Hi-Drive
Designing Automation

Deliverable D4.5 /

Effects evaluation methods

Version: 1.0

Dissemination level: PU

Lead contractor: ika

Due date: 30.06.2023

Version date: 25.09.2023

This project has received funding from the
European Union's Horizon 2020 research and innovation
programme under grant agreement No 101006664.

Hi-Drive

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Project funding

Horizon 2020

DT-ART-06-2020 – Large-scale, cross-border demonstration of connected and highly automated driving functions for passenger cars

Contract number 101006664

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Glossary of terms

Term	Definition
Automated driving function	A common feature addressed by a group of automated driving systems.
Automated driving system	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.
Baseline (data)	Set of data to which the performance and effects of the technology under study are compared.
Driving scenario	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.
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.
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.
Measure	The magnitude of a quantity such as length or mass relative to a unit of measurement, such as a metre or kilogram.
Operational design domain	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.

Term	Definition
Performance indicator	A performance indicator is a scalar value for evaluation of a certain scenario which can be calculated from time series values and derived measures. Exceptionally, the indicator can also be a histogram. Quantitative or qualitative indicator, derived from one or several measures, agreed on beforehand, expressed as a percentage, index, rate or other value, which is monitored at regular or irregular intervals and can be compared to one or more criteria.
Research question	A general question to be answered by compiling and testing related specific hypotheses.
Test scenario	Description of a sequence of triggers, events, and actions among use case entities (ego vehicle, other traffic participants, etc.) in order to reach a use case goal.
Test run	A test run is a test instance that includes at least one test or driving scenario. It can be repeated within one experiment several times – also while slightly changing the setting (parameter, test person etc.). It is comparable to a trip but typically more commonly used in the context of a test track, simulation, or simulator test. In contrast, trip is often used in the context of a pilot or NDS/FOT and typically includes more driving scenarios.
Traffic scenario	Traffic scenarios have a broader horizon than the driving scenarios and cover a specific road section with certain traffic characteristics.
Treatment (data)	Part of the data collected with the system or feature under evaluation switched on by the experimental leader, such that they are either active all the time or can be switched on or off by the driver.
Trigger	Event that initiates or ends an action.
Use case	Abstract description of the interaction between an ADF and its environment in order to reach a particular goal.

Executive summary

The overall goal of the *Effects evaluation* of the Hi-Drive project is to study how technology enablers support automation to extend and defragment its operational design domain (ODD) and what the impacts of these enablers are on highly automated driving. Enablers are technological tools (software, hardware, or methodology) that have the potential to enable new or upgrade existing automated driving functions. The *Effects evaluation* is divided into three main areas: technical evaluation, impact assessment, and socioeconomic impact assessment.

The technical evaluation focuses on the effect of the enablers on the operational design domain extension and the robustness of the automated driving functions. Additionally, it explores the effect of automated driving (AD) and its enablers on driving behaviour using the data collected during Hi-Drive operations.

The impact assessment estimates the effects of AD and its enablers on the European market. The following impact areas are considered: safety, efficiency, the environment, the transport system, and mobility in general. The safety impact assessment evaluates the effects of AD and its enablers on the prevention of accidents and injuries. The efficiency impact assessment addresses effects on travel time and delays, and the environmental impact assessment looks at energy demand and emissions. The transport system and mobility impact assessments consider the effects on the transportation system as a whole and the mobility patterns of individuals, respectively. In all impact areas special focus is given to how the enablers change the impacts compared to manual driving and compared to automated driving functions (ADFs) without enablers.

The socio-economic impact assessment focuses on evaluating the societal welfare effects of AD and its enablers. A cost-benefit analysis is employed to compare the costs and benefits of the technology. This assessment considers both the results of the impact assessment and data from external sources.

This deliverable presents the methods and evaluation plans for the three evaluation areas described above. The evaluation plans lay the foundation for further work in subproject SP7 *Effects,* which implements and carries out the plans to get the results. The comprehensive evaluation of AD and its enablers in the Hi-Drive project provides valuable insights into the technical performance of AD as well as the potential impacts of AD and its enablers on the European Market. The findings will contribute to well-informed decision-making and help shape the future of AD.

1 Introduction

1.1 The Hi-Drive project

Connected and automated driving (CAD) has become a megatrend in the digitalization 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 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.

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).

The evaluation will focus 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 standardization, business innovation, extended networking with interested stakeholders, and coordinating parallel activities in Europe and overseas.

1.2 Overall implementation plan for Hi-Drive

The FESTA Handbook (FOT-Net, CARTRE & ARCADE (2021)) compiles the knowhow gained since 2007 on 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 adjustment of the FESTA implementation plan, described as the "FESTA-V" structure, was needed to accommodate the testing of AD.

Figure 1.1 illustrates the FESTA implementation plan adapted for Hi-Drive. The plan is divided into three phases: (I) prepare, (II) operate, and (III) evaluate. In 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 organized as high-, medium-, and low-level questions. The state-of-the-art is summarized for topics covered by these research questions. The feasibility of each research question is checked next

[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.

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) required.

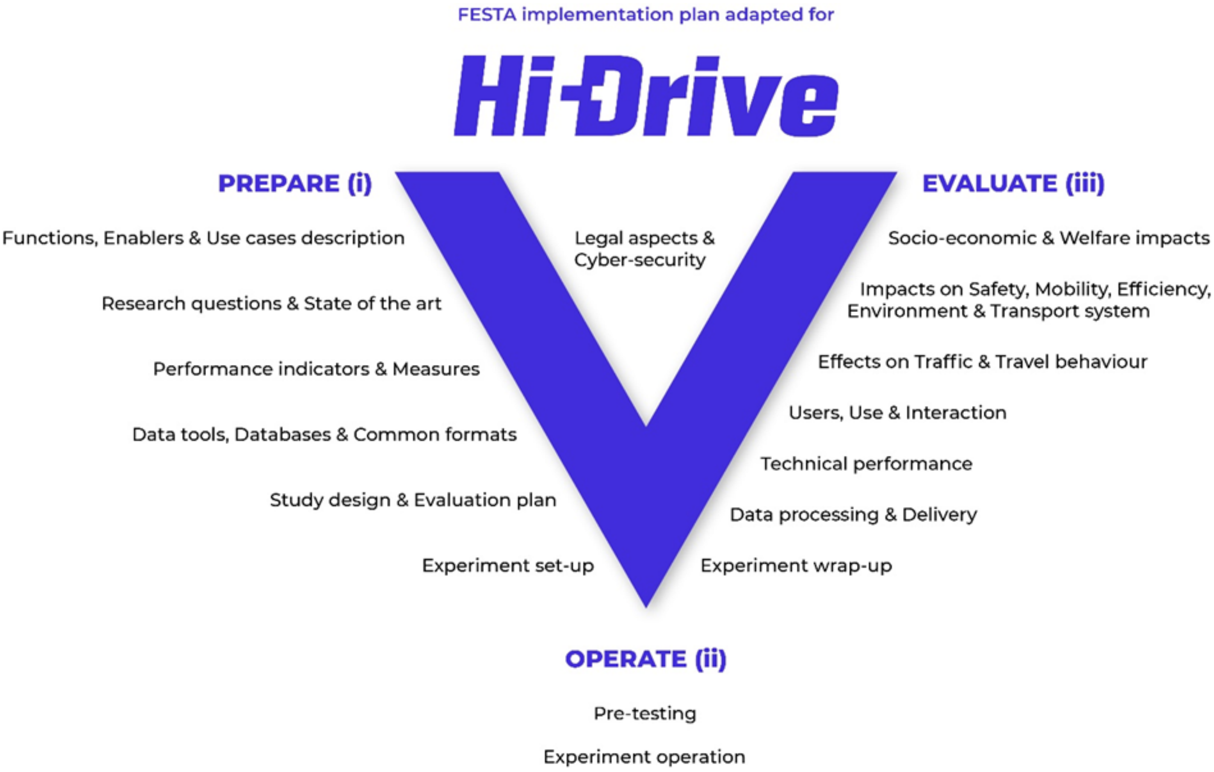

Figure 1.1: FESTA implementation plan adapted for Hi-Drive.

Next, the performance indicators and other data with which the research questions are answered are defined, and the relevant evaluation tools are calibrated. Based on these requirements for evaluation, five lists—one for different data categories[2]—with the required information are defined. In the following step, the five lists with the required information are merged into one signal list which specifies all the signals needed. Next to the signal list, a common data format (CDF) applicable to the project evaluation is specified for 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 allow to test highly automated driving and its technology enablers, and to provide data for evaluation. The

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

plans for all operation sites are approved among the site owners and those setting the methodology for evaluation.

An evaluation plan is developed for all research question 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 timeline.

The experiment setup includes preparation of test vehicles, testing of selected parts of the technology and use cases, getting permissions (e.g., for test drives on public roads), selection of participants, and implementation of 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 experiment operation begins. This phase involves the actual data collection.

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

1.3 Activity objective, scope, and structure of the deliverable

To be able to follow the described implementation plan in a structured way, the work within Hi-Drive is organized as subprojects (SP). This deliverable is part of the SP4 *Methodology* subproject. The objectives of this subproject are as follows:

- Specify the Hi-Drive research questions for both *Users* (SP6) and *Effects* (SP7) evaluation, how they will be addressed, and the related data needs.
- Agree on CDF for provision of different datasets.
- Agree on experimental design and procedures for testing and evaluation of ADFs and related enablers in challenging environments.
- Reconsider the theoretical background and impact mechanisms to build a multidisciplinary evaluation methodology, covering not only the expected positive impacts on safety, comfort, and the environment, but also the unintended and possibly negative impacts on users and the transport system.

- Refine the state-of-the-art methods to address user and human-factor aspects of high-level driving automation and facilitate understanding of possible effects on the transport system level, addressing travel behaviour, safety, efficiency, and emissions.
- Provide lessons learned from the methodological point of view.

Within SP4 *Methodology*, three deliverables define the basic requirements and goals of data collection from a methodological point of view: Specifically, these are the deliverables on the research questions (D4.1 *Research questions* by Metz et al., 2023), on the data requirements (D4.2 *Data for evaluation* by Fahrenkrog et al., 2022), and on the experimental design (D4.3 *Experimental procedure* by Sintonen et al., 2023). Based on that, detailed analysis plans for user evaluation (D4.4 *User evaluation methods*) and effects evaluation (this deliverable D4.5 *Effects evaluation methods*) were developed. All input and requirements will guide the work in SP5 *Operations*, which will collect the data needed for effects evaluation, and SP7 *Effects* which will analyse it to answer the research questions on effects. In a similar way, SP6 *Users* will collect and evaluate data to answer the user-related research questions. At the end of Hi-Drive, the project results on the research questions will be presented in the deliverables of SP6 *Users* and SP7 *Effects*. See Figure 1.2 for an overview.

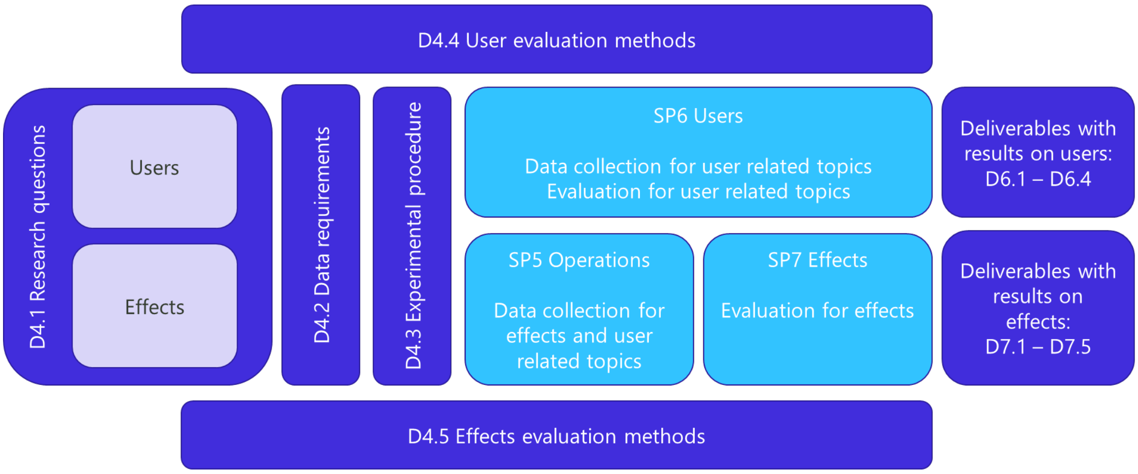

Figure 1.2: Role of different deliverables on methodological and evaluation results.

This deliverable is structured as follows:

- Chapter 2: Technical evaluation methods and evaluation plan
- Chapter 3: Impact assessment methods and evaluation plan
- Chapter 4: Socioeconomic impact assessment methods and evaluation plan
- Chapter 5: Conclusions and an outlook on the next steps in the project

It should be noted that this deliverable reflects the project's status as of June 2023, i.e., month 24 of the project. In a project that runs for four years, changes might occur that have implications on the experiments that will take place after publication of the deliverable.

2 Technical evaluation

2.1 Scope

2.1.1 Approach and research questions

The goal of the technical evaluation is to evaluate the ADFs and their enablers developed and tested in Hi-Drive from a technical perspective. This will be done based on vehicle data collected during the Hi-Drive operations[3]. The evaluation is divided into two research areas: The first concerns to what extent the enablers contribute to the *availability of AD*. The second area is about the effects of AD and its enablers on *driving behaviour* in various conditions. In both areas, the effects are evaluated with respect to research questions, which are already reported in D4.1 *Research questions* (Metz et al. 2023).

The high-level research questions of the research area on availability of AD are:

- To what extent do the enablers extend the AD functionality?
- To what extent do the enablers enhance AD robustness?

The high-level research questions of the research are on the effects of AD and its enablers on driving behaviour:

- What is the effect of AD and its enablers on safe driving behaviour?
- What is the effect of AD and its enablers on comfortable driving behaviour?
- What is the effect of AD and its enablers on efficient driving behaviour?
- What is the effect of AD and its enablers on interacting with other road users?
- What is the effect of AD and its enablers on position in lane?
- What is the effect of AD and its enablers on the time to complete a test-driving scenario?

The factors for the technical evaluation and their connections are depicted in Figure 2.1. The dark blue boxes are factors which were previously reported in the Hi-Drive project:

- **Enabler**: developed, tested, and evaluated, listed in D3.1 *Use case definition and description* (Bolovinou et al. 2023)
- **Use case**: addressed by the enablers, reported in D3.1 *Use case definition and description* (Bolovinou et al. 2023)

[3] Operation is the execution of experiment(s) in a defined place and time.

- **Operation**: tests the enablers in the use cases, reported in D5.1 *Description of operations* (Sauvaget et al. 2023). How the data shall be collected by the operation owner[4] is reported in D4.3 *Experimental procedures* (Sintonen et al. 2023).

