario frequency, overall injury-risk, and severity shares across scenarios, vehicle types, and environments.

$$Impact_{i,p} = \sum_j T_{i,j} \cdot \left(\Delta f_{j,p} \cdot \Delta r_{total,j,p} \cdot \Delta s_{i,j,p} - 1\right)$$

$T_{i,j}$ = Number of target accidents with severity *i* for driving scenario *j*

$\Delta f_{j,p}$ = Change in the frequency of driving scenario *j* for penetration rate *p*

$\Delta r_{total,j,p}$ = Change in total injury-accident risk for driving scenario *j* for penetration rate *p*

$\Delta s_{i,j,p}$ = Change in accidents' share of severity *i* for driving scenario *j* for penetration rate *p*

Note: The value for all deltas in the formula is 1.00 for 0% change, 0.95 for -5% change, 1.05 for +5% change, etc.

The basic formula is extended to account for penetration rates of different vehicle types (such as ADAS and ADF) and for new crashes arising from initiated MRMs.

3.2.3.2 Results

Prevented target accidents

The number of target accidents in total by environment for EADF was estimated to be 1,033 fatal, 6,172 severe, and 39,750 slight accidents on motorways, and 4,454 fatal, 50,264 severe, and 354,325 slight accidents in urban environments in the EU today. For BADF, the number of target accidents was somewhat smaller: 990 fatal, 5,935 severe, and 38,606 slight accidents on motorways, and 3,509 fatal, 42,951 severe, and 303,707 slight accidents in urban environments. The difference in the number of target accidents results from the ODD extension for the EADF. The BADF results below reflect the effectiveness of an ADF without enablers (BADF) inside the ODD of the EADF, to show the added value of the enablers in our treatment (EADF).

The impact of 10% of passenger cars using EADF in traffic today was estimated to be a 6.6% reduction in fatal accidents taking place within the EADF's ODD on motorways, and a 19.7% reduction for a 30% EADF penetration rate (Figure 3.8). The contribution by enablers is an 8% increase in the proportion of fatal accidents already prevented by the BADF. In an urban environment, these reductions were slightly higher: 7.3% and 21.8%, with a 27% contribution from enablers. With the same EADF penetration rate, the reduction was slightly smaller when the baseline condition was full penetration of mandatory ADAS compared to the traffic-today baseline. In this case, the reduction in the number of fatal accidents by EADF was estimated to be 17.1% for a 30% penetration rate and 28.4% for a 50% penetration rate inside the ODD on motorways, with an 11% addition to the BADF impact from the enablers, and 18.1% and 30.2% on urban roads with a 29% addition from the enablers.

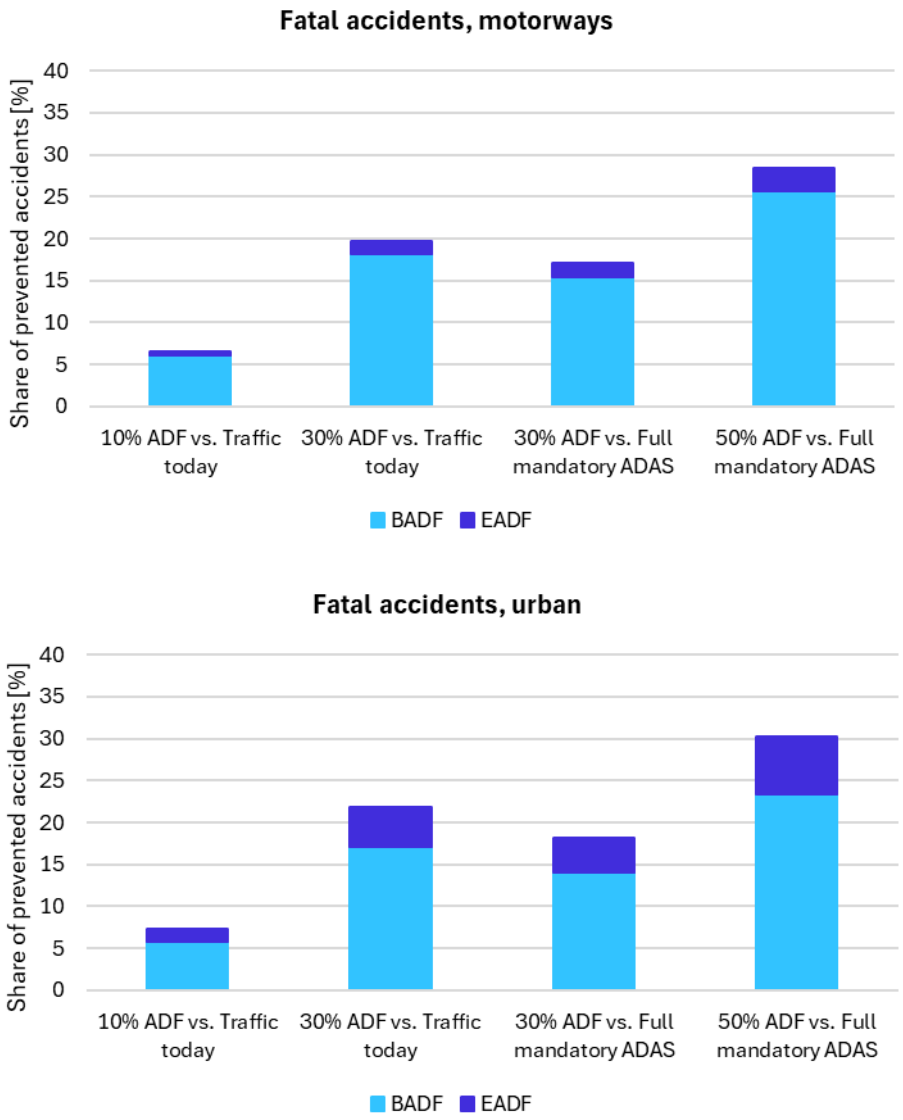


Figure 3.8: Impact of EADF on the number of fatal accidents for different penetration rates of automated driving and baseline conditions, by environment. Light blue bars show the impact for BADF and bark blue the additional impact of the enablers supporting automated driving (EADF).

New accidents

Initiation of MRMs will likely cause new accidents, reducing the benefits of preventing accidents. Their proportion in relation to the target accidents of EADF ranges from a 0.1% increase with a 10% EADF penetration rate when compared to the traffic-today baseline to a 0.6% increase with a 50% penetration rate when compared to the full-mandatory-ADAS baseline on motorways. For BADF, the corresponding proportions are somewhat higher: 0.2%

and 0.8%**,** respectively. On urban roads, the proportions are smaller: at most 0.1% in all cases for EADF and up to 0.2% for BADF.

Accidents prevented outside the ODD

Rural roads were outside the ODD of the EADF and BADF. However, their enhanced ADAS functions (EADAS) led to an additional reduction on those roads: a 3.5% reduction in fatal accidents at a 10% penetration rate and a 10.6% reduction at a 30% rate when compared to the traffic-today baseline. When the baseline was full mandatory ADAS, the reduction was estimated to be 4.9% at a 30% penetration rate and 8.1% at a 50% penetration rate.

Impact in total

New accidents reduce the benefits of automation in preventing current target accidents. This reduction is taken into account in Table 3.2. The impacts on other severities were of a similar magnitude to those for fatal accidents in the respective environments. On rural roads, the impacts were somewhat larger for less severe accidents compared to fatal ones.

Table 3.2: Total impact of EADF per severity and environment, accounting for the percentage of prevented and new accidents across different baseline and EADF penetration combinations for the target accidents occurring within the ODD of the EADF.

		Traffic today		Full mandatory ADAS	
	% of EADF	10%	30%	30%	50%
Motorway	Fatal	6.3%	18.9%	16.2%	27.0%
	Severe	6.1%	18.2%	15.7%	26.2%
	Slight	6.5%	19.5%	17.1%	28.6%
Urban	Fatal	7.2%	21.7%	18.0%	29.9%
	Severe	7.3%	21.9%	18.2%	30.3%
	Slight	7.4%	22.1%	18.3%	30.6%
Rural	Fatal	3.5%	10.6%	4.9%	8.1%
	Severe	3.7%	11.1%	6.6%	11.0%
	Slight	4.0%	11.9%	6.7%	11.2%

3.2.4 Indirect impacts on safety

Potential indirect impacts were investigated qualitatively based on the literature. The approach followed the nine impact mechanisms outlined in Innamaa et al. (2018). Specifically, this allowed for addressing impact mechanisms IM3 (indirect modification of AV user behaviour), IM4 (indirect modification of non-user behaviour), IM7 (modification of modal

choice), and IM8 (modification of route choice). According to the literature, these impact mechanisms may lead to both positive and negative consequences, for example due to potentially reduced driving skills and an increased amount of travel. The estimated effect sizes of these indirect impacts range from small to medium. Details are provided in Deliverable D7.3 (Sonntag et al., 2025).

3.3 Discussion

This Hi-Drive safety impact assessment for AD is the most complex and extensive up to the knowledge of the authors of its kind. More results and details can be found in the corresponding Hi-Drive Deliverable D7.3 (Sonntag et al., 2025). The Hi-Drive safety impact assessment has pushed the boundaries of available simulation tools. The number of scenarios and complexity of the analysed systems made it – in particular in the scaling-up – particularly challenging. Another challenge and limitation of the assessment was the availability of data (e.g. crash data for driving scenarios, level of detail in national crash databases), which constrained the accuracy of the assessment. While the assessment utilised all available data, these limitations inevitably affect its precision. Although the discussion of limitations is not exhaustive in this report, several constraints exist and must be carefully considered when interpreting the results. The assumptions and limitations are presented in detail in Hi-Drive Deliverable D7.3 (Sonntag et al., 2025).

The scenario results indicate that, for many of the simulated driving scenarios, mandatory ADAS could already substantially reduce crash rates. BADF contributed to a further reduction in crashes, while EADF, particularly in urban driving scenarios, yielded additional reductions in crash rates across various scenarios. For some driving scenarios, no further reduction beyond the BADF was observed.

Traffic scenarios showed slightly higher average speeds under EADF compared with other conditions. Additionally, both EADF and BADF reduced lane changes by 22% relative to manual driving.

The scaled-up results were based on target accidents in CARE within the corresponding ODD. Estimated target accidents per year and ODD for the EADF are as follows: on motorways, 1,033 fatal, 6,172 severe, and 39,750 slight accidents; and in urban environments in the EU today, 4,454 fatal, 50,264 severe, and 354,325 slight accidents. With an exemplary ADF penetration rate of 30%, 19.7% of fatal motorway target accidents could be avoided with EADF. The contribution of enablers can improve accident prevention, here it is an 8% increase over the proportion of fatal accidents in addition to those already prevented by BADF. In urban settings, 21.8% of fatal target accidents could be avoided, with a 27% additional contribution from enablers.

ADF deployment may also introduce new accidents, e.g. due to MRMs. The simulations indicate a 0.3% increase in motorway accidents at a 30% EADF penetration. Thus, the positive effect of ADFs outweigh their potential negative consequences. Beyond effects within the ODD, ADFs can also yield benefits outside the ODD (e.g. rural areas) through enhanced ADAS functionality enabled by the upgraded sensor suite and computing resources. The simulations indicate a 5% reduction in fatal accidents compared with mandatory ADAS.

Finally, additional indirect impacts of ADFs were estimated qualitatively across nine impact mechanisms, yielding a range of effects from small to large. When interpreting the safety impact assessment results, it is important to consider the stated limitations and assumptions outlined in this document.