The light blue boxes represent the factors that are addressed in this deliverable:

- **Driving scenario**: relevant for the scenario-based assessment in the technical evaluation and presented in chapter 2.1.4
- **Performance indicator**: used in the technical evaluation for answering the research questions based on data collected by the operations and listed in chapter 2.2.1
- **Pooling**: data collected by different operations can be pooled to create joint results. The methods for joint evaluation are presented in chapter 2.2.1. The plan for the data pooling is given in chapter 2.2.4

[4] A project partner who plans and carries out an operation and provides data in the common data format (CDF).

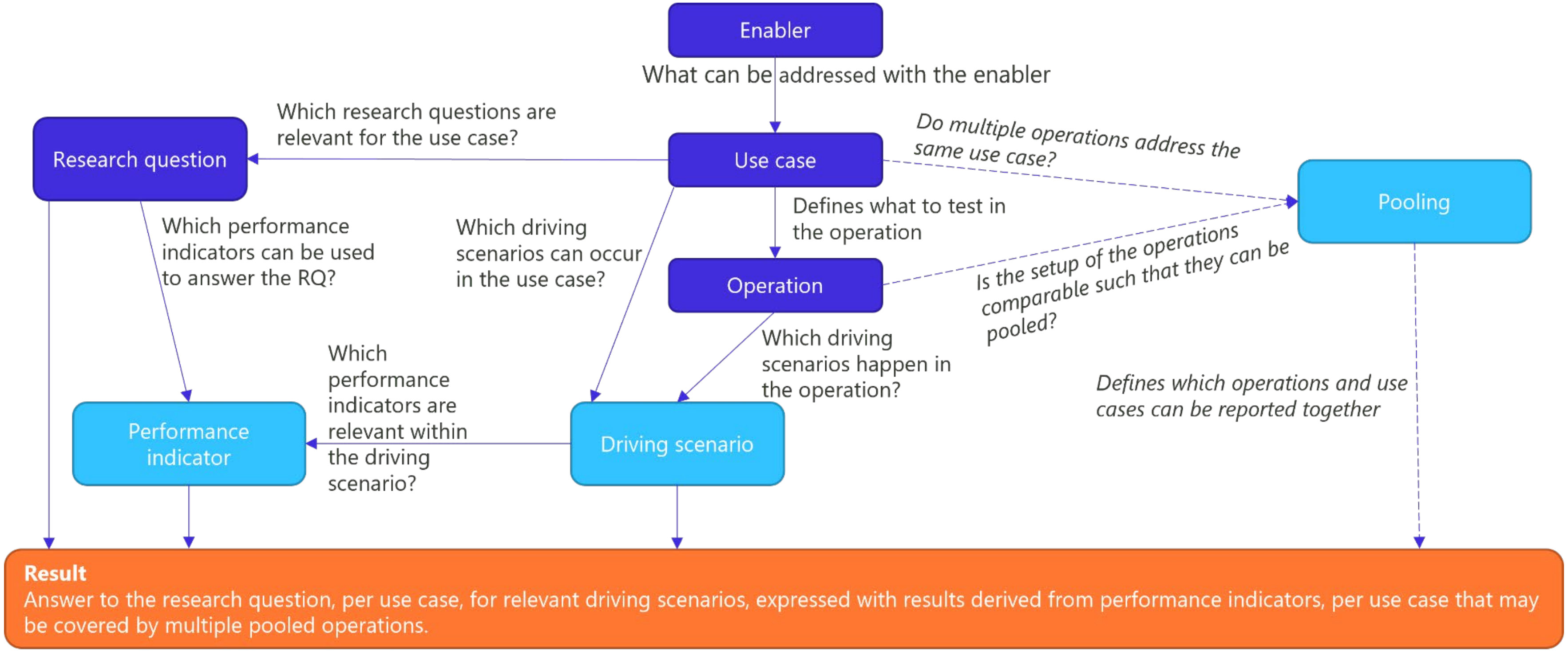

Figure 2.1: Overview of factors relevant for the technical evaluation in the Hi-Drive project.

Figure 2.2 shows the process for the technical evaluation: it starts with the data collected by the operations which is provided in the common data format (CDF) as reported in D4.2 *Data for evaluation* (Fahrenkrog et al., 2022). This data will be handed over by the operation owner to an analysis partner[5]. The analysis partner will use scripts that are created in the project to calculate the required performance indicators and upload them to the consolidated database (CDB). The calculation of the performance indicators will be done on three different *evaluation levels*: the trip level, the test run level and the driving scenario level. For the latter, driving scenario instances are detected in the data and then performance indicators are calculated per driving scenario instance. For the calculation on trip or test run level, the segmentation of the CDF data into driving scenarios is not necessary.

There are three approaches for evaluating data collected by multiple operations jointly (*pooling*). These approaches are explained in chapter 2.2.1. After all performance indicators have been uploaded to the CDB, the evaluation partners download the performance indicator data to create the results using the methods for data analysis presented in chapter 2.2.2. All results will be presented in D7.1 *Technical evaluation results*.

[5] A project partner that has been selected by an operation owner to process the operation's data and to provide it in aggregated form to the group of evaluation partners, who are responsible for creating the results from the performance indicators.

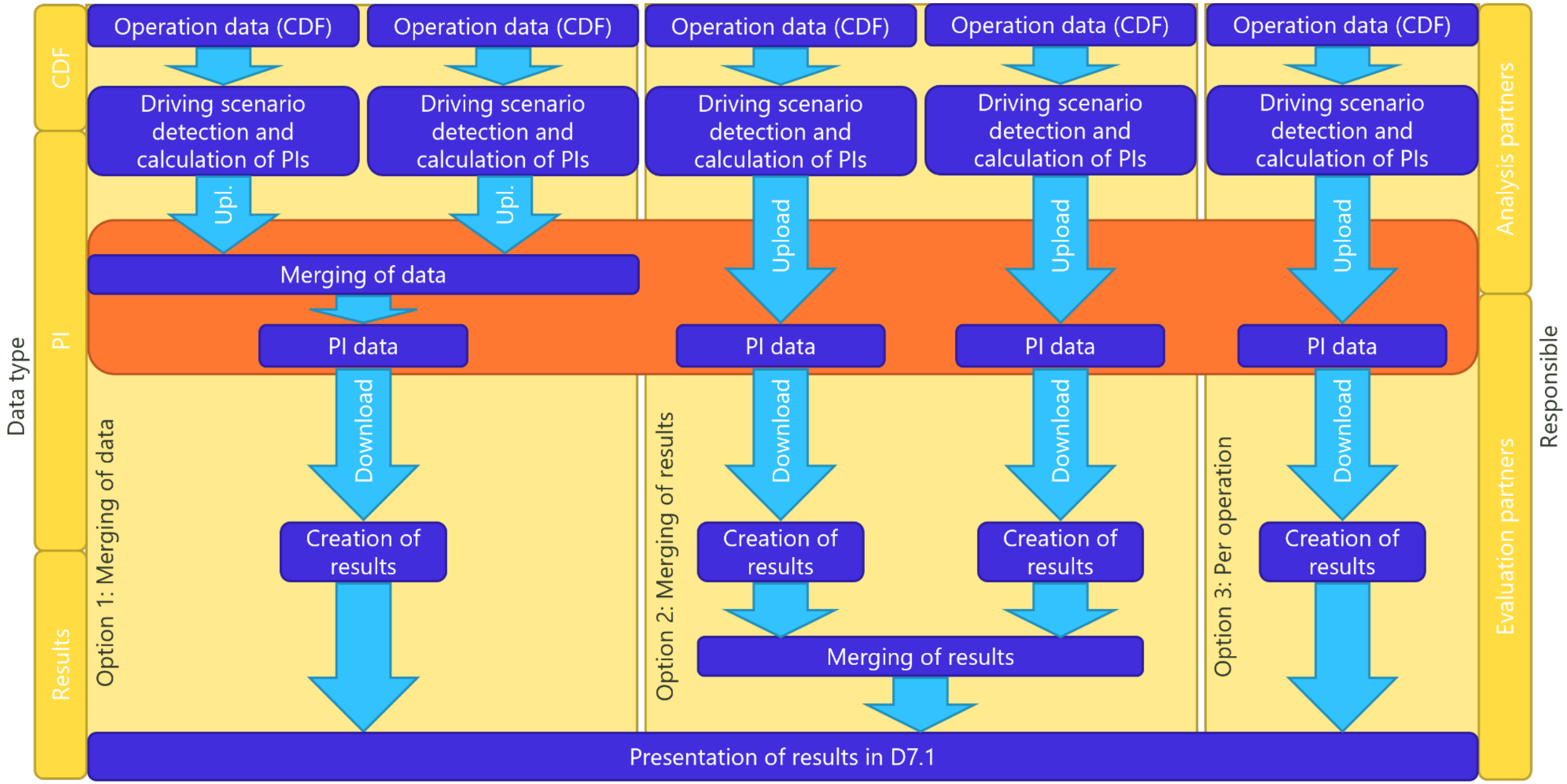

Figure 2.2: Approach to using the data collected by multiple operations to evaluate the ADFs and their enablers, and to answer the research questions.

To develop the plan in Figure 2.1, tables have been compiled mapping the factors (research question, use case, driving scenario, performance indicator) to each other. The tables were combined by dedicated data analysis teams. This was necessary to develop the complete process including the pooling of data from multiple operations and solving challenges addressed by different enablers and use cases in the operation. The following steps were taken:

1. Mapping between use cases and research questions
2. Mapping between use cases and driving scenarios
3. List of performance indicators per research question
4. Mapping between performance indicators and driving scenarios per use case

The templates used in this process can be found in Annex 1.

2.1.2 ADFs and enablers covered

In the Hi-Drive operations four main types of ADFs are considered: motorway, urban, rural, and parking. In each ADF, and according to its targeted ODD, one or multiple enablers are integrated. The goal of the integration of the enablers is to defragment the ODD in various driving scenarios by

- reducing the number of take-over requests to human drivers,
- addressing driving situations beyond the vehicle sensor range,
- further increasing the ODD awareness during runtime.

The enablers in Hi-Drive are grouped in four thematic areas and 12 groups as presented in detail in D3.1 *Use case definition and description* (Bolovinou et al., 2023). In total, the ADFs that are covered by the technical evaluation consists of: nine motorway, eight urban, three rural, and two parking ADFs that are evaluated across 33 operations executed by 15 operation owners. Together, there are over 60 different enablers integrated into the ADFs. The full list of tested ADF instances covered by the technical evaluation is provided in Annex 2.

The goal of the technical evaluation is to assess the effects of enablers on the availability and driving behaviour of current ADFs when enablers are integrated into them. In other words, the technical evaluation focuses on the effects of the enablers on the ADFs. Thus, in the technical evaluation, only enablers are considered that have a direct effect on the ADF in the operation.

2.1.3 Use cases and test scenarios

As described in D3.1 *Use case definition and description* (Bolovinou et al., 2023), each Hi-Drive ADF instance supports a specific set of use cases, where each use case has been decomposed into a small set of test scenarios[6] that will be executed during the Hi-Drive operations. More than 100 test scenarios have been prepared as part of the Hi-Drive use case and test scenario catalogue. The scenario-based technical evaluation of the project is built on this catalogue. Chapter 2.1.4 describes the driving scenarios considered as the basis for the scenario-based analysis. In principle, one test scenario from the catalogue will be analysed via a set of one or more driving scenarios defined below.

Annex 2 provides the full list of use cases supported by the ADFs considered for the technical evaluation. In total, 18 use cases in a motorway environment, 14 in urban, three in rural, and two in a parking environment will be analysed across the 33 operations.

2.1.4 Driving scenarios

The driving scenario concept (Sonntag et al., 2023) is based on broad experience of scenario databases among the partners such that it serves the purposes of Hi-Drive. A full list of all driving scenarios for the technical evaluation, including further description and top view diagrams, is provided in Annex 3. The driving scenarios are based on the actions of the ego vehicle and its interaction with other road users. Other factors (e.g., road characteristic or weather) can be described by additional tags in each driving scenario instance. The driving scenarios are categorized into four groups:

- ***in lane***: the ego vehicle is driving in a lane
- ***lane change***: the ego vehicle is changing lane
- ***crossing***: the ego vehicle passes straight through an intersection
- ***turning***: the ego vehicle turns either left or right at an intersection

The driving scenarios will be mutually exclusive (no parallel occurrence) to avoid double-counting in the performance indicators. Long driving scenarios (e.g., free driving for 3 minutes) will be chunked into multiple shorter sections (e.g., 18 sections of 10 seconds). This method is explained in more detail in L3Pilot D7.3 (Weber et al., 2023).

[6] 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, according to ISO 34501. A test scenario usually consists of a starting and ending triggering point and a sequence of driving scenarios in between.

2.2 Plan

2.2.1 Methods for data pooling

As described in chapter 2.1.1, the technical evaluation will analyse the data per use case that might come from the different operations to answer research questions at project level. To obtain conclusive results, it will be necessary to merge the information from the different operations and present it in a harmonized and aggregated way.

In principle, there are three different options of how this can be done:

1. **Merging of data**: The data from multiple operations are combined and analysed together. Results from the combined data are presented and discussed.
2. **Merging of results**: Each operation is analysed separately. The results from the different operations are taken together and presented in a combined way.
3. **Per operation**: Each operation is analysed and presented separately. Then the results from the different operations are discussed together and an overall conclusion is reached.

From the perspective of the project, option 1 (merging of data) is the best solution. It avoids the identification of single operations in the results and ensures that the presented results reflect what has been achieved in Hi-Drive. However, there are requirements on data and data collection that need to be fulfilled to provide meaningful and reliable results with option 1:

- recorded data at the different operations is similar enough so that the data can be treated as coming from one data source,
- different operations contribute equally to baseline and treatment datasets to avoid single operations contributing more to the overall result than others.

If multiple operations are similar, but the datasets provided by them are unbalanced in some way, option 2 (merging of results) can be applied for making a meaningful combined result, better than by pooling the original datasets. If an operation is unique (e.g., very specific use case), it cannot be combined directly with the other operations but must be presented as a standalone (option 3). The requirements, advantages, and disadvantages of all three options are listed in Table 2.1.

In Hi-Drive it will be decided per use case how the information is merged based on the following considerations:

- How many operations will collect data for the use case?

- What will the data collection look like regarding the
  - type of baseline data (manual driving, AD without enablers, see D4.3 *Experimental procedure* by Sintonen et al. 2023 for detailed descriptions),
  - test track or public road,
  - characteristics of the tested use case,
  - relevant conditions, e.g., speed limit, road type and layout, and
  - amount of data to be collected?

In certain cases, there might be statistical approaches to data handling that can deal with differences between operations (e.g., in the amount of data or differences in conditions) such that merging of data (option 1) becomes possible. Such approaches could be standardization[7] of the data or bootstrapping (see also chapter 2.2.2). Alternatively, the various operations could be balanced by normalizing with the driving time. Whether and in which cases such approaches will used to allow more frequent merging of data will be decided later by the analysis team, in a data driven way per use case and research question.

Table 2.1: Requirements and appraisal for data pooling.

	Merging of data	Merging of results	Presentation per operation
Requirements	Different operations need to address the same use case. Data collection for baseline and treatment needs to be highly harmonized between operations. Amount of data collected in the different operations (baseline & treatment) needs to be comparable.	Different operations need to address the same use case. Data collection between operations needs to be harmonized on a lower level. A sufficient amount of data (baseline & treatment) needs to be collected per operation.	A sufficient amount of data (baseline & treatment) needs to be collected per operation.
Advantages	Single operations cannot be identified. Full statistical power of data collected is used.	Single operations cannot be identified.	Can be applied to use case addressed by single operations. No harmonization between operations needed.

[7] Standardization in this context refers to statistical scaling.

	Merging of data	Merging of results	Presentation per operation
Disadvantages	Contributing operations need to be highly harmonized (baseline, treatment, amount of data). Impact of different operations on overall results cannot be judged. Contradictory results from different operations cannot be identified.	Full statistical power of data set is not used. Statistical power of each analysis is based only on data collected in one operation.	Single operations can be identified. Statistical power of each analysis is based only on data collected in one operation.

2.2.2 Methods for data analysis

To answer the research question for each operation separately, evaluation partners will evaluate the performance indicators (see chapter 2.1.1) with appropriate statistical methods. This will include comparing manual driving baseline data, ADF driving without enabler baseline data, and ADF driving with enabler treatment data to show statistically significant evidence for each research question through a mixed quantitative and qualitative assessment. Special care will be given to the selection of appropriate methods for data pooling according to the individual characteristics of the data sets. Specifically, in cases where ADF driving without the enabler is not an option (e.g., crossing a tunnel without lane markings), comparison against manual driving will be made.

Even though operations that are evaluated jointly are aligned, they still have some differences that complicate evaluation. For instance, the operations will differ with respect to number and type of baseline data. In addition, the criteria set out in chapter 2.2.1 will impact the specific analysis procedure.

It must be checked individually per data set which analysis methods fit best. Especially for the second option (merging of results) presented in chapter 2.2.1, there are reasons why the original data collected by the different operations could not be merged. For these, we can have additional methods that allow meaningful merging of results, i.e., merging of data after some interim processing steps. Possible methods that have already been proven to be effective in a similar context in the L3Pilot project are (Weber et al., 2023):

- *Bootstrapping*: to deal with large differences between amounts of data from Operation Owners in a pool.

- *The "Median-Shifted PI" approach* in non-parametric testing. This approach made it possible to pool data even when sub-sets originate from Operations with largely different speed limits.

2.2.3 Performance indicators

The performance indicators used in the evaluation plan are presented per research question (Table 2.2 – Table 2.9). For each high-level research question there is one table. Each of these tables has the same structure. They comprise the following columns:

- The first column lists the corresponding medium-level research questions (see D4.1 *Research questions* by Metz et al. 2023). The second column lists the low-level research questions for each medium-level research question. These are more specific research questions focusing on different aspects of the corresponding medium-level research question. In some cases, there is no low-level research question. If there are no low-level research questions in a table, the column is dropped.
- The next column features the performance indicators that shall be calculated to answer the low-level research question.
- The last column lists the number of use cases for which the performance indicator can be calculated. The use cases are aggregated on the four high-level ODDs (as done in D3.1 *Use case definition and description* by Bolovinou et al., 2023) and the number is given separately for motorway, urban, rural, and parking.

Table 2.2 and Table 2.3 summarize the evaluation plan for the research area on the availability of AD. The *relevant condition* mentioned in the performance indicators is defined by the respective use case. There is a difference between the relevant condition for ODD extension and AD robustness. For ODD extension, the relevant condition is e.g., a road infrastructure element, where the ADF could not drive without the enabler. For the AD robustness, the relevant condition is e.g., a road infrastructure element where the ADF could drive without the enabler, but usually take-overs are expected due to e.g., the complexity of the situation. Some road infrastructure elements can also be relevant for ODD extension and AD robustness in the same use case. This can, for instance, be the percentage of successful merges onto the motorway in use case M2 *Cooperative lane merging at motorway entry via V2V*. The condition would be the merging area road infrastructure element in this example. The term *take-overs* refers to take-over requests (TORs) initiated by the ADF, as well as take-overs initiated by the (safety) driver.

The evaluation plans for the research area on the effect of AD and its enablers on driving behaviour are summarized[8] in Table 2.4 – Table 2.9.

[8] The symbols v, v_x and v_y refer to the total speed, longitudinal speed, and lateral speed of the ego vehicle, respectively. The symbols a, a_x and a_y refer to the total, longitudinal, and lateral acceleration of the ego vehicle. The thresholds mentioned in the performance indicators are individually defined per performance indicator.

Table 2.2: "To what extent do the enablers extend the AD functionality?" (Summary of the evaluation plan)

Medium-level research question	Performance indicators	Use cases
To which environmental conditions do the enablers extend the ODD?	%driving scenario instances managed per relevant condition; %time AD active, %time AD available per relevant condition	2 motorway 3 urban 1 rural
To which road infrastructure elements do the enablers extend the ODD?	%driving scenario instances managed per relevant condition; %time AD active, %time AD available per relevant condition	12 motorway 4 urban 1 parking
To which driving scenarios do the enablers extend the AD functionality?	%driving scenario instances managed per relevant condition	4 motorway 1 urban
	%time AD active, %time AD available per relevant condition	6 motorway 1 urban 1 rural

Table 2.3: "To what extent do enablers enhance AD robustness?" (Summary of the evaluation plan)

Medium-level research question	Low-level research question	Performance indicators	Use cases
To what extent do enablers enhance AD robustness in challenging environmental conditions?	What is the effect of AD and its enablers on the number and frequency of take-overs?	Frequency of take-overs, %time AD active per relevant condition	1 motorway 3 urban 1 rural
To what extent do enablers enhance AD robustness in challenging road infrastructure conditions?		Frequency of take-overs, %time AD active per relevant condition	13 motorway 9 urban 1 parking
To what extent do enablers enhance AD robustness in challenging driving scenarios?		Frequency of take-overs, %time AD active per relevant condition	10 motorway 9 urban

Table 2.4: "What is the effect of AD and its enablers on safe driving behaviour? " (Summary of the evaluation plan)

Medium-level research question	Low-level research question	Performance indicators	Use cases
What is the effect of AD and its enablers on the frequency of incidents?	What is the effect of AD and its enablers on the frequency of close distances to other traffic participants?	number(THW<threshold), number(TTC<threshold) per driving scenario instance; mean(duration((THW<threshold) per driving scenario instance)); mean(duration(TTC<threshold) per driving scenario instance))	18 motorway 13 urban 2 rural
		number(PET<threshold) per driving scenario instance; mean(duration(PET<threshold) per driving scenario instance)	12 motorway 9 urban 1 rural
	What is the effect of AD and its enablers on the frequency / time spent in scenarios with oncoming traffic?	Frequency, %time spent in driving scenario instances with oncoming traffic	9 motorway 8 urban 1 rural
	What is the effect of AD and its enablers on the frequency of emergency brakings?	number(ax<threshold) per driving scenario instance	18 motorway 14 urban 1 rural 1 parking
	What is the effect of AD and its enablers on the frequency of lane departures?	number((abs(position in lane)>threshold) per driving scenario instance	18 motorway 11 urban 2 rural

Medium-level research question	Low-level research question	Performance indicators	Use cases
	What is the effect of AD and its enablers on the frequency of speeding?	%time(v>speed limit); %distance(v>speed limit)	16 motorway 12 urban 2 rural
To what extent do enablers support timely re-routing to avoid an ODD exit?	What is the effect of the enablers on the timing of re-routing manoeuvres (e.g., a lane change) to avoid an ODD exit?	mean(min(distance)), std(min(distance)), min(distance), std(distance) to hazard when lane change	2 motorway
To what extent do enablers support timely system-user control transition in the case of a TOR due to an upcoming ODD exit?	What is the effect of the enablers on the time after which the ADF is deactivated after a TOR?	mean(time ADF deactivated after TOR); median(time ADF deactivated after TOR)	3 motorway

Table 2.5: "What is the effect of AD and its enablers on comfortable driving behaviour?" (Summary of the evaluation plan)

Medium-level research question	Low-level research question	Performance indicators	Use cases
What is the effect of AD and its enablers on lateral acceleration?	What is the effect of AD and its enablers on the variation of lateral acceleration?	std(ay)	16 motorway 10 urban 2 rural
	What is the effect of AD and its enablers on the maximum lateral acceleration?	max(abs(ay))	16 motorway 10 urban 2 rural
What is the effect of AD and its enablers on longitudinal acceleration?	What is the effect of AD and its enablers on the variation of longitudinal acceleration?	sum(a^2) per km	15 motorway 12 urban 1 rural
		std(ax)	17 motorway 13 urban 2 rural, 1 parking
	What is the effect of AD and its enablers on the maximum/minimum longitudinal acceleration?	min(ax); max(ax)	18 motorway 13 urban 2 rural, 1 parking
	What is the effect of AD and its enablers on the frequency of uncomfortable brakings?	number(ax<threshold) per driving scenario instance	18 motorway 13 urban 2 rural, 1 parking

Table 2.6: "What is the effect of AD and its enablers on efficient driving behaviour?" (Summary of the evaluation plan)

Medium-level research question	Low-level research question	Performance indicators	Use cases
What is the effect of AD and its enablers on longitudinal driving stability?	What is the effect of AD and its enablers on speed?	mean(v); std(v)	18 motorway 13 urban 2 rural
	What is the effect of AD and its enablers on the variation of gap?	std(THW)	18 motorway 13 urban 2 rural
	What is the effect of AD and its enablers on positive acceleration?	sum(ax) for ax>0	17 motorway 13 urban 2 rural
	What is the effect of AD and its enablers on the frequency of braking?	Frequency of braking	18 motorway 14 urban 2 rural
	What is the effect of AD and its enablers on distance to end of merging lane during merging?	mean(min(distance)), std(min(distance)), min(time), std(time) to end of merging lane	11 motorway 2 urban

Table 2.7: "What is the effect of AD and its enablers on interacting with other road users?" (Summary of the evaluation plan)

Medium-level research question	Low-level research question	Performance indicators	Use cases
What is the effect of AD and its enablers on the relative speed to surrounding road users?	What is the effect of AD and its enablers on the variation of relative speed?	std(relative speed), mean(relatve speed) to relevant vehicles or VRUs	18 motorway 13 urban 2 rural
	What is the effect of AD and its enablers on the min/max of relative speed?	min(relative speed), max (relative speed) of relevant vehicles or VRUs	18 motorway 13 urban 2 rural
What is the effect of AD and its enablers on the distance to surrounding road users?	What is the effect of AD and its enablers on the min/max distance of any object in the path of the ego-vehicle?	min(distance), mean(distance), std(distance) to the object in path	18 motorway 13 urban 2 rural
		min(THW), std(THW), min(TTC)	18 motorway 13 urban 2 rural

Table 2.8: "What is the effect of AD and its enablers on position in the lane?" (Summary of the evaluation plan)

Medium-level research question	Performance indicators	Use cases
What is the effect of AD and its enablers on variation of lane position?	std(position in lane)	17 motorway 11 urban 1 rural
What is the effect of AD and its enablers on the preferred lane position?	mean(position in lane)	17 motorway 10 urban 1 rural

Table 2.9: "What is the effect of AD and its enablers on the time to complete a driving scenario?" (Summary of the evaluation plan)

Medium-level research question	Performance indicators	Use cases
What is the effect of AD and its enablers on the time to complete a driving scenario?	Scenario execution time; mean(scenario execution time); std(scenario execution time)	5 motorway 5 urban 1 rural 1 parking

2.2.4 Data pooling

Performing data pooling increases the validity of the results and harmonizes the analysis efforts performed for different operations in the project. As described in chapter 2.2.1, and following the initial considerations on operation pooling reported in D4.3 *Experimental procedure* (Sintonen et al., 2023, chapter 3.2.2), pooling of data should be performed for each operational environment (i.e., motorway, urban, rural, parking) following two main guidelines:

- Test tracks and public roads shall be analysed separately, as they are considered fundamentally different experimental setups.
- Operations focusing on a specific use case shall be clustered only with operations supporting the same use case or a very similar one according to the scenario-based approach.

Table 2.10 and Table 2.11 present the plan for the data pooling of different operations in the technical evaluation for the test track and public road operations, respectively. The selection of data pooling type is based on the factors presented in chapter 2.2.1, the guidelines from D4.3, and the driving scenarios that will take place in the operations.

As described in chapter 2.2.1, the following options are differentiated by also giving an example:

- Option 1: Merging of data

  Suitable for scenario-based analysis of the same use case executed by different operations sharing very similar or identical baseline and treatment conditions (e.g,. V2V-enabled motorway merging tested on the same test track).

- Option 2: Merging of results

  Suitable for scenario-based analysis of various use cases supported by multiple operations. (e.g,. V2X-enabled hazard awareness on motorway for different types of hazards).

- Option 3: Per operation

  Suitable for scenario-based analysis of a specific use case executed by one operation owner featuring a speciality in the experimental setup conditions in comparison with other operations executing the same use case (e.g,. V2V-enabled motorway merging including a truck agent).

Table 2.10: Data pooling plan for test track operations.

ID	Use case IDs	Title	Number of operations	Data pooling option
1	M2	Cooperative Lane Merging on motorway entry via V2V (2 actors)	3	1
2	M4	Cooperative Lane Merging on motorway entry via V2V (2 actors, truck)	1	3
3	M4	Cooperative Lane Merging on motorway entry via V2V (3 actors, truck)	1	3
4	M3	Cooperative Merging Awareness on Motorway entry via V2V (2 actors)	3	1
5	M3	Cooperative Merging Awareness on Motorway entry via V2V (2 actors, truck)	1	3
6	M5	Cooperative Merging Awareness on Motorway entry via V2V (3 actors, truck)	1	3
7	M1	Cooperative Overtaking via V2V with rear vehicle	1	3
8	M7	Cooperative Lane Merging and cyber-attack	1	3
9	M8, M9, U6	Cooperative Hazard Awareness and Avoidance or Dynamic Signage Awareness (lane changing or speed adaptation required)	4	2
10	M6	Lane exiting/interchange (cooperative)	1	1
11	U1, U3	Cooperative signalized/non-signalized intersection crossing via V2X (RSU and connected vehicles)	2	2
12	U4, U5	Smart traffic light crossing (SPATEM, MAPEM, CAM, DENM)	3	2
13	U11	Driving through areas affected by GNSS interruption or map inconsistencies or deteriorated lane markings	2	1
13	R2	AV-Truck Cooperative Overtaking on 2-directional road via V2V object info sharing from truck	1	3
15	P1	Automated Valet Parking	3	2

Table 2.11: Data pooling plan for public road operations.