4 Mobility impact assessment results

4.1 Approach

The mobility impact assessment examined the effects of AD on travel quality, travel patterns, and amount of travel. The assessment relied on survey data from the Hi-Drive common questionnaires and the Hi-Drive Global Surveys conducted in 2023 and 2024. A high-level overview of the method is provided in Figure 4.1

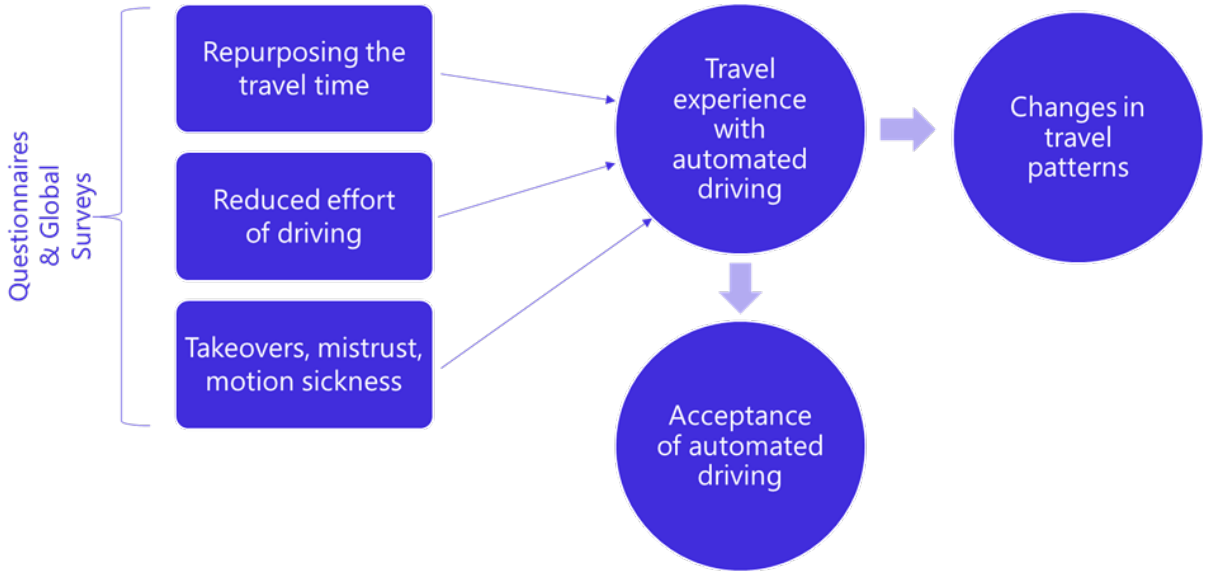


Figure 4.1: High-level overview of the mobility impact assessment method.

The Hi-Drive common questionnaires focused on the experience with AD and the factors influencing them. For the mobility impact assessment, the questionnaires also inquired about current travel patterns and potential changes if the respondents had access to AD.

The Hi-Drive Global Survey 2023 focused on public expectations regarding AD and how these expectations relate to its acceptability. Questions addressed, for example, aspects important for willingness to purchase AD and general expectations towards AD. The Hi-Drive Global Survey 2024 examined expectations about the travel experience with AD and willingness to accept additional travel time when using AD. The online survey was conducted in 2023 across eight countries (China, Germany, Greece, Japan, Poland, Sweden, the United Kingdom (U.K.), and the United States (U.S.)) with a total of 8,345 responses (over 1,000 per country), and in 2024 across nine countries (China, France, Germany, Japan, Poland, Spain, Sweden, U.K., U.S.), with a total of 9,025 responses.

4.2 Results

The Hi-Drive common questionnaires found that AD could help people realise some of their currently unmet travel needs (Figure 4.2). Forty per cent of respondents would travel more frequently if travelling were more comfortable, while 47% would travel more if it were easier. Most participants (58%) stated that they would travel more if they could engage in non-driving related activities (NDRAs) during their journey. At the same time, after the drive, the vast majority of respondents indicated that driving with the ADF active was comfortable and not demanding, and that they would engage in NDRAs such as using digital media, messaging, or making voice calls (Figure 4.3). Together, these results suggest that ADFs are likely to be well received, and some users will probably increase their travel frequency and/or distances.

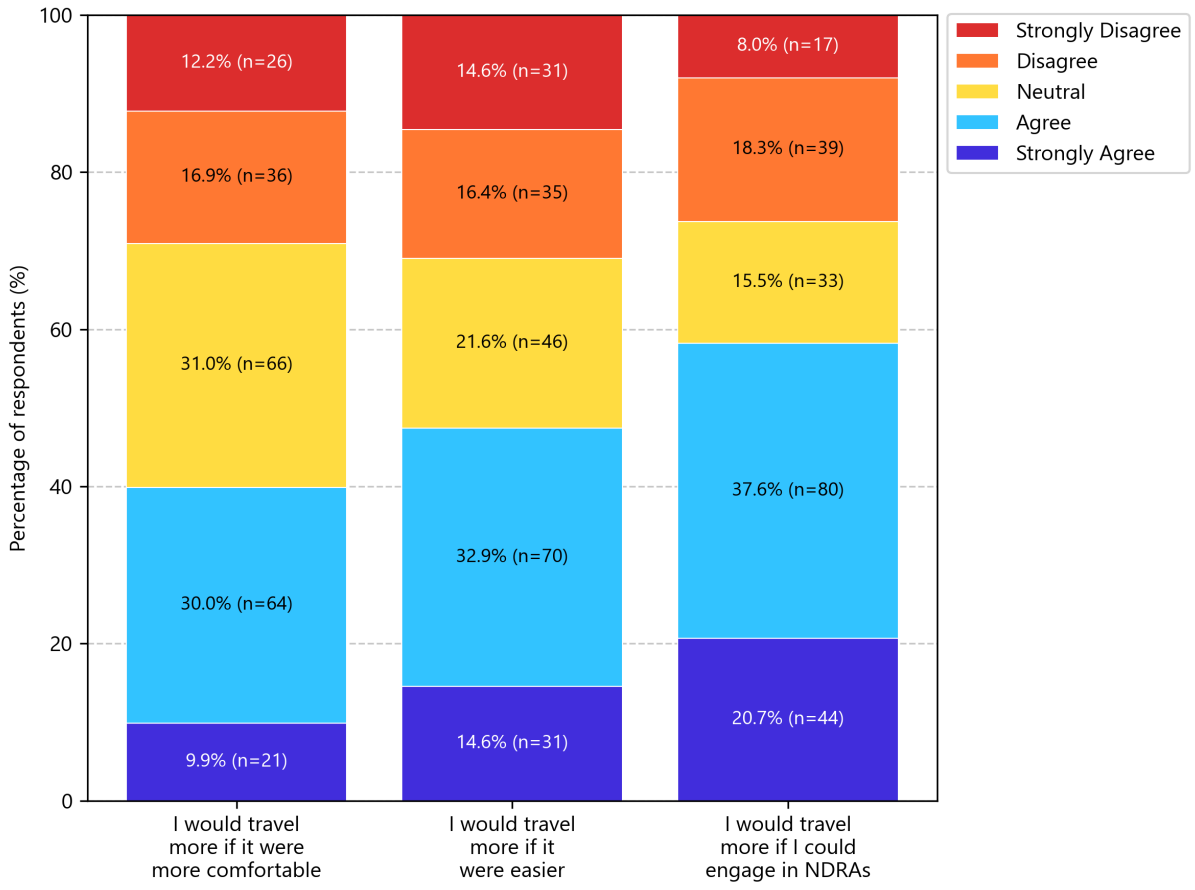


Figure 4.2: Distribution of responses regarding willingness to travel more and the influencing factors in the pre-drive questionnaire.

Among NDRAs, results indicate that working will be much less prevalent than resting or engaging in leisure activities (Figure 4.3). Nevertheless, working will still be a frequent NDRA

among part-time and full-time workers whose jobs could be partially done during an automated commuting trip. This finding suggests that the ability to work while commuting in an AV may particularly affect the value of travel time (VTT) for these professionals.

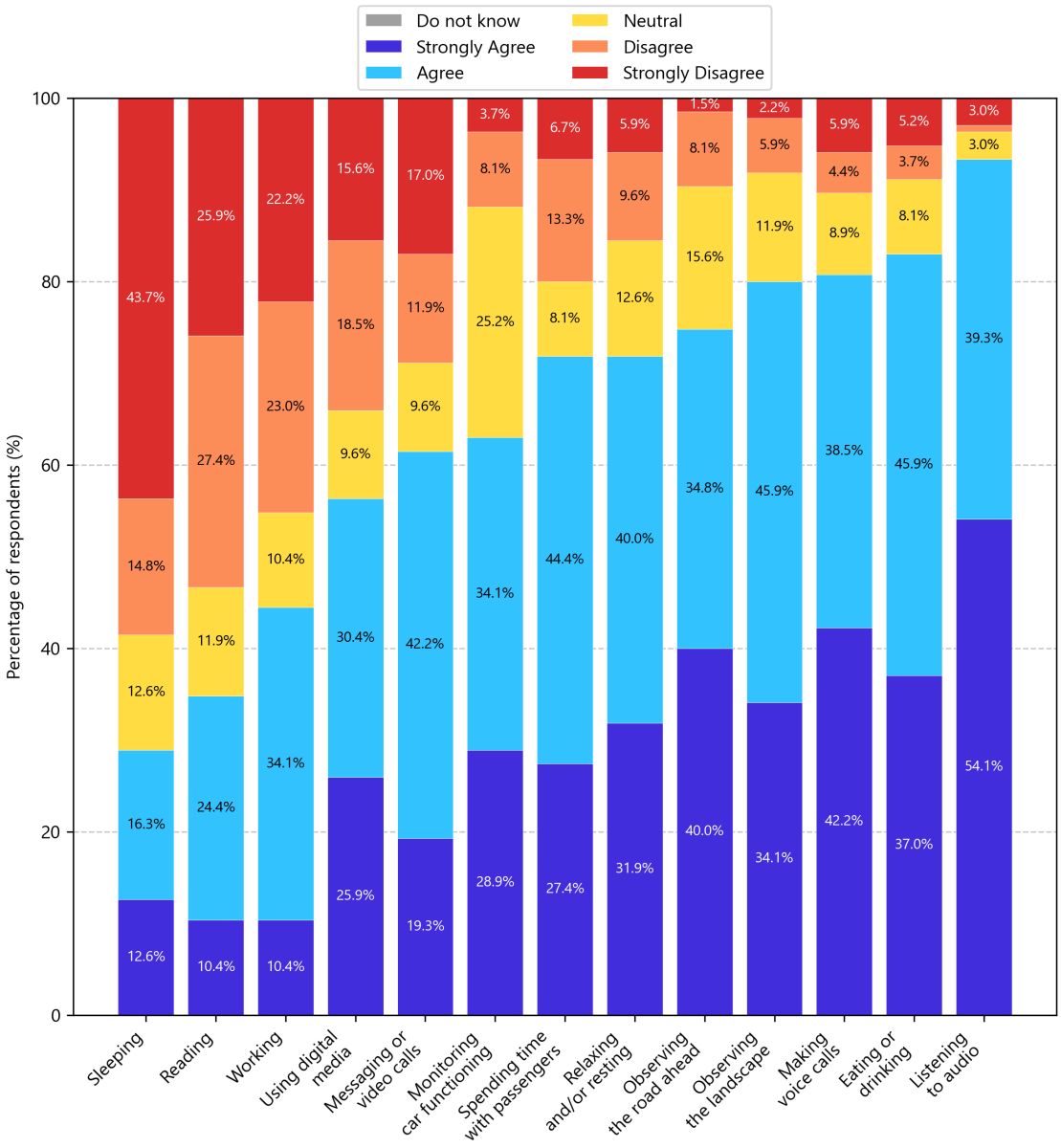


Figure 4.3: Distribution of responses regarding willingness to engage in different NDRAs in the post-drive questionnaire.