No.	Use case IDs	Title	Number of operations	Data pooling option
1	M1	Cooperative Overtaking via V2V with rear vehicle (2 vehicles minimum)	1	3
2	M7	Cooperative Lane Merging and cyber-attack	1	3
3	M8, M9	Cooperative Hazard Awareness and Avoidance or Dynamic Signage Awareness (lane changing or speed adaptation required) on motorways	2	2
4	M10	Driving through a tunnel	3	1
5	M11	Driving through a road construction zone	2	1
6	M14	Driving in lane under rain/fog/heavy rain	2	2
7	M15	Approaching elevated bridge	2	1
8	M16	Driving through areas affected by GNSS interruption or map inconsistencies or deteriorated lane markings	2	1
9	M6, M17	Lane exiting (cooperative/non-cooperative)	1	3
10	M12, M13, M19	Various scenarios in motorway nominal ODD	7	1
11	U4, U5, U8	Non cooperative/Cooperative signalized intersection crossing (RSU and connected vehicles)	5	2
12	U2	Cooperative non-signalized roundabout crossing via V2I (focus ion conflicts between CAV and other vehicles)	1	3
13	U12	Driving in rainy weather or with missing lane markings	5	2
14	U7, U9, U10, U13, U14	Various scenarios in urban nominal ODD	7	2
15	R1	Urban-to-rural transition	1	3
16	R3	(Cooperative) Arctic driving on road covered by snow	3	2

3 Impact assessment

3.1 Scope

3.1.1 Overall aim and impact areas covered

The overall aim of the impact assessment is to estimate what are the impacts of highly automated driving and its enablers in specific scenarios and on European level after their market introduction, and what is the contribution of the technology enablers on the impacts. In addition to the direct impacts, the aim is also to assess the indirect impacts, which cover the broader effects of individual direct impacts and result from a chain of impacts, often with complex interactions and external factors (Innamaa et al., 2018).

Of the impacts, our assessment covers those on safety, efficiency and environment, and mobility and the transport system. They are addressed with 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 the 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?

3.1.2 ADFs and enablers covered

The impact assessment in Hi-Drive will address highly automated driving in two different environments: motorways and urban areas.

Hi-Drive is concerned with the extension of an ADF's ODD and improving its performance within the ODD using enablers. These enablers will affect the behaviour of the AD system within certain use cases. The impact assessment in Hi-Drive will investigate what impact the introduction of enabling technologies has within the different impact areas, and what impact the introduction of these advanced systems has compared to today's traffic, which largely consists of manually driven vehicles.

For these evaluations, the following configurations of ADF are 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 and less on which enablers are needed to realize these functionalities, because multiple enablers can support the same use case.

BADF ("Baseline ADF" or ADF without enablers) is the baseline for a comparison between the envisioned advanced ADF with today's state of the art. It refers to a system which does not include enablers and thus cannot realize the extended functionalities. Still, it is a market-ready system which 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. Therefore, the impacts will be evaluated in two pairings of systems:

- ADF with enablers (EADF) ↔ Manual Driving (incl. ADAS)
- ADF with enablers (EADF) ↔ ADF without enabler (BADF)

These comparisons will be reflected via the integration of systems in the defined scenarios.

A general description of ADF driving behaviour and ODDs is needed for the impact assessment. Furthermore, to enable the second comparison, it is necessary to define how the enablers and their use cases affect the behaviour of the ADF with enablers (EADF) compared to the ADF without enablers (BADF) in a way that is possible to integrate in a simulation tool to quantitatively evaluate the effects.

3.1.2.1 Relation to L3Pilot

Within the predecessor project L3Pilot (L3Pilot consortium, 2021), an impact assessment for conditional driving automation systems was carried out (L3Pilot D7.4 by Bjorvatn et al., 2021). Certain assumptions were made on how a market-ready AD system would function, which deviated slightly from observations of the pilot study. These so-called mature ADFs are defined in L3Pilot D7.4 (Bjorvatn et al., 2021). The definitions went into a certain level of detail and considered a collection of relevant ODD elements for definition of the ADF's capabilities. For example, the ODD was defined to include light and not heavy rain.

For Hi-Drive, in contrast, two ADF versions (EADF and BADF) need to be defined per environment (motorway, urban). Therefore, the definitions of the ADF's ODD and capabilities need to be more precisely refined to investigate possible differences in exposure between the ADF with enablers and ADF without enablers. This concerns, for example, the characteristics of tunnels or bridges, which have been identified as some of the challenging ODD conditions in which the ADF will benefit from the integration of enablers (the set of targeted ODDs per use case is described in detail in D3.1 *Use cases definition and description* (Bolovinou et al., 2023). For the impact assessment in Hi-Drive, however, it is important to define whether a certain ODD aspect or capability is covered already by the BADF or a feature that distinguishes the EADF from the BADF.

3.1.2.2 Considerations for defining the scope of enablers

The impact assessment will not include an assessment at single Hi-Drive enabler level, but rather an overall assessment of a combination of different Hi-Drive enabling technologies. This simplification is necessary due to limited time and resources available for the assessment. The decision on which enablers are considered is made by the impact assessment partners in light of the use case descriptions, available resources and capabilities, and consideration of which combination of enablers promises a sufficient effect. This could lead also to decisions in which only one enabler is considered even though multiple enablers address the same scenario. One example is the construction site. There is a Hi-Drive enabler that enables driving near construction sites (see Hi-Drive use case M11), meaning that unlike the BADF, no deactivation before a construction site is necessary with this EADF. It also means that in the safety impact assessment, the simulated EADF does not need an enabler providing information on the construction site via V2X (see Hi-Drive use case M8). In reality, this enabler could be highly relevant for certain ADFs for which the ODD does not cover construction sites. Thus, the inclusion or exclusion of a certain enabler in the assessment is not necessarily a statement about its importance in certain use cases. Limitations in terms of the assessed ADF and enabler combination need to be imposed to keep the impact assessment at a feasible level.

It is possible that enablers also have an impact in use cases or driving scenarios that are not listed in the overview of use cases addressed in Hi-Drive. However, if those use cases are not addressed by any operations within Hi-Drive, it is difficult to define plausibly how the enablers would affect the ADF in these scenarios. Therefore, the impact assessment within Hi-Drive will investigate (principally) the use cases and related enablers tested within the Hi-Drive experiments which hence form part of the use cases catalogue in D3.1 *Use cases definition and description* (Bolovinou et al., 2023).

For the integration of use cases and their related enablers, two options are possible:

- The first approach is modelling the enabler in the simulation. Here, it is important to model the differences between the BADF and EADF in the simulations properly. A virtual representation of the enabler can be done either by modelling it in the simulation or by implementing the resulting improved capabilities of the ADF. For instance, the advantage of looking further ahead by means of V2V communications could more easily be implemented with an extended sensor view range that is not affected by occlusions. This can be implemented in simulation tools more straightforwardly than direct modelling of the communication.

- The second approach is addressing the differences via the scaling up of certain impacts, e.g., via additional vehicle kilometres travelled (VKTs) when supported with enablers. In this way, the impacts within a driving scenario can be scaled up differently to European traffic for the EADF and BADF. For instance, a certain impact may be associated with minimum risk manoeuvres (MRMs). This impact may be identical for both ADF versions, but the BADF can be assumed to encounter more such MRM instances given its stricter limitations in the ODD, resulting in less VKT driven with an activated system compared to the EADF with extended ODD.

Given the limited resources within the project, it is not possible to investigate all Hi-Drive use cases within all impact areas. The decisions on the use cases covered by the impact assessment are outlined together with the evaluation plan within the different impact areas in chapters 3.3 to 3.5. For this, use cases have been grouped based on how they can be integrated within the impact assessment and a preliminary decision made on whether the use case will be considered within the different impact areas. These decisions are based on the judgement of the project partners implementing the impact assessment. During the setup of the actual assessment simulation tools, certain aspects may turn out not to be feasible to integrate into the simulations or not to deliver plausible results. The indications given for the individual assessment areas represent items whose integration within the different tools in detail appears feasible.

Apart from the balance between the assumed magnitude of certain impacts and the required efforts for assessment, the following aspects were considered when judging the feasibility of including use cases and enablers in the impact assessment:

- The mechanism of how an enabler creates an impact in a certain scenario may be unknown or vague, such that it is not possible to model it meaningfully in a simulation.
- Models that allow integration of certain aspects of the simulation tools used for the impact assessment are not available and not feasible to be implemented within the scope of the project.
- As a basis for the quantification of impacts, suitable input data are required such as detailed crash data, road infrastructure data, traffic statistics, etc. If such data are not available or not detailed enough to investigate a certain use case or enabler, no meaningful evaluation of impacts can be achieved.

3.1.2.3 Global decisions on scope

Certain high-level decisions on the scope of the impact assessment have been made:

- Rural AD will not be considered for the impact assessment, given that in general, systems intended for the use of rural areas are rather immature. Rural use cases bear a lot of challenges such as high relative speeds and non-separated oncoming traffic. Furthermore, rural cases span a wide variety of possible scenarios, which also cover greater parameter ranges compared to motorways or urban scenarios. Hi-Drive operations target certain rural use cases, but their testing efforts are limited to roads which do not come with a great variety of conditions or driving scenarios. Given the large efforts and complexity of the integration of rural automation in its entirety, it was decided that rural automation will not be considered in the Hi-Drive impact assessment.
- Parking automation will also not be considered within the impact assessment of Hi-Drive. Although parking automation offers great perceived personal benefits for the owner, the impacts in terms of injury accidents or travel time are not as extensive. Furthermore, the data basis for an assessment of the impacts of parking automation is small, since they are typically heavily underreported in national accident databases. Within L3Pilot, a comprehensive safety impact assessment of parking ADF was carried out, but given the structure of insurance databases, it was not possible to generate a trustworthy estimate of how many accidents could be avoided, due to the unknown overlap of motor-own and third-party-liability damages (Bjorvatn et al., 2021).

The remaining use cases as defined in D3.1 *Use cases definition and description* (Bolovinou et al., 2023) were grouped in the following categories to be efficiently discussed from an impact assessment perspective:

- Cooperative and Non-cooperative merging at on-ramps: *M2, M3, M4, M5, M18, M19*
- V2V communication for speed adaptation: *M18, M19*
- Green Light Optimal Speed Advisory (GLOSA): *U4, U5*
- I2V for hazard notifications: *M8, U6*
- I2V for dynamic road signage: *M9*
- Driver monitoring: *Does not directly link to a certain use case but will be treated as use case in the impact assessment*.
- Adding infrastructure elements to the ODD: *M10, M11, M15, U1, U2, U11, U14*
- External HMI: *U15, U16*
- V2V communication for overtaking: *M1*
- (Cooperative) lane exiting: *M1, M6*
- Basic scenarios for motorways and urban roads: *M12, M13, U3, U9, U10, U12, U13*

- Challenging ODD conditions (including weather low GNSS coverage): *M14, M16*

Depending on the impact area, decisions on the use cases covered have been made on individual use case level or on the level of this grouping. A summary of use cases covered overall is given in Figure 3.1 and Figure 3.2. Dark blue and purple elements show the use cases covered; light blue elements show aspects that are generally covered also by the BADF, but in which the introduction of the enabler may result in an improved performance, e.g., higher driven speeds in complex driving scenarios. Figure 3.1 shows a summary of the aspects that distinguish the EADF from the BADF in the impact assessment. Not all aspects are addressed in each impact area. The detailed decisions on use case level are given in the relevant subchapters. Dynamic road signage can in principle also be handled by the BADF. However, the possible rerouting and an earlier adaptation to speed limits are capabilities assigned to the EADF.

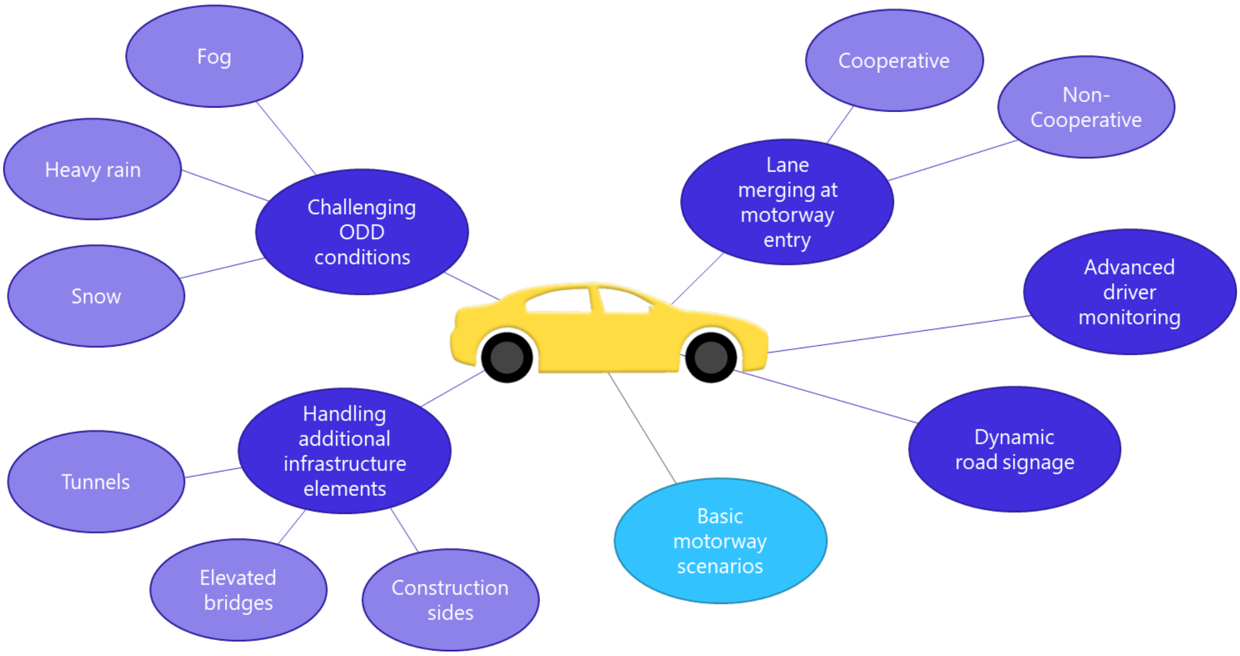

Figure 3.1: Aspects which distinguish the motorway EADF from the motorway BADF.

Figure 3.2 highlights the aspects in which the urban EADF is advanced compared to the baseline BADF. In general, the BADF is assumed to already handle a large variety of driving scenarios safely, such as passing an intersection. Within these scenarios, the EADF can still offer benefits compared to the BADF. For instance, in the case of turning at intersections, the BADF needs to adapt its speed to consider the possibility of occluded objects entering the intersection. For the EADF, V2V communication can help the ADF know about such objects before they become visible and consequently pass the intersection at higher speed, increasing the intersection throughput.