Regarding acceptable travel times, findings demonstrate that car drivers would accept a median increase of 25% in travel time with AD, while car passengers would accept a median increase of 19% (Table 4.1). Such increases in acceptable travel times translate into a 20% lower VTT for car drivers, and a 16% lower VTT for car passengers. These findings provide

additional evidence that the introduction of ADFs, which allow users to engage in NDRAs and improve travel quality, is likely to increase travel by automated cars.

Table 4.1: Current travel durations for commute and leisure trips combined, and the additional travel times respondents would accept with an AV. Median values and 25% and 75% quantiles are reported.

Current travel mode	N	Current duration one-way (min)			Relative duration with AD		
		Median	25%	75%	Median	25%	75%
Car as a driver	1,702	25	15	40	1.25	1.00	1.67
Car as a passenger	419	30	15	50	1.19	1.00	1.50

Finally, results show that 68–69% of individuals with health issues that prevent them from driving or limit how much they drive would drive again or more if they had access to an AV (Table 4.2). All in all, the results suggest that ADFs will likely promote a modal shift towards cars and induce additional travel demand, especially among individuals whose driving abilities are hampered by health-related conditions, provided the technology enables them to use AVs.

Table 4.2: Willingness to drive again or more among respondents with health-related conditions that impact their driving ability, based on the Hi-Drive Global Survey 2024.

Question	Yes	No
If you do not drive anymore due to a health-related condition, would you drive again if you had an automated car?	69% (n=322)	31% (n=139)
If you have reduced your driving due to a health-related condition, would you drive more if you had an automated car?	68% (n=762)	32% (n=359)

4.3 Discussion

The findings suggest that ADFs are likely to have significant impacts on mobility. By enabling users to engage in NDRAs, these systems can enhance travel quality, potentially leading to more frequent and longer trips.

5 Efficiency and environmental impact assessment results

5.1 Approach

In efficiency and environmental impact assessment, two baselines were used for manual driving: traffic today and full mandatory ADAS. The latter was modelled as Intelligent Speed Assistance (ISA). Third baseline was scenarios with BADF. These were used to estimate the contribution of the enabler on top of the impact of BADF.

The efficiency and environment-related research questions were addressed by microscopic traffic simulations, an emissions calculation tool, a formula for assessing tractive energy use, and a scaling-up approach based on available external data. Specifically, simulations with the microscopic traffic simulation tool PTV Vissim provided the efficiency indicators as well as vehicle trajectories, which were used to calculate CO_2 emissions by the EnViVer tool, and tractive energy demand by a formula considering resistive forces.

Common indicators for efficiency assessment were travel time and delay. In Hi-Drive they were defined as follows:

- **Travel time** is the average travel time of all vehicles on the network per vehicle kilometre travelled.
- **Delay** is defined as the difference between the theoretical travel time based on a vehicle's desired speed and the actual travel time on the network. Calculated per vehicle kilometre travelled.

For environmental impacts, tailpipe CO_2 emissions and tractive energy use were studied. Their definitions in Hi-Drive are as follows:

- **CO_2 emissions** equal tailpipe emissions per vehicle-kilometre travelled (VKT). The vehicle fleet reflected the average EU vehicle fleet in 2023, with an electric vehicle share of 4%.
- Tractive **energy use** captures the physical energy needed to overcome resistance forces and move a vehicle, thus providing a powertrain agnostic measure for the energy use and its differences between conditions. It is calculated per vehicle kilometre travelled.

The scenarios set up for simulation can be divided into two categories: road-type-specific scenarios designed to investigate the performance of BADF on different networks, and enabler-specific scenarios designed to investigate the benefits of enablers in the context they were designed for.

For the road-type-centric scenarios, simulations were conducted for four motorway networks and five urban networks with varying ADF penetration rates, traffic volumes, speed limits, and

other network attributes. A combination of Lasso regression and ordinary least squares linear regression was used to model the traffic simulation outcomes. Lasso facilitated automatic variable selection, and ordinary least squares provided interpretable estimates based on the selected predictors. The impact estimates were derived using these models.

The enabler-centric scenarios addressed cooperative merging and dynamic speed limit enablers on motorways, and green light optimal speed advisory (GLOSA) and complex intersection enablers in urban environments. Impacts of the enablers were estimated directly from the simulation outcomes.

The scaling up was based on combining the estimated effect sizes with the prevalence of VKT in the corresponding conditions. External road infrastructure, traffic, and weather data were used in this process. See a high-level overview of the methodology in Figure 5.1.

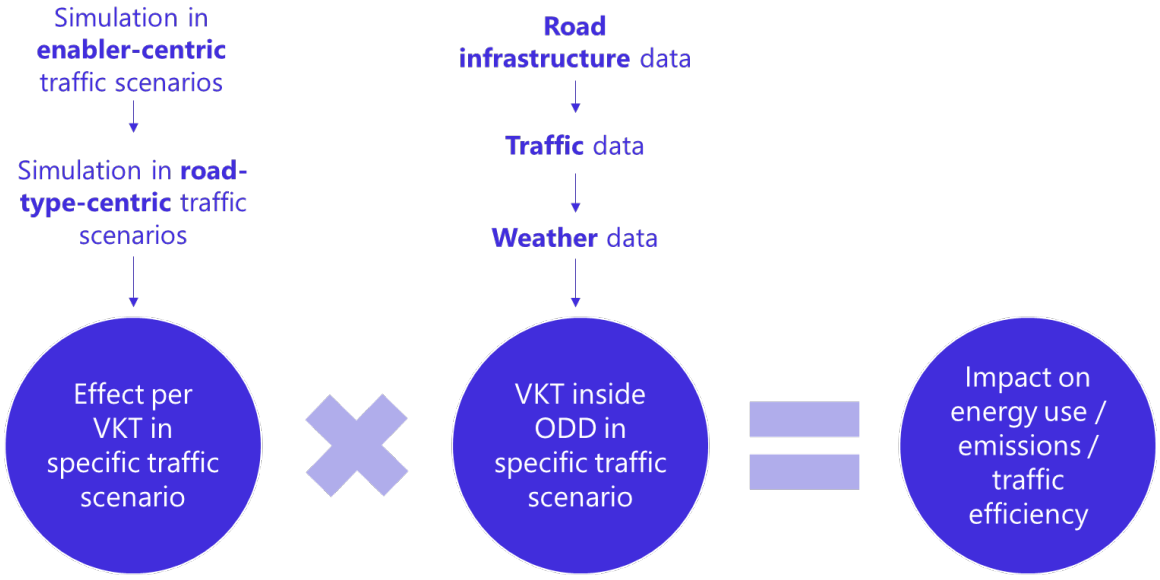


Figure 5.1: High-level overview of the efficiency and environmental impact assessment method.

5.2 Results

5.2.1 Impacts on efficiency

5.2.1.1 Enabler-centric motorway scenarios

Enabler-centric simulations focused on assessing the additional contribution of enablers, by comparing EADF scenarios against BADF scenarios.

Cooperative merging

With the cooperative merging enabler (EADF), the travel time reductions for all vehicles in the network were 4–9%, at a 50% penetration rate within the full-mandatory-ADAS scenario compared to the corresponding BADF scenarios. In other scenarios with lower penetration rates, no significant impact of the cooperative merging enabler was observed.

The reduction in travel time and delay grew as the traffic volume on the ramp increased. The results for a 100 km/h speed limit were comparable to those for 120 km/h. The efficiency benefits observed at 50% EADF were slightly lower, averaging around 5%.

Dynamic speed limits

Results indicate that the dynamic speed limit enabler (EADF) had a negative effect on traffic efficiency, namely increase of delay, especially for higher demands and higher penetration rates. There were higher delays in these EADF scenarios than in the corresponding BADF scenarios, and higher than in the baseline scenario without automation. This was already expected due to the earlier reaction to the reduction in the speed limit. For travel time, there was almost no effect compared to BADF scenarios.

5.2.1.2 Road-type-specific motorway scenarios

Road-type-specific evaluation focused on the impact of BADF across two baselines: (i) traffic today, and (ii) full penetration of mandatory ADAS.

Travel time per VKT generally increased slightly with increasing BADF penetration rate. Across both baselines, increases were largest at a traffic volume of 2,000 veh/h/lane. In the traffic-today baseline, with a 30% BADF penetration rate compared to 0%, travel times per VKT increased by up to 10% (4 s per VKT). Travel times decreased at low to moderate traffic volumes and high speed limits by up to 9% (3 s per VKT). With full mandatory ADAS, at a 50% BADF penetration rate compared to 0%, travel time per VKT increased by up to 18% (7 s per VKT) and decreased by up to 6% (3 s per VKT).

The number of lanes influenced outcomes. At low and moderate traffic volumes, travel time increases were larger on three-lane motorways than on two-lane ones, whereas at a volume of 2,000 veh/h/lane, the pattern reversed.

Ramps amplified the effect of the BADF penetration rate in the traffic-today baseline. Additionally, speed limits affected travel time outcomes. Increases in travel time per VKT were larger at high speed limits, especially in the full-mandatory-ADAS baseline. Decreases in travel time per VKT mainly occurred at the highest traffic volumes (2,500 veh/h/lane) and under high speed limits.

5.2.1.3 Scaled-up impacts at EU level for motorways

The scaled-up impact of the BADF on travel time per VKT across the EU motorway network over one year is shown in Figure 5.2. In both comparisons, with 30% BADF compared to traffic today and with 50% BADF compared to full mandatory ADAS, average travel times per VKT increased slightly by approximately 3–4%. The relative impacts of the scaled-up EADF were similar to those of the BADF. At the network level, the conditions assumed in the enabler-centric simulations were relatively uncommon.

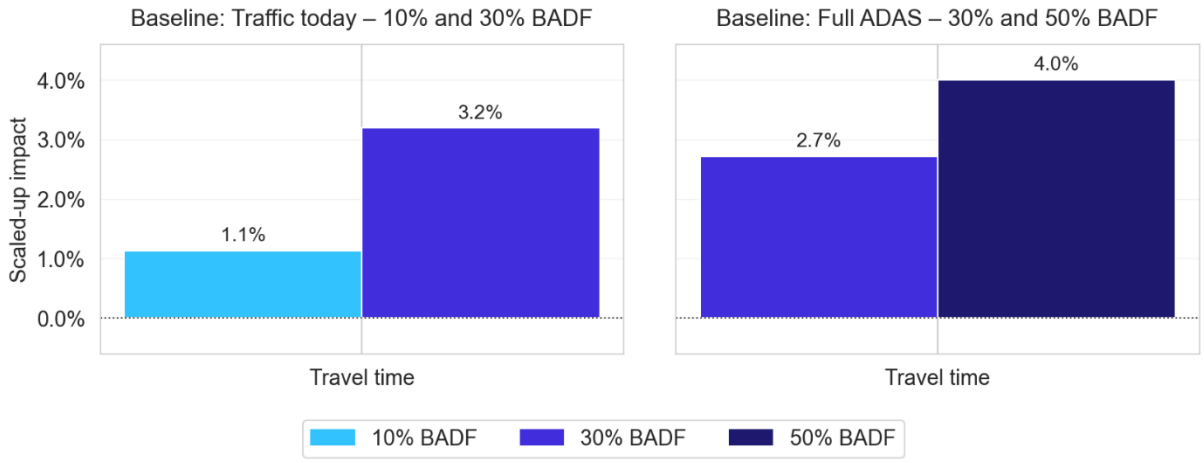


Figure 5.2: Scaled-up impacts of the BADF on motorway travel time per VKT compared to the traffic-today and full-ADAS baselines.