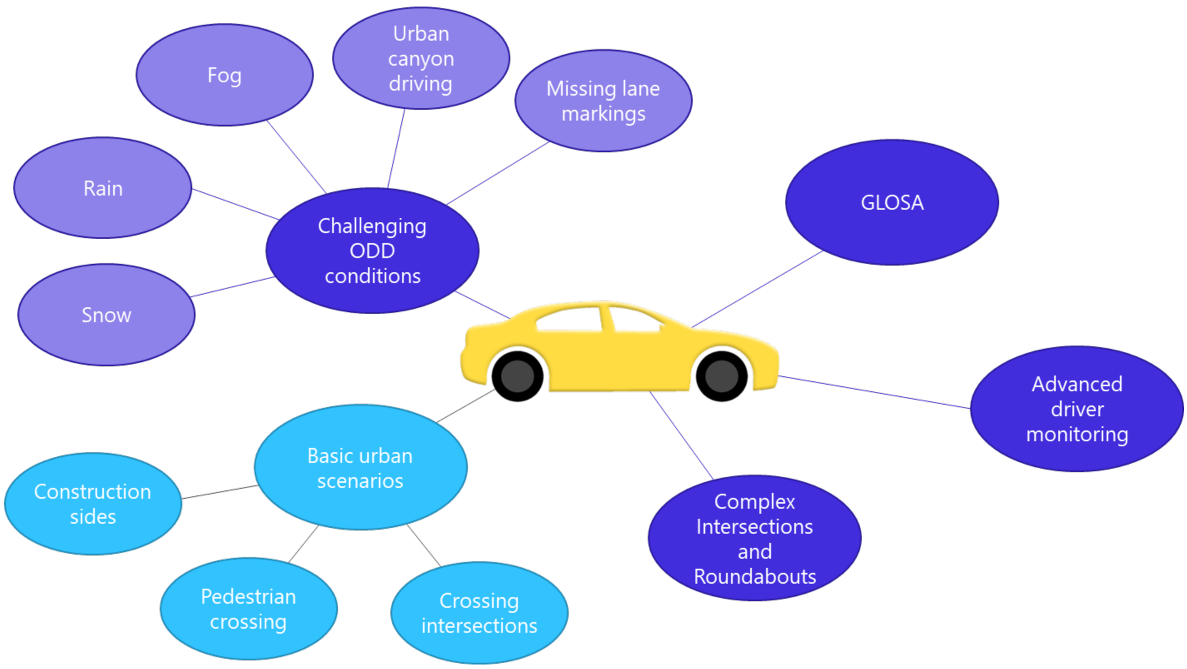

Figure 3.2: Aspects which distinguish the urban EADF from the urban BADF.

Within the plans of the different impact areas, decisions will be stated, how the different aspects of the EADF are to be integrated into the assessment approaches. The categories for these aspects are:

- **Simulation** → The aspect will be modelled to distinguish the EADF from the BADF in the simulations.
- **Scaling up** → The aspect will be not directly simulated but considered within the scaling up of individual impacts. (Note that also the modelled direct impacts will be scaled up to European level.)
- **Baseline ADF** → The aspect is considered already to be part of the BADF in the impact assessment and thus the comparison between EADF and BADF is not made. However, simulations for scenarios in which this aspect is relevant will be executed to compare the EADF with manual driving.
- **Not covered** → The aspect will not be analysed as part of the impact area.

3.1.3 Overall approach

3.1.3.1 Main methodological approach

For most impact areas, effect sizes in different driving or traffic scenarios (see chapter 3.1.3.3 for their definitions) will be analysed. Scenarios are chosen based on the expected impact mechanisms for the technology enablers and to cover the most relevant scenarios in the

ODD of the AD. The main approach to effects estimation is to use simulations, but these will be complemented with survey results, literature reviews, expert knowledge of the systems, and developer insights when simulation is not possible. The scenario-specific effects will then be scaled up to European level using European statistics, supplemented with additional information from national in-depth data and statistics. Regarding impact assessment, data collected from the operations within Hi-Drive will mainly be used for calibration of the simulation tools and models.

The indirect impacts of highly automated driving will be assessed via impact mechanisms identified for AD as defined by Innamaa et al. (2018):

- IM1: Direct modification of the driving task, driver behaviour or travel experience
- IM2: Direct influence by physical and/or digital infrastructure
- IM3: Indirect modification of AV user behaviour
- IM4: Indirect modification of non-user behaviour
- IM5: Modification of interaction between AVs and other road-users
- IM6: Modification of exposure / amount of travel
- IM7: Modification of modal choice
- IM8: Modification of route choice
- IM9: Modification of consequences due to different vehicle design

3.1.3.2 Study design

The basic study design for impact assessment (see Table 3.1) is to compare scenarios with a certain penetration rate of passenger cars equipped with ADF supported by technology enablers (EADF) with manually driven passenger cars. For manual driving, two different baselines will be considered based on the different considerations of advanced driver assistance systems (ADAS):

- "As in traffic today," which aims to reflect the penetration of ADAS in the near future,
- "Full penetration of mandatory ADAS," which aims to reflect the situation where the full potential of the decision to make certain ADAS mandatory for new passenger cars (European commission 2022) is reached.

To assess the contribution of the technology enablers on these impacts of EADF, the treatment condition is compared to scenarios where passenger cars are equipped with an ADF without these enablers (BADF).

Table 3.1: Study design for the impact assessment. BADF = ADF without enablers, EADF = ADF supported by enablers.

	Baseline	Treatment	Impact
Comparison to traffic today	Fully manual fleet with ADAS% as in traffic today	EADF% = 10% and 30% + otherwise fully manual fleet with ADAS% as in traffic today	Benefit of EADF on situation today
	BADF% = 10% and 30% + otherwise fully manual fleet with ADAS% as in traffic today		Contribution of enablers to this benefit
Comparison to “full penetration” of mandatory ADAS	“Full penetration” of mandatory ADAS	EADF% = 30% and 50% + otherwise “full penetration” of mandatory ADAS	Benefit of EADF over “full penetration” of mandatory ADAS
	BADF% = 30% and 50% + otherwise “full penetration” of mandatory ADAS		Contribution of enablers to this benefit

As the comparison to traffic today is most meaningful for smaller ADF penetration rates, the impact assessment addresses penetration rates of 10% and 30% of EADF and BADF in use among passenger cars. However, at the time when full penetration of mandatory ADAS is reached, also higher penetration of ADF can be expected. Therefore, for the comparison to full penetration of mandatory ADAS, larger penetrations of ADFs of 30% and 50% are selected. Note that “full penetration” of mandatory ADAS is likely less than 100%, thus 90% penetration will be used. Impact area-specific evaluations are also free to include other penetration rates if resources allow, in order to identify the specific conditions when impacts can be expected.

3.1.3.3 Scenario definitions

Following the methodology, the ADF and enabler will be assessed in two different types of scenarios, namely traffic scenarios and driving scenarios.

A **traffic scenario** describes a larger traffic context, which includes different (not pre-defined) driving scenarios. Typically, in a traffic scenario many vehicles are analysed over a longer time period. An example of a traffic scenario could be on a 3-lane highway section with 10 motorway entrances and exits and a speed limit of 130 km/h for a period of 1 h.

Driving scenarios describe the development of a **situation** within a traffic context in which at least one actor performs a (pre-) defined **action** or is influenced by a (predefined) **event**. The action or event is specified without the definition of concrete parameters. The influenced actor may either be the ego vehicle (e.g., performing a lane change or a minimum risk manoeuvre) or another traffic participant (e.g., performing a lane change from an adjacent lane, moving in front of the ego vehicle).

An example of both types of scenarios is given in Figure 3.3.

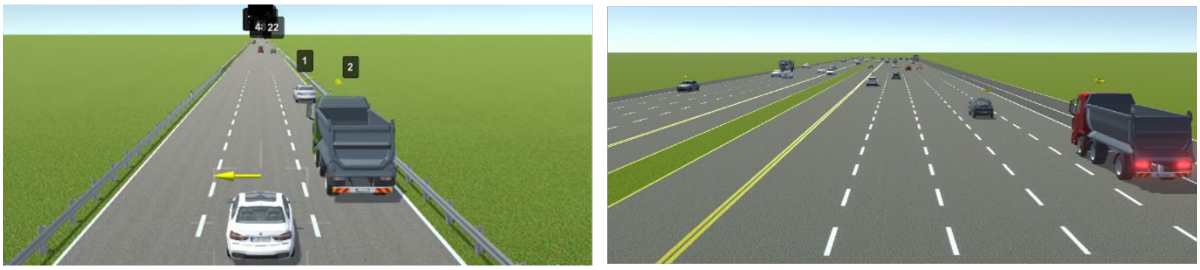

Figure 3.3: Examples of driving scenario (left, ego vehicle in white) and traffic scenario (right).

3.2 Safety impact assessment plan

3.2.1 Methodology and research questions

For the safety impact assessment, the research question "What is the impact of AD and its enablers on safety?" (D4.1 *Research questions* by Metz et al., 2023) has been the initial point for planning the assessment. For the work in the safety impact assessment, this question has been subdivided into three medium-level research questions addressing the AD and its enablers' effects regarding direct impacts on scenario level (question 1), indirect impacts on safety (question 2), and the scaling up of safety impacts to European level (question 3):

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?

The methodology to assess these research questions builds upon the methodology of the L3Pilot safety impact assessment (Bjorvatn et al., 2021) as well as on the P.E.A.R.S. (Wimmer et al., 2023) and ISO 21934-2 (ISO 21934) activities. Additional relevant literature and background information to the safety impact assessment is described in D4.1.

As for the other impact assessment areas, the starting point for the safety impact assessment is the nine-safety mechanism approach (see chapter 3.1.3.1). The assessment is mainly focused on the direct effects of ADF. Here, the chosen approach consists basically of two sequential steps. The first is to determine the effects of the ADF under test in the defined driving scenarios, in terms of crash avoidance and crash mitigation. It is important to highlight that in the driving scenario analysis, the safety impact assessment focuses only on the changes in terms of crashes and their severity. Surrogate measures like avoidance of critical events that do not lead to a crash are not within the scope of analysis of driving scenarios. Changes in the driving scenario frequency are only investigated in the traffic scenarios. The second step is the scaling up of these effects to derive safety impacts on a European level. Both steps are described in more detail in the following sub-chapters.

Regarding the other safety mechanisms, such as changes in exposure or changes in non-user behaviour, chapter 3.2.5 describes how they are addressed in the Hi-Drive safety impact assessment (see Table 3.8).

Note: *In this chapter, both the terms "accident" and "crash" are used to describe scenarios in which either two traffic participants collide or one traffic participant leaves the road unintentionally.*

3.2.1.1 Assessing direct impacts

The assessment of the direct safety impact of an ADF and its enablers (for more on the classification of direct and indirect effects see chapter 3.2.5) starts with investigating the safety performance in individual scenarios. The overall approach is given in Figure 3.4. In the first phase of the assessment, input data sources are defined and the models for the simulation are prepared (1st step). Then, the scenarios to be assessed are identified. The input data consist of traffic and accident data, as well as data on the performance of human drivers and the ADF (see the more detailed overview in chapter 3.2.2). Based on the input data, the scenarios are described and the models for the simulation of different scenarios are calibrated (2nd step).

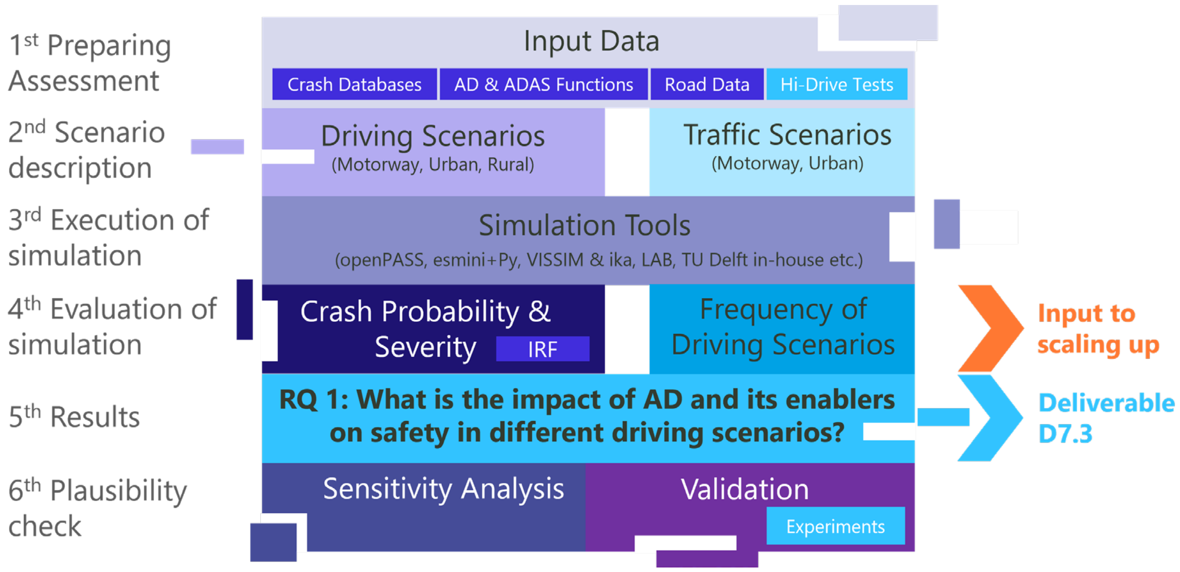

Figure 3.4: Approach to assessing the ADF and enabler effects in scenarios.

The model for the ADF and the enablers is applied in the simulations. In this context, it is important to highlight that two ADF versions are assessed: one without the Hi-Drive enabler (BADF – Baseline) and one with the Hi-Drive enablers (EADF – Treatment). For more information, see chapter 3.2.3.

The scenarios together with the applied driver behaviour (applied in the baseline condition for the manually driven ego vehicle and in all conditions for all manually driven vehicles) and baseline ADAS models build the baseline for the assessment. The additional baseline is the simulation with BADF without the enablers. These are then compared with the treatment condition with an EADF-equipped ego vehicle.

The assessment is mainly done by means of simulations (3rd step). However, for a few scenarios the assessment is done by means of expert judgements. The reason for choosing expert judgement evaluation for such driving scenarios is that the ADF effect in the scenarios is rather obvious or the required models for establishing the baseline and/or treatment are not available to the Hi-Drive partners.

For the simulation, the Hi-Drive safety impact assessment determines the safety effects in scenarios that are defined in the 2nd step based on two different simulation approaches, which can be classified according to P.E.A.R.S. (Wimmer et al., 2021) into:

- *Simulation approach B "Re-simulation of original cases with modification"*: In this approach the starting point is a real-world scenario that was recorded either during a test (e.g., from naturalistic driving studies or field operational tests) or reconstructed crash data. The trajectories over time for the relevant traffic participant must be available in this approach. For the assessment, the original scenario is modified with respect to the kinematic parameters and the driver reaction to account for uncertainties in the data collection. The variation is defined either before the simulation (change of kinematic parameters) or during the simulation (e.g., driver, ADAS or ADF models to react to the given situation). The modified cases are simulated for all three conditions (i.e., baseline without ADF, baseline BADF and treatment EADF).
- *Simulation approach C2 "Stochastic sampling of cases"*: In this approach, multiple artificially generated runs of each driving scenario are analysed. The basis for the generation of the cases is either recorded driving data, data from static traffic observation, or detailed accident data depending on the parameters. The analysis aims at deriving distributions for the relevant parameters. Thus, in contrast to the previous approach, in this approach the aim is not to derive trajectories but rather the starting values for the kinematic parameters of the scenarios. Here, sampling techniques (e.g., Monte Carlo) are applied to derive the starting parameters for the cases to be simulated. In the simulation, either a driver

behaviour model (used for the ego vehicle in the baseline without ADF and non-ADF traffic participants in all conditions) or the ADF model (used only by the ego vehicle in BADF and EADF condition; ADF traffic participants in all conditions) defines the movement of the individual traffic participants.

The simulation approach used (B or C2) for each driving scenario is chosen based on the available data, the type of conflict, and the available simulation models (i.e., typically the availability of appropriate driver models for simulating the scenario).

In addition to the effects in driving scenarios, the effects of ADF and enablers are also analysed in larger traffic scenarios (see chapter 3.2.4). This way, the effects resulting from the long-lasting operation of the ADF are analysed. Here, it must be noted that safety effects can result from crash avoidance or mitigation, but also from changing the frequency of a certain safety relevant scenario. For instance, the ADF's operation strategy (e.g., keeping a larger gap to other vehicles or keeping exactly the speed of the given speed limit) could lead to fewer lane change manoeuvres performed by the ADF compared to manually driven cars. This reduces the risk of encountering a collision during a lane change. Therefore, these exposure effects in terms of changed frequencies of driving scenarios also need to be considered in the safety impact assessment of AD.

Execution of the simulation is the 3rd step in the process (Figure 3.4). Here, the work will be split among the Hi-Drive safety impact assessment partners. An overview of the applied simulation tools is given in chapter 3.2.2. To harmonize the assessment between the different tools, the models and parameters are discussed between the involved partners.

After the simulation, the simulation results are processed in automated toolchains to derive the relevant output for the scaling up (4th step). The relevant output is the estimated crash/event frequency as well as the estimated severity of collisions. The collisions' severities are determined by means of injury-risk functions (IRFs). Here, Hi-Drive builds on the IRFs that were used in the L3Pilot project (Bjorvatn et al., 2021). The output will also be used to answer the research question "What is the impact of AD and its enablers on safety in different driving scenarios?" (5th step).

The work of assessing the direct effects of the ADF and enablers is accompanied by activities related to verifying the results (6th step). Namely, this step includes validation and verification of the simulation output as well as sensitivity analysis of the simulations. The details of this step depend on the simulation results. Which data from the Hi-Drive experiments can be used for this purpose will be investigated.

3.2.1.2 Assessing indirect impacts

As is the case for direct impacts, the assessment of indirect impacts also uses the nine-impact mechanism framework (see chapter 3.1.3.1) and focuses on the impact mechanisms M3 "Indirect modification of AV user behaviour", M4 "Indirect modification of non-user behaviour", and M6–M9 "Modification of exposure/amount of travel, modal choice or route choice". There, the process starts with identification of relevant questions for the indirect impacts of ADF and its enablers under each mechanism. The Hi-Drive results, especially of mobility impact assessment, are reviewed on these chosen focal topics. A literature review supplements the Hi-Drive results.

Finally, a qualitative assessment is performed on the findings to assess the direction and magnitude of their effects on the overall safety impact. This qualitative assessment was chosen because experience from the L3Pilot project (Bjorvatn et al., 2021) showed that there is insufficient evidence on long-term impacts to provide the needed input for a quantitative assessment of indirect impacts.

3.2.1.3 Scaling up of the safety impact

Once the AD's effects in different scenarios are determined, they need to be brought together and projected for the EU and annual level by scaling up (see Figure 3.5). The scaling up focuses on direct effects with three main inputs: external accident databases, Hi-Drive inputs such as ODD descriptions and defined penetration rates, and input from the simulations in terms of changes in the crash risk, crash severity, and scenario frequency. All inputs are processed with the ERiC scaling-up tool (see chapter 3.2.2). The output of ERiC is used to answer the medium-level research question on the direct safety impact of EADF on European level and on the contribution of enablers to it.

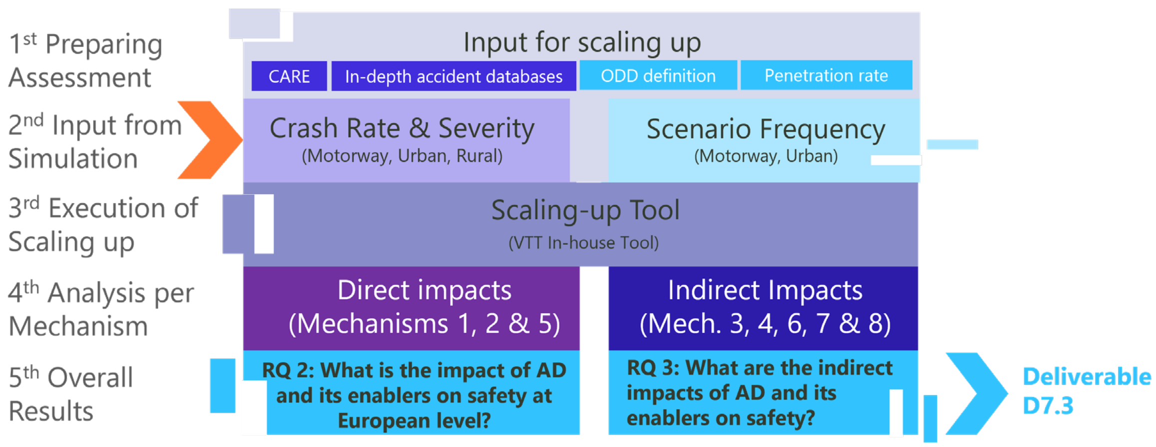

Figure 3.5: Approach to scale up the ADF and enabler effect to the European level.

3.2.2 Assessment tools and input data

With respect to data, the safety impact assessment will exploit several data sources derived within as well as outside the project. One of the crucial external inputs is accident databases. Here a distinction must be made between national/European databases, which provide the information needed for scaling up, and detailed accident databases, which provide input parameters or crash cases for simulations. An overview of the data sources used in the safety impact assessment is given in Table 3.2.

Table 3.2: Data types used in the safety impact assessment.

ID	Data Type	Example of the used data	Purpose
In1	National Accident database	• CARE database (CARE Team, 2023) • BRON (Rijkswaterstaat, 2023)	• Scaling up of the scenario effects • Scenario definition and prioritization
In2	Reconstructed Accident Database	• GIDAS-PCM (VUFO GmbH, 2023.a) • TASC dataset (VUFO GmbH, 2023.b) • VCTAD (Isaksson-Hellman and Norin, 2005) • VOIESUR (French National Research Agency, 2020) • EDA (Perron, 2001)	• Identifying the effects within driving scenarios • Model calibration • IRF Calculation
In3	In-depth Crash Database	• Finland Fatal Road Accident Data (The Finnish Crash Data Institute, 2023) • VOIESUR (French National Research Agency, 2020) • GIDAS (BASt and the Research Association of Automotive Technology (FAT), 2023) • EDA/CDA (Perron, 2001)	• Identifying the effects within driving scenarios • IRF Calculation • Scenario definition • Target accident definition
In4	Field/Pilot Data on ADF Behaviour	• L3Pilot field/pilot data (L3Pilot, 2023) • Hi-Drive field/pilot data (Hi-Drive, 2023) • ADAS behavioural data	• Model calibration • Driving scenario reconstruction
In5	Motorway Traffic Data	• VTT database (Bjorvatn et al., 2021)	• Traffic scenario analysis • Scaling up of scenario effects

ID	Data Type	Example of the used data	Purpose
		• IRF traffic data (International Road Federation, 2023) • NDW data (National Road Traffic Data Portal, 2023)	
In6	Infrastructure Data	• IRF road infrastructure data (International Road Federation, 2023) • OSM road infrastructure data (OpenStreetMap Foundation, 2023)	• Traffic Scenario Definition (e.g., number of lanes, speed limit, etc.)

As discussed previously in chapter 3.2.1, the safety impact assessment will apply assessment tools. Table 3.3 lists the tools used by different partners.

Table 3.3: Assessment tools used in the safety impact assessment.

ID	Tool name	Partner	Covered scenarios and approach	Reference/Link
T1	openPASS	BMW, TU Delft	Simulating driving and traffic scenarios Simulation approach B & C2	Eclipse openPASS
T2	Esmini	Chalmers	Simulating driving scenarios Simulation approach B	Esmini GitHub
T3	OpenTrafficSim (OTS)	TU Delft	Simulating driving and traffic Scenarios Simulation approach C2	OpenTrafficSim
T4	VISSIM	VTT, PTV, TNO	Simulating traffic scenarios Simulation approach C2	PTV VISSIM
T5	LSMS	TNO	Simulating traffic scenarios Simulation approach C2	Klunder et al., 2023
T6	In-house toolchains developed by partners	IKA, TU Delft, LAB	Simulating driving scenarios Simulation approach B & C2	-
T7	ERiC	VTT	No simulations (Purpose scaling up)	For details see below.

ERiC Tool (T7)

The scaling-up process transforms the different effects estimated for single scenarios into an estimate of the annual safety impact on European level. The assessment of numerical safety effects in the European accident data will involve the ERiC (European risk calculation) tool (see e.g., Silla et. al. 2017; Malone et al., 2014), which derives from the assessment method of Kulmala (2010). The safety impact assessment using ERiC follows the earlier mentioned theoretical background of Nilsson (2004), according to which traffic safety has three dimensions. The method was adapted for the AD context in L3Pilot (L3Pilot D3.4 by Innamaa et al., 2020 and L3Pilot D7.4 by Bjorvatn et al., 2021) and is being applied in Hi-Drive considering the integration of the technological enablers of driving automation.

Scaling up with ERiC requires concrete values for changes in the frequency, risk, and severity of accidents (i.e., the effects) for different types of accidents, and the number of target accidents to which these changes apply.

For determination of the number of target accidents by accident type, information about the system and its use is utilized to determine whether an accident could be affected by the system. The information is compared against the values of the available descriptive variables of the accident database, and if any of the values indicate that the accident took place when the system could not be active, the accident is ruled out as a target accident. The remaining accidents are the target accidents.

The number of target accidents for different scenarios and changes in the frequency, risk, and severity of those accidents are inserted into the scaling-up formula developed for AD in L3Pilot (D7.4 by Bjorvatn et al., (2021)):

$$T_{Prevented,i,p} = \sum_j \left(T_{total,j} \cdot \Delta f_{j,p} \cdot \Delta r_{total,j,p} \cdot \frac{A_{i,AT}}{A_{total,AT}} \cdot \Delta s_{i,j,p} \right) - \sum_j T_{i,j}$$

where

$T_{total,j}$ = Number of target accidents in total (injury accidents of all severities: slight, serious, fatal) for driving scenario *j* in the area for which the scaling up is done

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

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

$\frac{A_{i,AT}}{A_{total,AT}}$ = Proportion of accidents of severity *i* of injury accidents of all severities for target accident type (*AT*) in driving scenario *j*

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

$T_{i,j}$ = Number of target accidents in total with severity *i* for driving scenario *j* in the area for which the scaling up is done

This produces the number of accidents prevented in the area for which the scaling up is done for the given severity (*i*) and penetration rate (*p*).

The introduction of new technologies may create new accident causes not yet present in today's traffic. For these, there are no target accidents in the accident databases. Instead, the frequency of these accidents needs to be estimated. The number of accidents per severity and penetration rate is evaluated with the formula

$$T_{New,i,p} = \sum_{j \in N} TR_{total,EU} \cdot \left(\Delta rR_{total,j,p} - 1\right) \cdot VKT_{j,p} \cdot \frac{A_{i,j,p}}{A_{total,j,p}}$$

where

N = Driving scenarios that can cause new accidents (e.g., minimum risk manoeuvre)

$TR_{total,EU}$ = Injury accident rate of the target accidents (injury accidents of all severities: slight, serious, fatal) within the ODD

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

$VKT_{j,p}$ = Vehicle kilometres travelled (VKT) driven under influence of driving scenario *j* for penetration rate *p*

$\frac{A_{i,j,p}}{A_{total,j,p}}$ = Proportion of accidents of severity *i* of injury accidents of all severities for target accident type (*AT*) in driving scenario *j*

$A_{total,j,p}$ = Total number of injury accidents for driving scenario *j* for penetration rate *p*

This produces the number of new accidents of given severity (*i*) and penetration rate (*p*). The total impact in the scaling-up area is the sum of the prevented accidents and new accidents.

$$Impact_{i,p} = T_{Prevented,i,p} + T_{New,i,p}$$

3.2.3 ADFs and enablers covered

Based on the overall considerations described in chapter 3.1.2, use cases and enablers that will be covered by the safety impact assessment have been defined as represented in Table 3.4. An important consideration for the assessment of safety impacts is that for the BADF a system needs to be considered that is safe enough for operation on public roads and thus is assumed to have gone through proper safety assurance and already provides a high level of traffic safety. The scenarios that are added to the ODD of the EADF compared to the BADF mainly aim at increasing the operation time of the ADF (i.e., longer and more frequent usage of the ADF). This might not necessarily change the traffic safety level in driving scenarios but is considered in the exposure part of the safety impact (scaling up). Only those enablers that have a direct impact in the scenario (e.g., changed driving strategy compared to BADF, significantly improved perception performance) are considered in the simulation. An overview is given in Table 3.4.

Table 3.4: Consideration of use cases in safety impact assessment and related enabler categories.