In addition to travel time, delay relative to the desired speed was assessed. As magnitudes of delays per VKT were small, the relative increases with the BADF penetration rate were large. For 30% BADF compared to the traffic-today baseline, delay increased by approximately 80% (2.0 s per VKT compared to 1.1 s), and for 50% BADF compared to the full-mandatory-ADAS baseline, delay increased by 140% (2.4 s per VKT compared to 1.0 s).

It is important to note the different comparisons: For manually driven vehicles (MVs), desired speeds differed greatly, and at low traffic volumes in the baseline, desired speeds could often be met (negative delay compensated for some increases). In contrast, automated vehicles (AVs) had a constant desired speed set at the speed limit, which could not always be reached even at low traffic volumes, and no negative delay could occur for AVs as they did not drive faster than the speed limit allowed. In addition, low traffic volumes and high speed limits dominated the scaled-up results.

5.2.1.4 Enabler-centric urban scenarios

GLOSA

The GLOSA enabler provided speed recommendations for EADF vehicles. EADF (GLOSA) showed significant improvements compared to BADF in delay-related metrics, such as stop delay, with reductions observed at all penetration rates and traffic volumes. The effects became more noticeable with the increasing penetration rates.

When comparing BADF with EADF, the improvements in overall travel time and total delay were relatively modest, generally in the range of 0–3%, with better performance at higher penetration rates. Even at low penetration rates (10–30%), some benefits of GLOSA were observed compared to BADF, particularly in stop delay. The improvements increased with higher penetration levels, and at 100% penetration, noticeable efficiency gains were achieved even under high traffic volumes.

When comparing EADF (GLOSA) with BADF, as well as when comparing automated driving with manually driven scenarios, the effects tended to remain consistent at all traffic volumes. Higher percentages of improvements were observed at low traffic volumes, but more absolute effects were expected at high traffic volumes due to the higher number of vehicles affected.

Complex intersection

EADF vehicles with the complex yield-sign-controlled intersection enabler could detect conflicts earlier than BADF vehicles, and did not always need to decelerate when approaching an intersection. In contrast, BADF vehicles depended entirely on their onboard sensors and always stopped before the intersection without checking ahead for potential conflicts.

Improvements were observed in travel time, with reductions of up to 21% depending on traffic volume and AV penetration rate. Benefits were more pronounced under high traffic volumes and increased with higher AV penetration rates. Delay was reduced by 5% to 25%. These reductions increased with AV penetration, but there was no clear correlation with traffic volume.

Reductions were observed in the number of stops, ranging from 3% to 30%, depending on traffic volume and AV penetration rate. The benefits increased with the AV penetration rate. Overall, the AV penetration rate influenced performance across all metrics. At low penetration levels (10%), improvements were minimal, as the number of AVs was too low to influence traffic behaviour. As penetration increased to 30% and especially 50%, benefits became more noticeable.

Traffic volume also affected the results. At low volumes (200 veh/h), the network performed efficiently, leaving little room for major improvements. Under high-volume conditions, the effects became more pronounced.

5.2.1.5 Road-type-centric urban scenarios

In the road-type-centric urban scenarios, travel time per VKT generally increased with increasing BADF penetration rate. The magnitude of the effect depended on the conditions. Effects were larger with increasing penetration rate and greater under the full-mandatory-ADAS baseline. Increases were modest at low and moderate traffic volumes and grew with volume and penetration rate.

Travel time increases were moderate at low to medium traffic volumes. At high traffic volumes, increases were larger, especially on two-lane roads with traffic lights. When travel time per VKT increased, the increase grew with traffic volume. When it decreased, effects were largest at low traffic volume. The amplification with traffic volume was smaller at a speed limit of 30 km/h. Overall, increases in travel time per VKT were more pronounced at a speed limit of 50 km/h than at 30 km/h.

Traffic lights amplified the increase in travel times with BADF penetration rate. On long road sections, travel times slightly decreased, whereas short sections showed increases. Two-lane rod segments showed more prominent increases than one-lane segments, particularly at moderate to high traffic volumes.

5.2.1.6 Scaled up impacts on EU level for urban networks

The results scaled up to EU level show that travel time per VKT increased slightly, by 1% in the traffic-today baseline at a 30% ADF penetration rate and by 2% in the full-mandatory-ADAS baseline at a 50% ADF penetration rate (Figure 5.3). Impacts of the EADF, which allows the ADF to drive also in heavy rain and assumes that all urban traffic lights are equipped with GLOSA, were similar to those of the BADF.

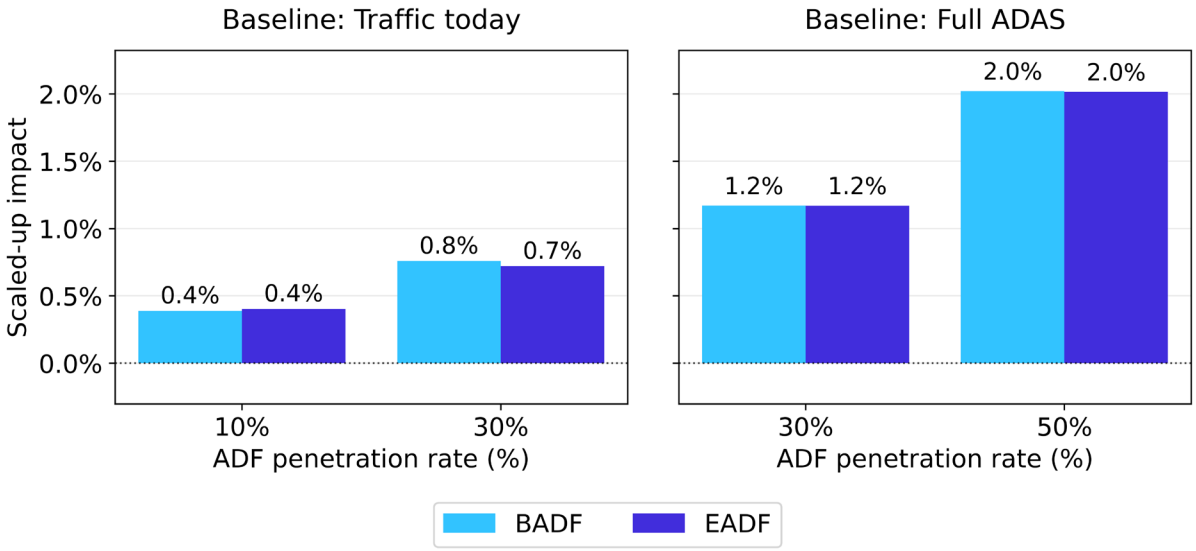


Figure 5.3: Scaled-up impacts of BADF and EADF on travel time per VKT on EU urban roads compared to the traffic-today and full-ADAS baselines.

The efficiency effects of the complex intersection use case were not considered in the socioeconomic analysis (see Chapter 7), due to lacking information on the number of relevant intersections (poor visibility etc.) and the fundamental difference to other scenarios caused by all vehicles being detected, also manually driven ones, and as no reliable cost figures could be derived for this use case, which requires equipping intersections with infrastructure sensors.

5.2.2 Impacts on the environment

5.2.2.1 Enabler-centric motorway scenarios

Cooperative merging

With cooperative merging enabler, tractive energy use and CO_2 emissions of traffic per VKT decreased slightly compared to the corresponding BADF scenarios at high penetration rates (50%). These reductions were more pronounced at high traffic volumes on the motorway and the on-ramp.

At a speed limit of 120 km/h, the effects were comparable to those at 100 km/h, in that the enabler had a positive effect on tractive energy use (2–3% reduction for on-ramp demands of 400 veh/h and 200 veh/h) and CO_2 (around 2% for on-ramp demands of 300–400 veh/h) compared to the corresponding BADF scenarios for high penetration rates and high demands, with the small difference that there was also a small (1%) reduction in CO_2 emissions at a 30% EADF penetration rate.

Dynamic speed limits

In scenarios with the dynamic speed limit enabler (EADF), CO_2 emissions were lower in scenarios with EADF than in the corresponding BADF scenarios. The BADF scenario performed comparably to, or slightly better than, the EADF scenario in terms of tractive energy use.

Traffic volume affected these outcomes. At a high traffic volume (2,000 veh/h/lane), EADF resulted in higher CO_2 emissions than the corresponding BADF scenario (6% higher for a 30% penetration rate and full mandatory ADAS). Only at a 50% penetration rate were the results comparable to the BADF scenario. At a high traffic volume and 50% penetration rate, the enabler led to slightly better outcomes, with 4% lower energy use per VKT compared to the corresponding BADF scenario.

5.2.2.2 Road-type-centric motorway scenarios

Road-type-specific evaluation focused on the impact of BADF over the manual baseline scenarios. Results indicate that tractive energy use per VKT generally mostly decreased with increasing BADF penetration rate. These reductions strengthened with higher penetration rates in most conditions.

For CO_2 impacts per VKT, the overall pattern was mixed. At many low and moderate speed limits at traffic volumes of 2,000 veh/h/lane, emissions per VKT increased, whereas at higher speed limits and traffic volumes, decreases were observed.

Traffic volume had an influence on both energy use and emissions. Reductions were greater at high traffic volumes. Increases peaked at traffic volumes of 2,000 veh/h/lane, while the strongest decreases occurred at 2,500 veh/h/lane for both CO_2 emissions and tractive energy use.

Road infrastructure also played a role. At low and moderate traffic volumes, reductions in energy were slightly larger on two-lane roads, whereas reductions in CO_2 emissions were slightly larger on three-lane roads. On three-lane motorways, CO_2 emissions per VKT decreased at lower penetration rates than on two-lane motorways. For energy use, the influence of the number of lanes was smaller.

Ramps attenuated the decreases in energy use per VKT. In the full-ADAS baseline, three-lane segments without ramps dampened the CO_2 effects with increasing traffic volume, while three-lane segments with ramps amplified them.

Speed limits further shaped the results. At low speed limits, CO2 emissions per VKT tended to increase, while at higher speed limits, small decreases were observed. For energy use, effect sizes were larger at higher speed limits.

5.2.2.3 Scaled-up impacts at EU level for motorways

The scaled-up impact of the BADF on CO_2 emissions and tractive energy use per VKT on the EU motorway network over one year is shown in Figure 5.4. In both comparisons, with 30% BADF compared to the traffic-today baseline and with 50% BADF compared to the full-mandatory-ADAS baseline, average emissions and energy use per VKT decreased. The order of magnitude for both cases was a 1% reduction in emissions and a 2% decrease in tractive energy use. The relative impacts of the scaled-up EADF were similar to those of the BADF.