Use case grouping for impact assessment	Use Case as defined in D3.1	Consideration in Safety Impact Assessment	CAD Connectivity	CAD High Precision Positioning Techniques	CAD Machine Learning Techniques
Cooperative Merging	M2 - Cooperative Lane Merging at motorway entry via V2V [AV drives on the on-ramp area (2 actors)]	Simulation	Y	Y	N
	M3 - Cooperative Merging Awareness at Motorway entry via V2V [AV drives on the motorway (2 actors)]	Simulation	Y	Y	N
	M4 - Cooperative Lane Merging at Motorway entry with lead vehicle via V2V [AV drives on the on-ramp area (3 actors)]	Simulation	Y	N	N
	M5 - Cooperative Merging Awareness at Motorway entry with lead AV vehicle via V2V - AV drives on the motorway (3 actors)	Simulation	Y	N	N
Non-cooperative merging	M18 - Lane Merging on motorway entry	Scaling up	N	N	Y
	M19 - Passing motorway entry and allowing other vehicles to merge	Scaling up	Y	Y	Y
V2V for speed adaptation	U7 - Cooperative speed adaptation applicable downstream via V2V	Not covered	Y	N	N
GLOSA	U4 - Smart traffic light crossing	Not covered	Y	Y	N
	U5 - Consecutive traffic light crossing	Not covered	Y	Y	N

Use case grouping for impact assessment	Use Case as defined in D3.1	Consideration in Safety Impact Assessment	CAD Connectivity	CAD High Precision Positioning Techniques	CAD Machine Learning Techniques
I2V for Hazard notification	M8 - Cooperative Hazard Awareness and Avoidance (lane changing or speed adaptation required)	Not covered	Y	Y	Y
	U6 - Cooperative re-routing to avoid congestion or hazard in front	Not covered	Y	N	Y
I2V for dynamic road signage	M9 - Cooperative Dynamic Signage Awareness (lane changing or speed adaptation required)	Not covered	Y	Y	Y
Driver Monitoring	*Not defined as a use case in D3.1 but explicitly considered in impact assessment*	Scaling up	N	N	Y
Adding Infrastructure Elements	M10 - Driving through a tunnel	Scaling up	Y	Y	Y
	M15 - Approaching elevated bridge	Scaling up	Y	Y	Y
	U1 - Cooperative non-signalized intersection crossing via V2X	Baseline ADF or modelled (scenario dependent)	Y	N	Y
	U2 - Cooperative non-signalized roundabout crossing via V2X (focus on conflicts between CAV and other vehicles)	Modelled	Y	N	Y
	U11 - Urban canyon driving	Scaling up	Y	Y	N
	U14 - Crossing intersection with left or right turn	Baseline ADF or simulation (scenario dependent)	Y	Y	Y
	M11 - Driving through a road construction zone	Scaling up	N	Y	N
External HMI	U15 - eHMI interaction on straight road segment towards the driver of the following vehicle	Not covered	Y	N	N

Use case grouping for impact assessment	Use Case as defined in D3.1	Consideration in Safety Impact Assessment	CAD Connectivity	CAD High Precision Positioning Techniques	CAD Machine Learning Techniques
	U16 - Interaction with VRU via eHMI on straight road segment (w/wo zebra crossing)	Not covered	Y	N	N
V2V for overtaking	M1 - Cooperative Overtaking via V2V with rear vehicle	Not covered	Y	Y	Y
Lane exiting	M6 - Cooperative Lane Exiting via I2V	Not covered	Y	Y	Y
	M17 - Lane exit/interchange from one motorway to next motorway (navigation system available)	Scaling up	Y	Y	N
Motorway basic scenarios	M12 - Support of basic set of scenarios in lane keeping mode: Free Driving, Car following, Passive cut-in	Baseline ADF	Y	Y	Y
	M13 - Lane change	Baseline ADF	Y	Y	Y
Challenging ODD	M14 - Driving in lane under rain/fog/heavy rain	Scaling up	Y	Y	Y
	M16 - Driving through areas affected by GNSS interruption or map inconsistencies or deteriorated lane markings	Scaling up	Y	Y	Y
Urban basic scenarios	U3 - Smart intersection crossing (RSU and connected vehicles)	Not covered	Y	N	N
	U9 - Support of basic set of scenarios: Free driving / Car-Follow / Cut-in	Baseline ADF	Y	N	Y
	U10 - Lane changing / Overtaking	Baseline ADF	N	N	Y
	U12 - Driving in rainy weather or with missing lane markings	Scaling up	N	N	N
	U13 - Pedestrian crossing (w/wo zebra crossing)	Baseline ADF	Y	N	Y

Some relevant considerations for the scope of the safety impact assessment are:

- Intersections in urban areas are ODD elements considered to be included for both BADF and EADF. It is assumed that the BADF is already capable of handling these scenarios in a safe manner, since an ADF according to regulation needs to reach a very high safety standard. Despite the safe behaviour of the BADF there are other traffic participants which, especially at intersections, may not always be within its field of view, making their behaviour unpredictable to the BADF. These situations are where an EADF with an extended sensor view could provide a safety benefit. Additionally, advancements in the EADF might allow better handling of intersections in urban areas, such as approaching at higher speeds or taking earlier decisions to brake. This could increase the traffic throughput and level of comfort. In conclusion, most turning scenarios will be covered by the BADF simulation, and the EADF simulation will only be considered for the simulated driving scenario 04|14 "Interacting - vehicle turning left when other vehicle going straight".
- Roundabouts are only considered for the EADF, as they are not expected to be part of the BADF. The decision is based on experience with the ADFs in L3Pilot (representing BADF) and in Hi-Drive (representing EADF).
- Hazard notification is an important feature of realizing a safe ADF operation. The question is how the information is transferred to the vehicle. The BADF is considered to be able to handle hazards safely, either by means of its onboard sensors or via backend communication. Even if the vehicle relies on onboard sensors, it must be assumed to be able to handle such situations, for example through speed adaptation or a dedicated driving strategy. For the EADF, V2I and V2V communications are considered in addition. Whether and to what extent the V2I and V2V aspect provides additional benefits in terms of traffic safety—which would be expressed in a decrease of simulated crashes—is a matter that needs to be assessed on scenario level. Different scenarios have been discussed qualitatively to understand the potential impacts of earlier information via V2I. However, only rare configurations of scenarios were identified in which the BADF would crash without the enabler. Given the significant effort required to simulate these scenarios and the lack of adequate driver models, it was decided not to consider these driving scenarios for simulations.
- Although external HMIs are assumed to increase people's trust in automation and to enable a safe and smooth interaction between VRUs and ADFs, these will not be considered in the safety impact assessment. The reason is that there are no appropriate and available safety assessment methods with which to quantify the safety impact of ADFs with and without eHMI. Nor will the experiments in Hi-Drive involve constructing them. Furthermore, the safety impacts of this technology may be relatively small, as AD vehicles

are likely to be able to avoid collisions in situations with confusion about intent, which are likely to occur several seconds before a potential collision and are therefore avoidable. For situations that are unavoidable because the VRU overlooked the vehicle, no technology will help if the vehicle is not seen, as the eHMI is then not seen either.

Note: The use cases are described within Hi-Drive based on preliminary plans for public road and test track operations with Hi-Drive prototype vehicles. The description covers all the scenarios being tested within Hi-Drive but not all potential scenarios in which the enabler could have safety impacts. This lack of input for scenarios outside of Hi-Drive cannot be overcome in the Hi-Drive safety impact assessment. Nevertheless, it might a topic for consideration in future projects.

3.2.4 Scenarios

3.2.4.1 Traffic scenarios in the safety impact assessment

Traffic scenarios to be simulated in the safety impact assessment aim to represent the traffic network in Europe. Thus, the European road network will be analysed. Since the analysis is still ongoing, the starting point for Hi-Drive will be the scenarios defined in L3Pilot (Bjorvatn et al., 2021).

For motorways, the scenarios will cover a combination of different road infrastructure and traffic parameters:

- Number of lanes: 2 and 3
- Traffic volume: 250, 500, 1000, 1500, and 2000 veh. per lane per hour
- Speed limit: 80 kph, 100 kph, 120 kph, 130 kph, 140 kph, 55 mph, 70 mph, and unlimited

The urban traffic scenarios are still under discussion.

3.2.4.2 Driving scenarios in the safety impact assessment

Analogous to the classification in the technical evaluation, the driving scenarios have been split into five categories: driving in lane, lane change, crossing, turn left, and turn right. The category name refers to the action of the ego vehicle in this scenario. The full list of driving scenarios for each category is provided in Annex 4. The list focuses primarily on use cases relevant to Hi-Drive. Scenarios beyond the scope of Hi-Drive may exist but have not been considered for the assessment.

3.2.5 Evaluation plan per research question

In this chapter, the building blocks explained in chapters 3.2.1 – 3.2.4 are combined to describe the assessment approach per research question. For each research question the approach is summarized in a table (Table 3.5 – Table 3.8).

Table 3.5: "What is the impact of AD and its enablers on safety in different driving scenarios?" (Evaluation plan)

What is the impact of AD and its enablers on safety in different driving scenarios?	
Approach	**1.** Direct scenario effects: simulation of driving scenarios to derive the direct impact on the traffic scenario in terms of crash risk and crash severity (simulation tools T1, T2, T3, T5; T6, see Table 3.3) **2.** Direct traffic effects: simulation of traffic scenario to derive changes in the occurrence frequency (exposure) of driving scenarios (T1, T4, T5)
Data	**1.** Driving Scenario parameters: In2, In3, In4, In6; see Table 3.2. **2.** Traffic scenario parameters: In4, In5, In6 **3.** Definition of ADF and other models: D4, D5
Process	**1.** Definition of driving and traffic scenarios **2.** Parametrization of scenarios, and definition and implementation of the BADF, EADF, and ADAS to be simulated **3.** Simulation of driving and traffic scenarios or performing expert judgment for the effects in non-simulated scenarios **4.** Estimating the crash risk and crash severity from driving scenario simulations by means of IRF **5.** Using the occurrence frequency estimates of driving scenario and vehicle kilometres travelled to adjust for exposure
Outcome	**1.** Direct scenario effects: **a.** Differences between fully manual driving, ADAS, BADF, and EADF in terms of crash risk (number of crashes / number of simulations) per driving scenario **b.** Differences between manual driving, ADAS, BADF, and EADF in terms of crash severity (property damage, crashes with slight, serious, and fatal injuries) per driving scenario **2.** Direct traffic effects: Change of occurrence frequency per vehicle kilometres travelled / time (i.e., exposure) for different penetration rates of BADF and EADF

The approach to assessing the direct impacts of ADF in combination with enablers (EADF) or the contribution of enablers follows the approach given in Figure 3.4. Overall, 60 driving scenarios plus traffic scenarios are considered for the assessment of direct effects (see chapter 3.2.4). The assessment will be done mainly by simulation. The simulations will be conducted by different partners depending on the simulation approach, the available tools/models, and available data. With respect to the different road environments the safety impact assessment aims to simulate 20 driving scenarios for the motorway and 37 driving scenarios on urban roads. In addition, the safety impact assessment aims to simulate 20 driving scenarios on rural roads to investigate the secondary effects of ADF, since the ADF with additional needed sensors will facilitate also more advanced ADAS systems in the vehicles that are equipped with ADF. Thus, for rural roads no ADF will be simulated as the ODD of the ADF considers only motorways and urban environments. The rural road simulations focus only on ADAS and manual baselines. To complete the picture, three driving scenarios on a motorway, 15 on urban roads and 10 on rural roads will be assessed based on expert judgment. The results of the traffic assessment in terms of crash risk, severity, and frequency of driving scenario are input into the next research question.

Table 3.6: "What is the impact of AD and its enablers on safety at European level?" (Evaluation plan)

What is the impact of AD and its enablers on safety at European level?	
Approach	Scaling up of scenario-specific effects to European level with ERiC (T6)
Data	CARE (In1), national (In1) and in-depth accident (In3) data
Process	**1.** Map simulated scenarios to accident types **2.** Determine target accidents of the systems assessed **3.** Calculate the impact of the technology on prevented accidents **4.** Calculate the impact on new accidents
Outcome	Number of prevented injury accidents annually in the EU by severity

In Hi-Drive, we scale up to European level (EU27) the direct effects produced by the driving scenario and traffic scenario simulations (see chapter 3.2.4), complemented with expert judgement on effects in scenarios not covered by simulation. The systems in question are the BADF, EADF, and ADAS as described in Table 3.1. They are assumed to be mixed into traffic with manual vehicles with different penetration rates for the ADF and the ADAS in use for passenger cars. The main accident data used for the scale-up is the European wide CARE accident database.

The socio-economic impact assessment follows the "snapshot" approach (for details, see chapter 4), where the AD system with the given penetration rate is introduced. As the scaled-up safety impact assessment results will be used as input in the socio-economic impact assessment, the same approach is used here. Thus, the accident statistics are taken as is. That is, the approach does not estimate how many years it may take to reach the respective penetration rates, nor does it consider other changes to the transport system in that time (and their impact to traffic safety), with one notable exception—the introduction of (by law) mandatory ADAS across the EU from 2024. That is, the socio-economic snapshot approach employed will consider the introduction of such systems.

The year of the accident data will be the most recent one available at the time of the evaluation. However, if accident data from some countries for 2022 or later are not yet available, for those countries an earlier year, either 2019 or the latest one before that, will be used. This is to avoid unusual situations that arose during the Covid-19 pandemic affecting the results.

In the scaling-up process, first, the accident types of CARE are mapped to the simulated driving and traffic scenarios. The finished mapping will point out the accident types that cannot be considered by simulations, the accident types that can be the outcome in multiple driving scenarios, the driving scenarios that are applicable to multiple accident types, and, in the case of multiple different types of simulation tools or approaches used, any possible missing changes in frequency, risk, or severity for any of the accident types. The missing changes will be complemented with information from the literature and by expert judgement. After this, the mapping is complete and will show the final plan on how the safety impact is assessed for each of the accident types.

The ODD specifications of BADF, EADF, and ADAS of Hi-Drive will be compared against the values of the descriptive variables of the accidents in CARE, to form the rules for determining whether an accident took place inside or outside the ODD for each of these systems. This determination will result in the selection of the target accidents in the assessment. The target accidents for the BADF in urban and motorway environments will be a subset of the target accidents for the EADF, which in turn is a subset of all the accidents that have taken place in the given environment. For the ADAS system of a car equipped with BADF or EADF, the target accidents will be a subset of the total rural accidents and other accidents outside the ODD of the ADFs. For the ADAS of cars not equipped with BADF or EADF, the target accidents are defined also inside the ODD of the ADFs.

The CARE accident database does not contain perfect information for each of the accidents reported in it. Instead, it has some limitations, for example, in terms of quality and availability of the data used to describe the accidents. Hence, if deemed necessary, and if data is available, the CARE data will be complemented with national (possible in-depth) road accident statistics before the data is processed to calculate the target accidents. This is unlikely to solve every issue found in the data. Thus, during the processing of the accident data, the remaining unknown or missing values will be solved by using the distributions of the known values from the more complete accidents.

The total impact will consist of prevented accidents (calculated from the comparison of number of accidents between baseline and treatment) and potential new accidents. First, to calculate the prevented accidents, the formula described in chapter 3.1.3.1 will be applied to both the BADF and EADF in the urban and motorway environments separately, and for the ADAS system in the rural environment and elsewhere outside the ODD. For each of these system and environment combinations the process will result in the percentage and number of prevented

- fatal accidents
- accidents with serious injuries
- accidents with slight injuries

on European level inside

- the nominal ODD
- the ODD extension
- the extended ODD (i.e., combination of the nominal ODD and the ODD extension)

and of all accidents, for each of the chosen penetration rates.

ADFs can create new accidents that do not generally happen in traffic today, for example by executing a minimum risk manoeuvre[9]. The technological enablers of the EADF could affect the frequency, risk, or severity of these accidents. Thus, the formula for new accidents (see chapter 3.2.1.3) will be applied to both the BADF and EADF simulation results of the driving scenarios where these new accidents could occur. Thus, the effect of the enablers can be studied for the new accidents. The enablers may affect the frequency of the driving scenarios, leading to new accidents and/or accident risk per scenario.

The total impact is the sum of prevented and new accidents. This will demonstrate the safety impact of the EADF compared to manual driving, and to the contribution of the enablers to

[9] Accidents can also result due to technical failures of the ADF. These accidents are not investigated in the Hi-Drive safety impact assessment, since it is expected that a market-ready ADF will achieve a technology maturity at which such accidents are much rarer events, since manufactures have implemented technical measures to reduce these failures to a technical feasible limit.

the impact by accident severity. These results will be supplemented by the qualitative assessment of indirect impacts.