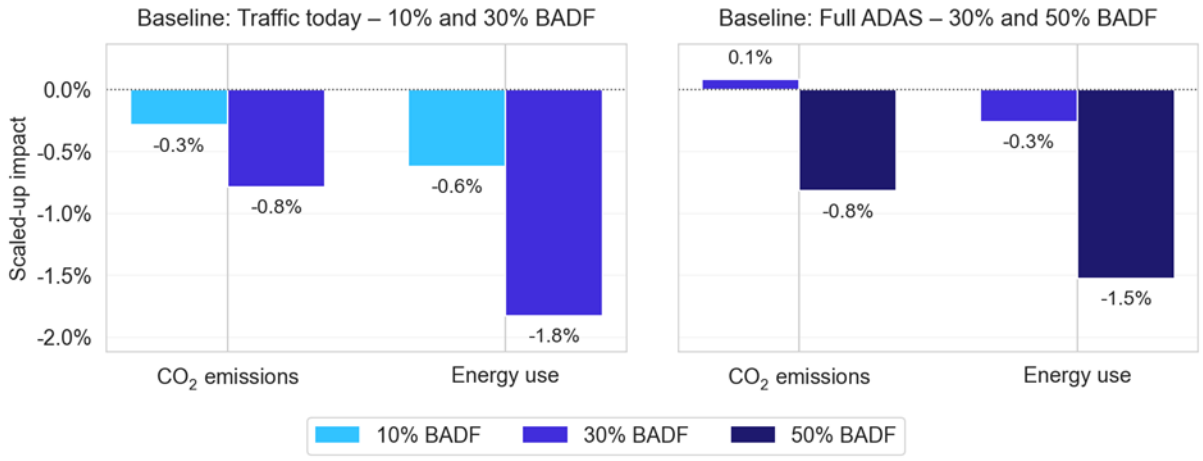


Figure 5.4: Scaled-up impact of BADF on CO_2 emissions and tractive energy use per VKT on the EU motorway network.

5.2.2.4 Enabler-centric urban scenarios

GLOSA

Since GLOSA aims to reduce unnecessary stops and vehicle idling at intersections, it is expected to have environmental benefits. When comparing EADF to BADF, improvements were observed in both CO_2 emissions and tractive energy consumption, especially at high traffic volumes and penetration rates. These benefits were more pronounced for CO_2 emissions than for tractive energy use.

The penetration rate of EADF played a significant role in determining the extent of environmental impact. At low penetration rates (10–30%), the impacts were limited to high traffic volumes. The effect size grew with higher penetration levels, and at 100% penetration, substantial environmental gains were achieved even at low traffic volumes.

Traffic volume itself also influenced the outcomes. Improvements in energy use and emissions were more pronounced at high traffic volumes.

Complex intersection

The evaluation of the complex intersection enabler showed a limited impact on energy demand (up to 2% reduction), with moderate improvements in CO_2 emissions (ranging from 3% to 6% reductions), especially as ADF penetration increased. These environmental benefits became more pronounced as the penetration rate of EADF increased.

5.2.2.5 Road-type-centric urban scenarios

Road-type specific evaluation focused on the impact of BADF under two baselines: (i) traffic today, and (ii) full penetration of mandatory ADAS.

Tractive energy use per VKT consistently decreased with increasing BADF penetration rates. At a 30% penetration rate, reductions ranged from 4% to 11% across three traffic volumes when compared to the traffic-today baseline. At a 50% penetration rate, reductions were even more substantial, between 4% and 16%, when compared to the full-ADAS baseline. CO_2 emissions per VKT also generally decreased, but the direction and size depended on the conditions. Effect sizes increased with BADF penetration rate, especially for tractive energy use.

Traffic volume had a notable influence on outcomes. Reductions strengthened with volume; at high traffic volumes, the effect sizes were larger for both tractive energy use and CO2 emissions per VKT. In scenarios showing increases in CO_2 emissions, the effect size was smaller at large traffic volumes.

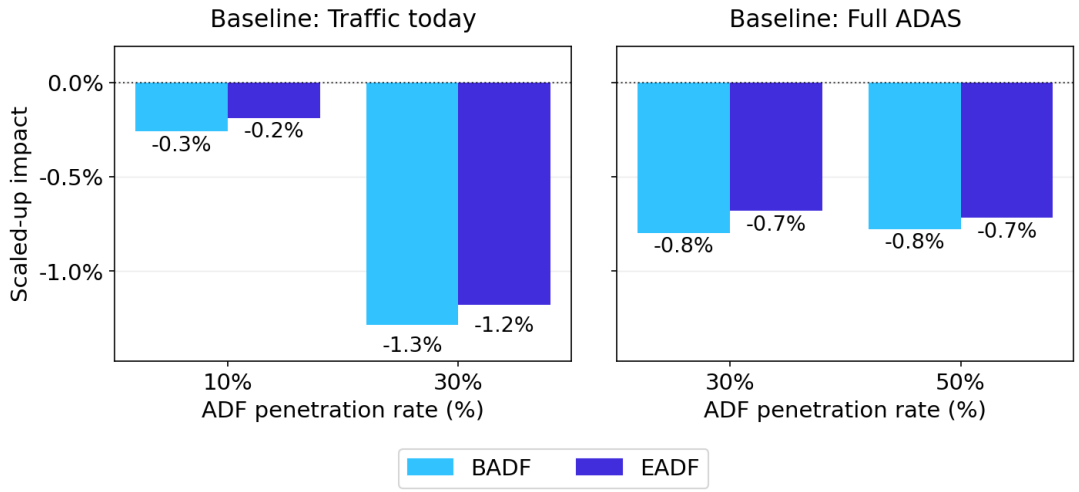
Road design also played a role. For CO_2 emissions, decreases were larger on two-lane road segments than on one-lane segments, where emissions increased in some low traffic volume conditions. For tractive energy use, decreases were larger on one-lane road segments than on two-lane segments.

Traffic lights and road section length further shaped the results. CO_2 reductions were slightly larger in scenarios with traffic lights, and slightly larger on long than on short sections. For energy use in the full-mandatory-ADAS baseline, decreases were larger in scenarios without traffic lights and slightly larger on long sections than on short ones.

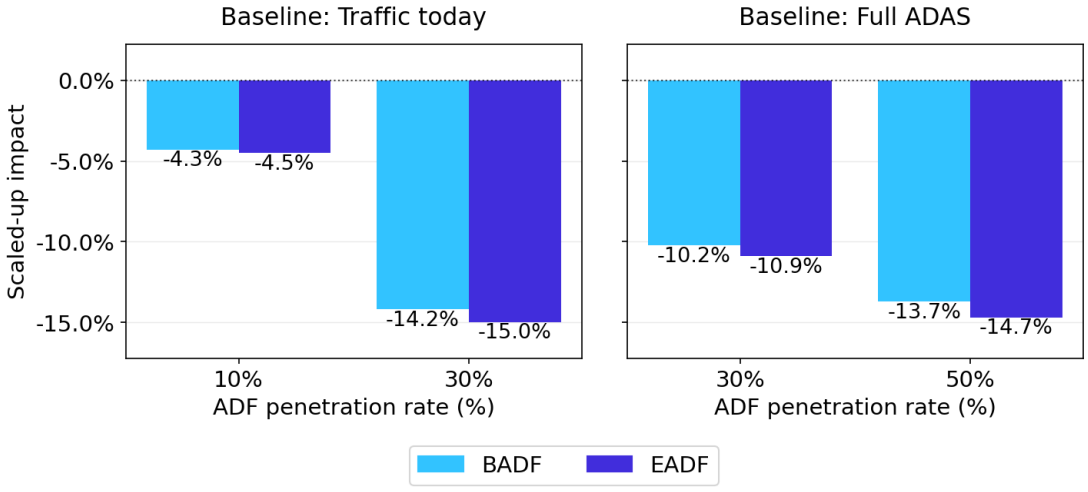
5.2.2.6 Scaled-up impacts at EU level for urban networks

Figure 5.5 shows the scaled-up impacts of BADF and EADF on CO_2 emissions and tractive energy use, respectively. At the EU level, introducing BADF to traffic resulted in a decrease of tractive energy use by 14% at a 30% penetration rate compared to traffic today, as well as at a 50% penetration rate compared to the full-mandatory-ADAS baseline. For CO_2 emissions, impacts were smaller and mixed, with a decrease of 1% at a 30% BADF penetration rate compared to traffic today, as well as at a BADF penetration rate of 50% compared to full

mandatory ADAS. Relative impacts of the EADF, including an ODD extended to heavy rain and assuming that all urban traffic lights are equipped with GLOSA, were similar to the BADF impacts. For tractive energy use, the scaled-up reductions of EADF were slightly larger than those of BADF.



a) CO_2 emissions



b) Tractive energy use

Figure 5.5: Scaled-up impacts of BADF and EADF on CO_2 emissions (above) and tractive energy use (below) per VKT on EU urban roads compared to the traffic-today and full-mandatory-ADAS baselines.

The environmental effects of the complex intersection use case were not considered in the socioeconomic analysis (see Chapter 7), due to lacking information on the number of relevant intersections (poor visibility etc.) and the fundamental difference to other scenarios caused

by all vehicles being detected, also manually driven ones, and as no reliable cost figures could be derived for this use case, which requires equipping intersections with infrastructure sensors.

5.3 Discussion

The efficiency impact assessment focused on impacts on travel time per VKT. With AVs in traffic, travel time generally increased slightly, mostly due to changes in desired speed. The technology enablers could mitigate these increases under specific conditions. At the European network level over one year, increases in travel time per VKT of 0–4% were found at ADF penetration rates up to 50%.

Tractive energy use per VKT decreased in most conditions, whereas impacts were mixed for CO_2 emissions due to interactions between internal combustion engine efficiency and speed. Also here, technology enablers have the potential to offset the CO_2 increases and further reduce energy use per VKT. At the European level, tractive energy use per VKT decreased by 0–15% at ADF penetration rates up to 50%. Network-level impacts on CO_2 emissions were small, ranging between –1% and 0%.

6 Transport system impact assessment results

6.1 Approach

The Hi-Drive methodology for transport system impact assessment is based on a traditional four-stage demand model, in which people's travel behaviour is replicated by a four-stage algorithm comprising trip generation, destination choice, mode choice, and route choice. It is further assumed that the introduction of AVs will, on the one hand, most likely have an impact on the perceived travel time of drivers and passengers, as they will have the opportunity to engage in other types of activities. On the other hand, it will have an impact on road capacity, as the driving behaviour of vehicles will change, for example by maintaining smaller or larger distances from the vehicle ahead. This is illustrated in Figure 6.1.

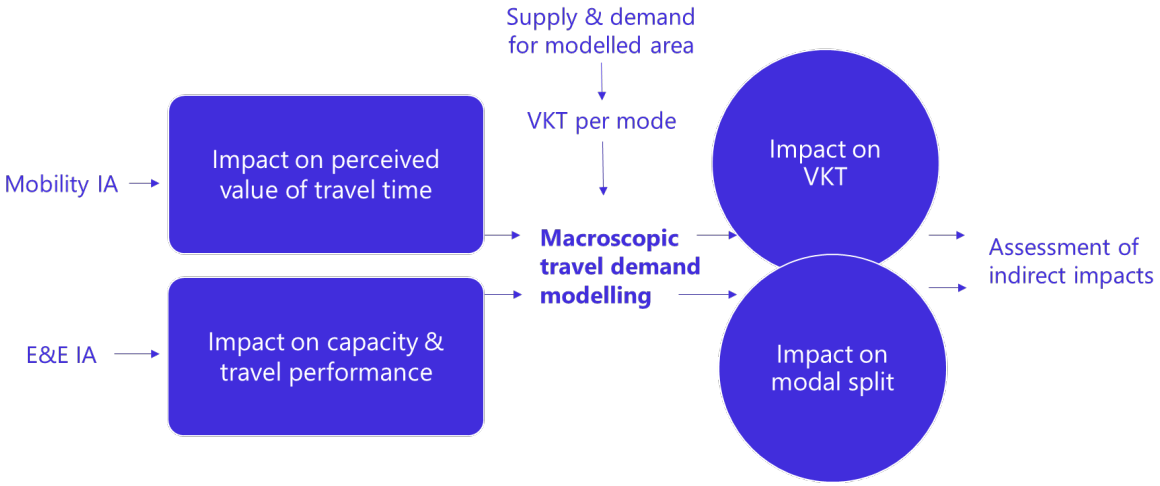


Figure 6.1: Simplified overview of the methodology for transport system impact assessment.

For mode and route choice, the travel time of manually driven vehicles (MVs) is replaced by a modified travel time reflecting the perceived travel time when travelling in an automated car. The value for perceived travel time was derived from the mobility impact assessment within the project. The median perceived travel time factor was estimated at 0.80 for car drivers and 0.84 for car passengers. To simplify the implementation in the transport model, a weighted average was applied using an average private transport occupancy rate of 1.33 for Bavaria, resulting in a combined correction factor of 0.81. This factor was applied to both BADF and EADF, as no distinction between these groups was identified in the survey.

The effect of AD on road capacity is modified using passenger car units (PCUs). PCU is a common concept in macroscopic assignment models and, in this context, is used to describe the change in performance of a network element (for example, a link or a node) compared to MVs. PCUs and travel time are linked through the so-called volume delay function, which

must be updated to incorporate AD into the model. For network elements outside the ODD, the PCU remains unchanged at a value of 1, which is the standard PCU value for MVs. PCUs were calculated by generating fundamental diagrams using network configurations and parameters from the efficiency and environment impact assessment. The fundamental diagrams indicated that road capacity decreased with the introduction of AVs, resulting in higher PCU values for AVs compared to MVs.

The macroscopic demand modelling software PTV Visum 23 was used together with a transport model of the state of Bavaria, provided by the Landesbaudirektion Bayern and its Centre for Traffic Management (ZVM), which was made available for the project.

The study area, the state of Bavaria, for which the results are presented, is shown in black in Figure 6.2. The choice of the model was made considering model availability, as building a new model as part of the project would have been too resource intensive. The large area of the model, covering all types of roads and transport modes, made it a good choice for a project looking at overall impacts. However, it should be noted that the model was not originally developed for this type of study; it does not contain a baseline for AD and, due to its extensive coverage, the urban network is not very detailed.

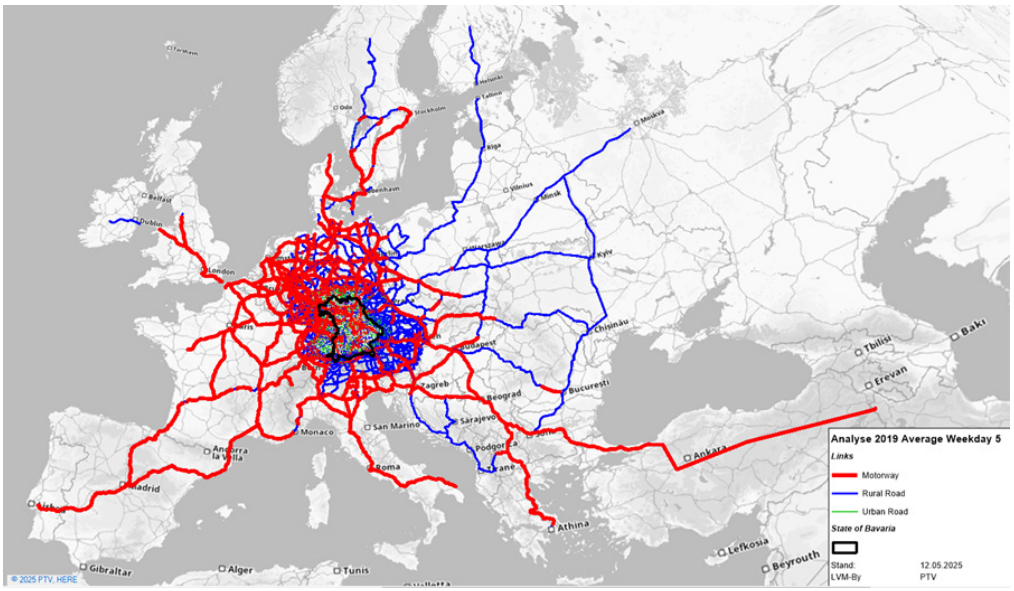


Figure 6.2: The Bavaria Model - PTV Visum 23. The area highlighted in black is the study area: the state of Bavaria.

6.2 Results

All results are provided for different penetration rates relative to a baseline in which AVs have the same PCU and perceived travel time as conventional vehicles. In the macroscopic model, there is no difference between the traffic-today and full-mandatory-ADAS baselines.

What is the impact of AD and its enablers on modal split?

The results (see Table 6.1) indicate a very slight increase in the share of trips made by car drivers and passengers, along with a slight decrease for the other modes of transport: public transport, cycling, and walking. The changes are so small that the impact on the modal split can be considered negligible.

Table 6.1: Modal split of the region of Bavaria given in shares of number of person trips (%).

Automation level	Baseline	BADF			EADF		
Penetration rate (%)	0	10	30	50	10	30	50
Car Driver	45.2%	45.2%	45.2%	45.2%	45.2%	45.3%	45.3%
Car Passenger	12.3%	12.3%	12.3%	12.3%	12.3%	12.3%	12.3%
Public transport	9.4%	9.4%	9.4%	9.4%	9.4%	9.4%	9.4%
Cycling	12.6%	12.6%	12.6%	12.5%	12.6%	12.5%	12.5%
Walking	20.5%	20.5%	20.5%	20.5%	20.5%	20.5%	20.5%

The very small changes in mode choice are due to the fact that the increase in PCU, which could push people towards other modes of transport, is offset by the decrease in perceived travel time, which pulls people towards AVs.

What is the impact of AD and its enablers on vehicle-kilometres travelled (VKT)?

As shown in Table 6.2, the relative increase in VKT in Bavaria is greater outside the ODD than inside, for both MVs and AVs. For example, under the EADF 50% scenario, AVs show a decrease of 0.1% inside the ODD, but an increase of 1.5% outside. This is due to an increase in PCUs within the ODD, leading to reduced capacity and higher network saturation. As a result, cars tend to reroute towards less congested areas outside the ODD. In contrast, heavy-duty vehicles (HDVs) do not exhibit any change in VKT, as they are restricted by road regulations and toll constraints, and their routing flexibility is very limited in the model.

Table 6.2: Relative change in vehicle-kilometres travelled within Bavaria.

Automation level	Penetration rate (%)	MVs		AVs		HDVs	
		inside ODD	outside ODD	inside ODD	outside ODD	inside ODD	outside ODD
BADF	10	0.0%	0.2%	0.0%	0.2%	0.0%	0.0%
	30	-0.1%	0.6%	-0.2%	0.7%	0.0%	0.0%
	50	-0.2%	1.0%	-0.7%	1.3%	0.0%	0.0%
EADF	10	0.1%	0.2%	0.1%	0.2%	0.0%	0.0%
	30	0.1%	0.7%	0.1%	0.8%	0.0%	0.0%
	50	0.1%	1.2%	-0.1%	1.5%	0.0%	0.0%

6.3 Discussion

The changes in modal split were found to be so small that the impact can be considered negligible. This is because the increase in PCUs, which could push people towards other modes of transport, was offset by the decrease in perceived travel time, which could pull people towards AVs.

To enhance the network performance impact of AVs, one of the most critical factors is the distance – whether measured in space or time – that these vehicles maintain from others in car-following situations. Reducing this distance increases road capacity; however, it comes at the cost of safety, as greater distances generally lead to safer conditions. If capacity improves, changes in PCUs and perceived travel time are likely to make AVs more attractive to users. This shift in preference could negatively impact public transport, highlighting the need for measures to protect and support its continued use.

Vehicle-kilometres travelled (VKT) in Bavaria were estimated to increase with driving automation. The impact was found to be somewhat larger outside the ODD than inside, for both MVs and AVs, due to an increase in PCUs within the ODD, leading to reduced capacity and higher network saturation. As a result, cars tended to reroute towards less congested areas outside the ODD. The decrease in capacity and the route choice decisions led to an even higher relative increase in vehicle-hours travelled, as shown in Deliverable D7.4 (Innamaa et al., 2025).

Most of the roads located outside the ODD to which cars are rerouting are rural roads. This could be a cause for concern regarding safety, as rural roads in most countries generally have higher accident rates per kilometre driven.

7 Socioeconomic impact assessment results

7.1 Approach

The main goal of Hi-Drive's socioeconomic impact assessment is to investigate the welfare effects of AD and its enablers for society and users of AVs. A cost-benefit analysis was performed to compare the costs and benefits of this technology. For the assessment, scaled-up data from impact assessments on safety, efficiency, and environmental impacts were incorporated, as well as data from Hi-Drive's global survey. In addition, external data sources were used for the estimation of associated costs. The socioeconomic impact assessment was performed for EU-27. Details are provided in Hi-Drive Deliverable D7.5 (Bjorvatn et al., 2025).

7.1.1 Analytical framework and data

A snapshot approach was employed to quantify the impacts of AD and its enablers at different penetration levels. This static approach compares the differences in outcomes between current traffic conditions and the estimated outcomes when specific fractions of current traffic are operated using AVs.

For the socioeconomic impact assessment, the analysis primarily considered the EADF, as the aim was not to evaluate single enablers in relation to the BADF, but to assess AD including technology enablers as a whole. Thus, the results presented for this impact assessment always relate to AD implementations based on the Hi-Drive EADF, even though just "AD" or "AV" is used in the text.

In accordance with the other impact assessments, the baselines considered in the socioeconomic impact assessment were the traffic-today baseline and the full-mandatory-ADAS baseline. Since mandatory ADAS represents a regulatory change that will apply regardless of AD, the full-mandatory-ADAS baseline serves as the primary reference for the socioeconomic evaluation.

Impacts relating to safety, efficiency, and environment were estimated for scenarios with 10% and 30% penetration relative to the traffic-today baseline. For scenarios with 30% and 50% penetration, these impacts were estimated relative to the full-mandatory-ADAS baseline. However, since impacts derived from the survey data are not related to any specific penetration rate, survey results were recalculated to align with the penetration rate used in the socioeconomic analysis, which focused on the 30% penetration rate. This approach allows assessment of the importance of impacts generated by the EADF beyond mandatory ADAS.

The main data sources for the assessment were the Hi-Drive impact assessments on safety, efficiency, and environmental aspects, providing upscaled estimates at the EU level. In addition, data from the Hi-Drive Global Survey (2024) of the general public in five European

countries (France, Germany, Poland, Spain, and Sweden) were used. A minimum of 1,000 responses were collected in each country. For the evaluation, respondents' willingness to pay above the average market price for a manual car to acquire an AD-equipped car, the factors behind their willingness to pay, willingness to use, and expectations of how AD might affect their driving patterns were considered. The descriptions of AD provided to the respondents were in line with the EADF capabilities, even though this Hi-Drive-specific term was not used in the surveys.

7.1.2 Implementation costs

The ADFs and enablers tested during Hi-Drive require different in-vehicle hardware and software components, as well as infrastructure components. Costs required to equip cars with, for example, sensors, are referred to as private goods, representing variable costs that increase with the number of vehicles equipped. In contrast, costs for road infrastructure represent a public good, with fixed costs that are largely independent of the number of vehicles using it.

The approach taken for the estimation of costs involved defining the necessary additional vehicle components required for AD compared with a manually driven vehicle. Industry experts were consulted during this process, with the aim of providing a realistic cost estimate ranging from the expected minimum to the maximum cost. The focus was predominantly on vehicle components in addition to those required for mandatory ADAS.

As for public-good enablers, the focus was on defining additional technical components required for road infrastructure so that it could handle the use cases investigated as part of Hi-Drive. For instance, use cases with communication with traffic lights required no additional technical components for AD specifically, since they are part of the Day 1 Cooperative Intelligent Transport Systems (C-ITS) specifications that are being rolled out for deployment. Thus, it is not expected that these enablers would incur any additional road infrastructure costs in comparison with the standard deployment of C-ITS. Moreover, use cases involving improved positioning (weak GNSS signals, missing/deteriorated lane markings) do not require additional costs for road infrastructure, as they rely on the ADF's on-board sensors.

Based on the estimated minimum and maximum costs of the individual components, the producer costs (covering only components and not development costs, etc.) for a combined package of ADFs, including urban, motorway, and parking ADFs, were calculated. The total producer costs are estimated to range from €1,570 (minimum) to €3,580 (maximum). Applying a price factor of three to account for consumer pricing results in an estimated price range of €4,710 to €10,740. Assuming a 10-year lifetime for AD equipment, a 3% discount rate was applied to annualise these costs at the societal level, and a 5% discount rate when

assessing user benefits, in line with the recommendations of the FESTA Handbook (FESTA, 2018).

7.1.3 Standard unit costs

To assign monetary values to the estimated safety impacts, the relevant standard unit costs were applied. Typically, these costs are based on the severity of human injuries: fatalities, serious injuries, and slight injuries. Cost units were used for each injury type as outlined by Wijnen et al. (2017) and the European Commission's Handbook (Essen et al., 2020), and then converted into standard unit costs by accident severity, following the method in Wijnen et al. (2017). According to this method, one fatal accident typically results in 1.1 human fatalities, 0.22 serious injuries, and 0.43 slight injuries; one serious injury accident involves 1.11 serious injuries and 0.44 slight injuries; and one slight injury accident involves 1.36 slight injuries. All values were adjusted to 2024 prices using the (Gross Domestic Product) GDP deflator index. The social values of the efficiency and environmental impacts were assessed by applying relevant standard unit costs for travel time per hour and CO_2 per tonne, according to Essen et al. (2020), and for fuel per litre (petrol, diesel, and LPG) at producer price for each energy source.

7.2 Results

7.2.1 Safety impacts

Table 7.1 presents the estimated reduction in the number of accidents, by severity, for 30% penetration of BADF and EADF, compared with the actual traffic situation in 2023, referred to as the traffic-today baseline. The estimates include reductions in accidents within ADFs' ODD on motorways and urban roads, as well as effects on rural roads. The target accident numbers and relative reductions, taken as a basis, are provided in Section 3.2.3.2.

Table 7.1: Annual reduction in the number of accidents relative to the traffic-today baseline, at 30% penetration.

	BADF (ADF without enablers)	EADF (ADF with enablers)
Fatal accidents	1,737	1,960
Severe injury accidents	13,374	15,385
Slight injury accidents	88,286	102,835

It can be derived from Table 7.1 that EADF is expected to prevent injury accidents by around 13–17% more than BADF for the different accident severities (12.8% for fatal accidents, 15.0% for severe injury accidents, and 16.5% for slight injury accidents).

Table 7.2 reports the accident reduction estimates for BADF and EADF relative to the full-ADAS baseline. Comparing the figures with those presented in Table 7.1, ADAS is estimated to prevent a slightly larger share of accident reductions for BADF compared to EADF.

Table 7.2: Annual reduction in the number of accidents relative to the full-mandatory -ADAS baseline, at 30% penetration.

	BADF (ADF without enablers)	EADF (ADF with enablers)
Fatal accidents	871	1,012
Severe injury accidents	7,412	8,718
Slight injury accidents	47,502	56,783

The difference between the number of expected accident reductions for EADF relative to the traffic-today baseline (Table 7.1) and EADF relative to the full-mandatory-ADAS baseline (Table 7.2) reflects the expected safety impacts of mandatory ADAS. Based on this comparison, mandatory ADAS is estimated to prevent 48.4% of fatal accidents, 43.3% of severe injury accidents, and 44.8% of slight injury accidents that EADF is expected to prevent relative to the traffic-today baseline.

EADF is also expected to reduce the number of property damage only (PDO) accidents. Since there are no comprehensive statistics on PDO accidents, the method by Wijnen et al. (2017) was followed, indicating that the magnitude of PDO accidents is roughly nine times the number of all types of injury accidents. The standard unit accident costs based on accident severity are shown in Table 7.3. Please refer to Hi-Drive Deliverable D7.5 (Bjorvatn et al., 2025) for details.

Table 7.3: Standard unit accident costs by accident severity, €$_{2024}$.

Accident severity	STANDARD UNIT ACCIDENT COST
Fatal accident	5,791,924
Severe injury accident	879,471
Slight injury accident	91,251
PDO accidents	5,196

These costs were applied to assess the economic value of reduced traffic accidents at the EU level, as shown in Table 7.4. The results were reported for 30% EADF penetration for the traffic-today and full-mandatory-ADAS baselines. When impacts were estimated relative to today's traffic situation, the results indicated societal savings of approximately €40 billion

from reduced accident costs, and approximately €22 billion relative to the full-mandatory-ADAS baseline.

Table 7.4: Accident cost savings at EU level, at 30% EADF penetration. Million €$_{2024}$.

Accident severity	Traffic-today baseline	Full-ADAS baseline
Fatal accidents	11,354	5,862
Severe injury accidents	13,531	7,667
Slight injury accidents	9,384	5,181
PDO accidents	5,620	3,110
Total accident cost savings	**39,889**	**21,821**

7.2.2 Impacts derived from user benefits

Willingness to pay (WTP) reflects how respondents value all types of benefits they expect to gain from acquiring an AV compared to a conventional car. To estimate the economic value of the different perceived benefits underlying individuals' WTP, the relative importance of these perceived benefits was first identified. These underlying WTP factors were then used to estimate the annual value of user benefits for the EU at 30% ADF penetration, making the results comparable to the scaled-up impact estimates for safety, efficiency, and environmental effects. This approach enabled the estimation of the economic value of user benefits at the EU level.

WTP expresses the utility that users expect from having an ADF installed in their next car. It measures the net present value that users expect to gain from AD. Table 7.5 shows the relative importance of the different attributes underlying respondents' WTP.

Table 7.5: Relative importance of different attributes, WTP>0.

Attribute	%
Increased safety	40.6
Increased comfort (less stressful driving)	22.6
Spending travel time on recreation	12.2
Fewer and shorter delays	11.2
Spending travel time on work-related activities	10.7
Other	2.7
N	3,372 = 100%

The major impacts, from users' point of view, are benefits they expect to gain from increased safety (40.6%), followed by benefits related to increased comfort, defined as less stressful driving (22.6%).

To utilise and scale survey data on user benefits to the EU-27 level, each respondent represented one vehicle, and respondents were representative of all drivers across the EU-27. Then, the selection of vehicles from the baseline to be equipped with an ADF was specified, and the share of ADF-equipped vehicles required to achieve the 30% AD penetration, measured as a share of VKT, was estimated.

Based on the information on respondents' WTP for AD in relation to their expected annual driving distance and their willingness to use AD, the number of respondents with the highest WTP required to achieve 30% AD penetration in terms of VKT was estimated. 40.7% of all vehicles need to be equipped with an ADF to achieve 30% activated functions in traffic based on VKT, as the drivers might not have the function always activated despite being available. Therefore, to upscale user benefits to the EU level to match 30% AD penetration, it was assumed that 40.7% of the EU's 256 million passenger cars, i.e. approximately 104.2 million cars, would need to be AVs.

To comply with the principle of applying economic measures that reflect all citizens, the average WTP was used for all respondents in the survey. However, the predefined WTP response categories were adjusted by excluding the possibility of a net present value of expected benefits equal to €0. The rationale was straightforward: AD would unambiguously increase traffic safety. While the magnitude of this benefit can be debated, its positive effect was certain. As everyone was assumed to assign some positive value to their own life, the net present value had to be greater than zero. Accordingly, the 32.5% of respondents who expressed a WTP of €0 were reclassified into the category "WTP less than €4,000". After this adjustment, the average WTP applied in the economic analysis amounted to €3,299, which is 24.5% higher than the average WTP calculated without reclassification. This value reflected the net present value of all expected benefits over the lifetime of the AD equipment, implying an annual WTP of €427, at a 5% annual interest rate. The economic value of user benefits at the EU level for 30% AD penetration was estimated as the benefit per car, based on the share of WTP attributes, using the annual WTP value of €427 and 104.2 million cars (for details, see Deliverable *D7.5*, Bjorvatn et al., 2025).

Table 7.6: AV users' valuation of expected benefits. EU-27. 30% AD penetration.

Type of benefit	Benefit per car, €	Aggregate economic impact, million €	Adjusted aggregate economic impact, million €
Increased safety	173.4	18,071	20,348
Increased comfort (less stressful driving)	96.5	10,054	11,321
Possibility to relax	52.0	5,423	6,106
Fewer and shorter delays	47.8	4,982	0
Possibility to work	45.7	4,761	5,361

The perception of increased safety was by far the most highly valued benefit (Table 7.6) and the increased comfort perception also represented a decisive factor. The possibility of being able to work instead of driving was valued as less important than all the other attributes. Comfort is, however, difficult to assess in relation to AD, as it is a multidimensional concept. When the risk of accidents is reduced, comfort tends to increase. This also applies when the risk of experiencing unexpected delays decreases and travel time predictability improves. Comfort may further increase when travel time can be used for relaxation and recreation instead of active driving. Hence, users' valuation of increased comfort due to AD is presumably much higher than what was captured when referring only to less stressful driving.

The users' valuation of the different types of benefits they expect to gain from AD does not necessarily add additional value from society's point of view. Among the user benefits, the valuation of increased safety, amounting to €18,071 million, is considered to be an integral part of the safety impacts already estimated as reductions in traffic accidents, where the accident cost savings for society were estimated at approximately €40 billion for traffic-today baseline. To avoid double counting in the cost-benefit analysis, user benefits from increased safety as perceived by AD users are excluded in the overall evaluation of AD. Therefore, user impacts not otherwise accounted for were included. This concerned the possibility for drivers to engage in activities other than driving, such as work and relaxation, and the benefit of increased comfort, as driving was experienced as less stressful.

After the survey was conducted, it became evident that the user benefit of fewer and shorter delays cannot be achieved unless AVs are fully connected. Since this condition is not met for the EADF, and given the estimated effects on safety, efficiency, and the environment, this user benefit is excluded from the overall economic evaluation of AD. As the estimated user benefits are derived from the stated WTP, which encompasses all types of perceived benefits, the economic values of the remaining four WTP attributes (increased safety, possibility to

work, possibility to relax, and increased comfort) were recalculated. A 12.6% upward adjustment was applied to the corresponding values reported in the table to ensure consistency with the revised scope, which excludes delay reductions.

7.2.3 Efficiency and environmental impacts

The estimated impact of the EADF on travel time indicated a decline in traffic efficiency (increased travel time) due to stricter adherence to speed limits, as shown in Table 7.7.

Table 7.7: Additional travel time, million hours, EU-27, 30% EADF penetration.

	Traffic-today baseline	Full-ADAS baseline
Urban	100.2	164
Motorway	220.2	191.3
Total	**320.4**	**355.3**

The increase in total travel time implies that the EADF reduces traffic efficiency, which comes as a cost to society. Applying the standard unit cost of travel time of €21.12 per hour, the costs amounted to €6,767 million in the traffic-today baseline and €7,503 million in the full-mandatory-ADAS baseline.

Table 7.8: Estimated change in fossil fuel consumption and CO_2 emissions. 30% EADF penetration. Fossil fuels include petrol, diesel, and liquid petroleum gas (LPG).

	Traffic-today baseline		Full-mandatory-ADAS baseline	
	Fossil fuels Million litres	CO2 emissions 1,000 tonnes	Fossil fuels Million litres	CO2 emissions 1,000 tonnes
Urban	562	1,362.3	327	790.6
Motorways	666	1,329.1	0	-100.1
Total	**1,228**	**2,690.4**	**327**	**689.7**

Table 7.8 presents the estimated changes in fossil fuel consumption, as well as CO_2 emissions for the traffic-today and full-ADAS baselines.

Fossil fuels: The estimated changes in fuel consumption showed a reduction of 1,228 million petrol-equivalent litres in fossil fuel consumption relative to the traffic-today baseline, and 327 million litres relative to the full-mandatory-ADAS baseline.

For the valuation of these impacts, the standard unit cost of one litre of petrol net of taxes, amounting to €0.75 in Europe, was applied. Based on this unit cost, the cost savings from

reduced fossil fuel consumption were €921 million relative to the traffic-today baseline, and €245 million compared to the full-mandatory-ADAS baseline.

CO_2 emissions: The estimated effects on CO_2 emissions were quite small. In the traffic-today baseline scenario, a 30% EADF penetration reduced CO_2 emissions by about 2.69 million tonnes in total for motorway and urban driving. In the full-mandatory-ADAS baseline scenario, CO_2 emissions increased for motorways, implying a total reduction in CO_2 emissions of about 0.69 million tonnes across urban and motorway driving.

The standard unit cost for CO_2 emissions is €342 per tonne, implying that the economic value of lower CO_2 emissions amounted to €920 million with the traffic-today baseline and €236 million with the full-mandatory-ADAS baseline. For details on the standard unit costs, see Deliverable *D7.5* (Bjorvatn et al., 2025).

7.2.4 Overall socioeconomic evaluation

Table 7.9 and Table 7.10 present a summary of the benefits and costs of the EADF for the scenarios with the traffic-today and the full-mandatory-ADAS baseline. The comprise two main components: the economic benefits and costs resulting from the EADF, and the associated costs of having the EADF installed in vehicles. The economic valuation of all estimated impacts is shown for each impact area. Accompanying costs are presented as minimum and maximum cost estimates, in addition to the average cost estimates.

Table 7.9: Costs and benefits of implementing the EADF in the EU for the traffic-today baseline. 30% penetration. Million €.

Impact	Million €2024
Total accident cost savings	39,889
Travel time efficiency	-6,767
Consumption of fossil fuels	921
CO2 emissions	920
Users' benefit of experiencing increased comfort (less stressful driving)	11,321
Users' benefit of being able to relax instead of driving	6,106
Users' benefit of being able to work instead of driving	5,361
Economic value of all impacts	**57,751**

	Minimum cost estimate	Maximum cost estimate	Average cost estimate
Cost of implementing the EADF	**19,173**	**43,764**	**31,469**
Net benefits	38,578	13,987	26,282
Benefit/cost ratio	**3.0**	**1.3**	**1.8**

Table 7.10: Costs and benefits of implementing the EADF in the EU for the full -mandatory-ADAS baseline. 30% penetration. Million €.

Impact	**Million €2024**		
Total accident cost savings	21,821		
Travel time efficiency	-7,502		
Consumption of fossil fuels	245		
CO2 emissions	236		
Users' benefit of experiencing increased comfort (less stressful driving)	11,321		
Users' benefit of being able to relax instead of driving	6,106		
Users' benefit of being able to work instead of driving	5,361		
Economic value of all impacts	**37,588**		
	Minimum cost estimate	Maximum cost estimate	Average cost estimate
Cost of implementing the EADF	**19,173**	**43,764**	**31,469**
Net benefits	18,415	-6,176	6,119
Benefit/cost ratio	**2.0**	**0.9**	**1.2**

The major components are the benefits of the safety impacts, estimated at approximately €40 billion for the traffic-today baseline and €22 billion for full-mandatory ADAS baseline, followed by gains for AV users, as they are able to combine work or relaxation while the vehicle operates in automated mode, and enjoy increased comfort (€23 billion). Increased travel time costs due to lower traffic efficiency represent another major component (€6.8 billion for the traffic-today baseline and €7.5 billion for full-mandatory ADAS baseline). Compared to these benefits, the estimated benefits of energy consumption and CO_2 emissions were smaller (€1.8 billion to €480 million). Overall, the total economic value of these impacts for society amounted to €58 billion for the traffic-today baseline and €38

billion for the full-mandatory baseline, at a 30% penetration rate of passenger cars with EADF.

Costs associated with the implementation of automated driving systems in passenger cars at the EU level were estimated as minimum, maximum, and average costs. When comparing the benefits and costs to society, it is evident that the economic value of the net benefits clearly exceeds the costs under all cost estimates for the traffic-today baseline. For the full-mandatory ADAS, the economic value of net benefits clearly exceeds the costs under the minimum cost estimate (benefit-cost ratio = 2.0) and falls slightly below the costs under the maximum estimate (benefit-cost ratio = 0.9). The average benefit-cost ratio of 1.2 indicates that benefits are expected to outweigh costs across most of the expected cost range. Hence, the predominant conclusion of the socioeconomic evaluation is that AD based on the EADF appears to be profitable from society's perspective when 30% of total traffic operates using AVs.

7.3 Discussion

The main findings indicate that AD based on the EADF is profitable from society's point of view. From an economic perspective, the most significant benefits stem from accident reduction, specifically from fewer human injuries and fatalities. Additional benefits include travel time cost savings due to reduced driving strain, the opportunity to engage in non-driving activities, and increased comfort. However, total travel time increases due to, for example, adherence to speed limits. Although this represents a negative externality that affects all road users, its economic magnitude is minor relative to the safety and comfort benefits.

Although AD appears profitable from society's point of view, not all consumers perceive it as profitable since the cost of implementing the EADF exceeds what they are willing to pay for it. This raises the question of whether public intervention is needed to accelerate adoption of AVs. While subsidies or financial incentives could theoretically enhance consumer uptake, the results suggest that this may not be necessary. In the survey, participants were informed that the technology would soon become available on the market. Hence, their strategic response or incentive may have been to understate their true WTP. It is therefore reasonable to assume that adoption rates will exceed those implied by the survey data and will be sufficient to stimulate early market demand. As AD becomes more familiar and its benefits become more observable, WTP is expected to increase, thereby expanding the potential market for AD without the need for government subsidies to promote its adoption.

In conclusion, while AD at its current level of maturity indicates net social benefits, its broader transformative potential will unfold gradually as technology, regulation, and social acceptance evolve together.

8 Overall conclusions, discussion, and lessons learned

To the knowledge of the Hi-Drive project partners, the results presented in this deliverable and the related detailed impact assessment deliverables originate from the most comprehensive impact assessment study conducted so far for the future use of automated vehicles (AVs) in European traffic. This applies to individual impact areas such as safety, but also, and in particular, to the combination of the impact areas (safety, mobility, efficiency and environment, transport system, socioeconomics). The impact assessments were based on a harmonised modelling of the automated driving functions (ADFs) and the considered enablers, calibrated using real-world driving data and supported by OEM expertise.

Thus, one of the main achievements of the Hi-Drive impact assessment was the development of a common Baseline ADF (BADF) model that was used in different impact areas and implemented in various simulation tools.

The use of a common tool, PTV Vissim, and common parametrisation in all simulations related to efficiency, environment, and transport system impact assessments allowed seamless use of individual results by the team members. The differences in impacts stemmed from differences in the scenarios and performance of ADFs, rather than from differences between simulation tools.

For the impact area of safety, the scenario results indicate that, for many of the simulated driving scenarios, the BADF contributed to a reduction in crashes beyond the reduction achieved through mandatory advanced driver assistance systems (ADAS). The ADF with integrated enablers (EADF), particularly in urban driving scenarios, yielded additional reductions in crash rates across various driving scenarios. With an exemplary ADF penetration rate of 30%, 19.7% of motorway fatal target accidents (accidents inside ODD) could be avoided by the EADF compared to today's traffic. In urban settings, 21.8% of fatal target accidents could be avoided. ADF deployment may also introduce new accidents, e.g. due to minimum-risk manoeuvres. The simulations indicate a 0.3% increase in motorway accidents at 30% EADF penetration. Thus, the positive effect of an ADF outweighs the potential negative consequences

The findings of the mobility impact assessment suggest that ADFs are likely to produce significant impacts on mobility. By enabling users to engage in non-driving-related activities (NDRAs), these systems can enhance travel quality, potentially leading to more frequent and longer trips.

Analysing the results of the impact areas of efficiency and environment revealed that, with AVs in traffic, travel time generally increased slightly, mostly due to changes in desired speed.

The technology enablers were found to reduce the increase under specific conditions. At the European network level over one year, increases of 0–4% were found at ADF penetration rates up to 50%. Tractive energy use per vehicle-kilometre travelled (VKT) decreased in most conditions, whereas impacts were mixed for CO_2 emissions due to interactions between internal combustion engine efficiency and speed. Here too, technology enablers showed potential to offset the CO_2 increases and further reduce energy use per VKT. At the European level, tractive energy use per VKT decreased by 0–15% at ADF penetration rates up to 50%. Impacts on CO_2 emissions at the network level were small (between –1% and 0%).

Hi-Drive achieved a comprehensive study by first addressing the impacts on individual travellers (mobility) and traffic flow (efficiency and environment), and by integrating these findings into the model used for assessing the impacts at transport system level. The changes in modal split can be considered negligible. This is because the increase in passenger car units (PCUs) that could push people towards other modes of transport was offset by the decrease in perceived travel time, which pulls people towards automated vehicles. The decrease in capacity and the resulting route choice decisions led to an increase in the VKT as well as the vehicle-hours travelled. For example, the VKT increased by 1.5% outside the ODD (mainly on rural roads) at 50% EADF penetration.

The results originating from the harmonised basis ultimately fed into an overall socioeconomic impact assessment. Based on standard unit costs estimated for the various impacts, the overall benefits were summarised. The major components were the benefits of safety impacts (approximately €22 to €40 billion) and gains for automated vehicle users, as they are able to combine work or relaxation while the vehicle operates in automated mode, and enjoy increased comfort (€23 billion). Increased travel time costs due to lower traffic efficiency represented another major component (€6.8 to €7.5 billion). Compared to these benefits, the estimated benefits from reduced energy consumption and CO_2 emissions were smaller (€480 million to €1.8 billion). Conversely, the costs for the EADF and the required infrastructure were estimated based on defined reference vehicles to calculate a benefit-cost ratio. The average benefit-cost ratio of 1.2 for the full-mandatory-ADAS baseline indicated that benefits are expected to outweigh costs across most of the expected cost range. For the traffic-today baseline, the ratio is even higher (1.8).

The results indicate that the impacts of AVs vary substantially across different impact areas. The harmonised models produced reliable results, providing the overall expected impacts for the AV behaviour defined in Hi-Drive, rather than fine-tuning individual models to perform optimally within each impact area. The model placed strong emphasis on safety, strictly adhering to legally defined gaps and speeds, which led to increase of travel time.

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