Table 3.7: "What are the indirect impacts of AD and its enablers on safety?" (Evaluation plan)

What are the indirect impacts of AD and its enablers on safety?	
Approach	Nine safety impact mechanisms, qualitative assessment, mechanisms 3-9
Data	Literature review (mechanisms 3-4, 9), input from mobility impact assessment (mechanisms 6-8)
Process	**1.** Define impact mechanisms relevant for technology tested in Hi-Drive **2.** Define questions relevant per mechanism **3.** Review of results related to these questions **4.** Description of expected changes in vehicle, driver, and road user behaviour by mechanism **5.** Qualitative assessment of the direction and magnitude of the safety impact
Outcome	Direction: Positive, negative Magnitude: Small, medium, large

The nine impact mechanisms (chapter 3.1.3.1) are used to cover all dimensions of traffic safety. The first two research questions present the approach for assessing direct impacts (IM1 "Direct modification of the driving task, driver behaviour, or travel experience", IM2 "Direct influence by physical and/or digital infrastructure", IM5 "Modification of interaction between AVs and other road users?"). The impacts of other mechanisms (IM3, IM4, IM6–IM9) are addressed in the third research question (see Table 3.8). The assessment first consists of defining the mechanisms. Then the expected changes in vehicle, driver, and road user behaviour are described and documented for each mechanism. This will be done based on the results of Hi-Drive's safety simulations, other Hi-Drive evaluation results (e.g., mobility impact assessment, user evaluation), findings from previous studies, and expert assessment by experts involved in Hi-Drive's safety impact assessment. Table 3.8 gives an overview of the questions to be answered per indirect mechanism.

Table 3.8: Relevant topics and input data per indirect impact mechanism.

	Examples of relevant topics	Input data
IM3	• What are the (long-term) impacts of change in driving skills? • What are the (long-term) impacts of behavioural adaptation in driver behaviour of the users of AV (when driving in non-ADF mode)? • What are the impacts of unintended use of AV?	Hi-Drive user evaluation, literature review, expert judgement
IM4	• What are the impacts of the behavioural adaptation of other road users (i.e., imitation of AV driver behaviour)?	Hi-Drive user evaluation, literature review, expert judgement
IM6	• What are the impacts on the number of journeys? • What are the impacts on the length of journeys?	Mobility impact assessment (chapter 3.4)
IM7	• What are the impacts on use of different transport modes / transport mode share?	Mobility impact assessment (chapter 3.4)
IM8	• What are the impacts of AVs' routes being different from those of the baseline?	Mobility impact assessment (chapter 3.4)
IM9	• What are the impacts of the AV design being different? • What are the impacts of AV including more passive safety systems?	Hi-Drive safety simulations, expert judgement

3.3 Efficiency and environmental impact assessment plan

3.3.1 Methodology and research questions

The objective of the efficiency and environmental impact assessment is to estimate the potential impacts of ADFs and relevant enablers on traffic flow, energy demand, and emissions. The efficiency and environmental (E&E) impact assessment considers AD both on motorways and in urban areas. These will be assessed in enabler-specific scenarios, road-type-specific scenarios, as well as on the European level. This process will provide the necessary inputs to the socio-economic impact assessment.

The high-level research question is subdivided into three medium-level research questions:

- What is the impact of AD and its enablers on energy demand, emissions, and traffic efficiency *in different scenarios*?
- What are the *indirect* impacts of AD and its enablers on energy demand, emissions, and traffic efficiency?
- What is the impact of AD and its enablers on energy demand, emissions, and traffic efficiency *at European level*?

The main method for E&E impact assessment is microsimulation of traffic scenarios. The simulations provide values for the indicators of interest for traffic efficiency assessment, while their output in terms of vehicle trajectory data is used to estimate the changes in energy demand and emissions with suitable tools.

Direct impacts describe the impacts arising from the changes in driving behaviour and traffic dynamics that are caused by the introduction of AD and its enablers into traffic. These changes are measured using performance indicators, such as average travel time, delay, energy demand, and CO_2 emissions per VKT.

Indirect impacts refer to those impacts and changes that cannot be directly modelled using traffic microsimulation but are derived from secondary impacts related to other impact areas such as changes in route choice or number of accidents. For example, accident-induced congestion may slow down traffic flow considerably, but as accidents are not modelled in the traffic simulation, their effects in traffic cannot be estimated directly.

The experimental setup, as specified in chapter 3.1.3.2, will include a baseline without AD and a baseline with the specified penetration rates of the BADF (10% and 30%), and a treatment with 10% and 30% of EADF. In addition, impacts may also be assessed for higher penetration rates, for example in enabler-centric scenarios, as the impacts of some use cases might only show at higher penetration rates.

The inclusion of ADAS in traffic today and the mandatory ADAS will be decided for this impact area in a later phase. It is not expected that either will have a large impact on efficiency and environmental indicators, with the exception of ACC (Adaptive cruise control, ADAS in traffic today) and Intelligent Speed Assistance (ISA, mandatory ADAS), which can potentially cause changes to the desired speed and time gap distributions. Reliable empirical estimates on these changes are needed as a prerequisite for including these systems in simulations.

The assessment of efficiency and environmental impacts is mainly based on two types of traffic scenarios: target scenarios specific to a use case and related enabler (”enabler-centric scenarios”) and relatively small networks or road sections, which represent certain types of roads overall ("road-type-centric scenarios"). Enabler-centric scenarios are designed to assess the impacts of enablers in sole use cases in relevant traffic scenarios, while road-type-centric scenarios aim at achieving the overall impacts of EADF in different road types and traffic compositions, used also for scaling up the effects to European level. The networks intended for scaling up include urban and motorway scenarios. These scenarios are detailed in chapter 3.3.4.

To answer the research question on impacts at European level, results from microsimulations are scaled up, covering the target year specified by the socio-economic assessment. First, for each road-type-centric scenario, the VKT is determined for the most common conditions in which the vehicles travel in Europe. Then, the results from microsimulations on the effect size in different traffic scenarios are allocated to the corresponding conditions. A similar process is used both for motorway and for urban environments. A simplified illustration of the efficiency and environmental impact assessment is depicted in Figure 3.6. The process is further detailed in chapter 3.3.5.

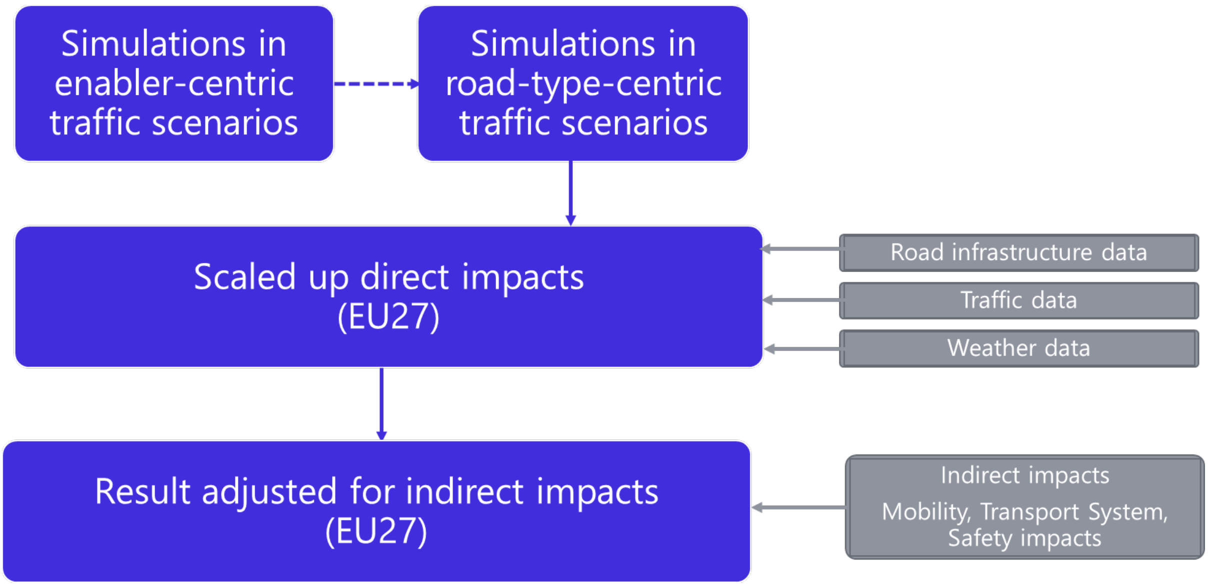

Figure 3.6: Simplified methodology for efficiency and environmental impact assessment.

3.3.2 Assessment tools and input data

Different assessment tools and input data will be used for the purpose of E&E impact assessment in Hi-Drive. To produce consistent results, all traffic simulations will be done in PTV Vissim, and in cases where this is not suitable for simulating specific scenarios, other tools might be used instead. Emissions will be calculated with EnViVer. Custom scripts will be used to calculate tractive energy demand in specific scenarios based on the trajectories from

Vissim. An overview of the assessment tools in the efficiency and environmental impact assessment is presented in Table 3.9.

Table 3.9: Overview of assessment tools for efficiency and environmental impact assessment.

Tool	Purpose
Traffic microsimulation tool PTV Vissim	Efficiency impacts in specific scenarios, trajectories as input for energy and emissions calculation
Emissions calculation tool EnViVer (Eijk et al., 2014, available for PTV Vissim)	Calculating CO2 emissions in specific scenarios
Custom scripts	Calculating energy demand in specific scenarios

Also, in order to achieve reliable results, sufficiently comprehensive input data are needed for designing the simulation experiments and calibrating the models. These data will include, but are not limited to, the description of ADFs and their enablers including the specifications of ODD, vehicle fleet statistics, road infrastructure data, traffic volumes, VKT information, and weather data across European countries, and results from other impact assessment areas where needed. A summary of the input data and their main purposes is provided in Table 3.10.

Table 3.10: Input data for designing the simulation experiments and calibrating the models.

Input	Purpose
EADF and BADF descriptions	Building simulation models
ODD specification	Creating traffic scenarios, scaling up of results
Vehicle fleet statistics	Representative European vehicle fleet in the baseline year
Road infrastructure data (OpenStreetMap)	Creating representative traffic scenarios
Traffic volumes and total VKT per type of environment (statistics)	Creating representative traffic scenarios, scaling up of impacts per VKT
Weather data (Muñoz Sabater 2019)	Defining VKT in weather ODD
Results from mobility and transport system impact assessment	Adjusting scaled-up estimates with changes in VKT by passenger cars on motorways and in urban areas
Results from safety assessment	Adjusting scaled-up estimates with information on changes in accident-induced congestion

3.3.3 ADFs and enablers covered

The E&E impact assessment considers the urban and motorway ADFs. The assessment of the impact of different enablers will be done by use case. A subset of the use cases chosen for impact assessment was selected for the E&E assessment. The covered enablers and use cases had to be feasible for modelling with microsimulation and have sufficient efficiency and/or environmental impact according to their potential impact mechanism. An initial estimate on the effect size was made by the E&E assessment group to decide whether or not a use case is included. The determining factors for inclusion were the expected impact mechanism, impact size and direction, and the expected difficulty of implementing the use case and related scenarios in simulations. The use cases are introduced in the following chapters and a summarizing table is presented in Annex 5.

There are two main approaches for addressing the impact of ADF and its enablers in a specific use case: simulation and scaling up. *Simulation* means that the effects are studied with traffic simulation in two types of traffic scenarios: enabler-centric and road-type-centric scenarios. *Scaling up* means that the impacts of the EADF will be scaled up from the road-type specific scenarios to the EU27 network. For some enablers, no differences in driving behaviour between the BADF and EADF are expected, but the use case allows driving in automated mode in EADF. In these cases, the impact of the use case can be assessed in the scaling up process and there is no need for separate simulations of the effect.

If sufficient effects are found in the enabler-centric scenario simulations, the corresponding use case and related enabler will be incorporated into road-type-centric traffic scenarios. In that case, the use cases and related enablers will also be included in the scaling-up process provided that sufficient data is available on the prevalence of the conditions addressed by the use case on the European urban road and motorway networks.

3.3.3.1 Use cases addressed by simulation

Cooperative merging

Cooperative merging via V2V communication enables seamless interaction between automated vehicles to enable efficient merging operations among multiple vehicles at on-ramps of motorways. It allows vehicles with the EADF to exchange real-time information about their intentions, positions, speeds, or trajectories, facilitating a more accurate understanding of the surrounding traffic environment. Cooperative merging may improve traffic flow near on-ramps if potential disturbances caused by the merging process can be avoided or reduced.

GLOSA

Green Light Optimal Speed Advisory (GLOSA) is a traffic management solution designed to optimize vehicle speeds in the vicinity of traffic signals, promoting a smoother and more efficient flow of traffic. This enabler utilizes V2I technology to provide a speed recommendation to drivers or AD, enabling them to reach the traffic signal during its green intervals or to brake smoothly at a red interval. Implementing GLOSA can potentially reduce traffic congestion and travel times by optimizing vehicle movements before and within intersections. Moreover, by minimizing the stop-and-go events near intersections, it can contribute to a reduction in fuel consumption and vehicular emissions.

I2V – Dynamic Road Signage

Infrastructure-to-vehicle (I2V) communication enables the exchange of information between road infrastructure and vehicles. One application of I2V communication is dynamic road signage, which facilitates the real-time transmission of road sign information to a vehicle's dashboard or driver assistance systems. Incorporating dynamic road signage through I2V communication is expected to lead to a more efficient way for automated vehicles to receive and process essential traffic information. Vehicles could adapt their driving behaviour in response to changing road conditions, such as incidents. With real-time information guiding vehicles to adjust their speed, sudden braking and acceleration could be minimized. Thus, the enabler can lead to a lower number of lane changes, smoother braking, and timely reaction.

Adding infrastructure elements – Cooperative non-signalized intersection

Cooperative non-signalized intersection supports the ADF to decide on passing priority in complex infrastructure elements, such as road junctions, based on location, speed, and intention data exchanged between vehicles via cooperative messages instead of taking decisions using only on-board sensor data. Such a process may be beneficial in terms of traffic efficiency, as the passing priority is confirmed by the involved vehicles which can minimize the number of stops and gos and unnecessary conflicts. This may also reduce the frequency of drivers' interventions and take-overs, and thus increase drivers' comfort and trust.

3.3.3.2 Use cases addressed by scaling up

Some enablers are not expected to change the driving behaviour of the AV but enable the AV to drive in automated mode also in conditions where it would not be possible without the enabler. In these cases, simulations are not needed, but the effects will be considered in the scaling-up process. Extending the ODD of the AV means that a larger share of VKT is driven in automated mode.

The use cases planned to be addressed by scaling up only are:

- Adding infrastructure elements – Driving through a tunnel
- Adding Infrastructure Elements – Urban canyon driving
- Adding Infrastructure Elements – Driving through a road construction zone
- Challenging ODD – Driving in rain/fog/heavy rain, Driving through areas affected by GNSS interruption, map inconsistencies or deteriorated lane markings

The assessment of the impact for these use cases requires that reliable estimates can be found on the VKT driven in the added infrastructure elements and in the challenging ODD conditions listed above.

In addition, impacts of the use cases addressed with simulations will be scaled up if feasible. These use cases are:

- Cooperative merging
- GLOSA
- I2V for dynamic road signage
- Adding Infrastructure Elements – Cooperative non-signalized intersection crossing via V2X

3.3.3.3 Use cases not considered or considered via indirect impacts

Some of the use cases are not covered in the efficiency and environmental impact assessment. This can be due to different reasons: e.g., it is not expected that the use case has such an impact on traffic efficiency or emissions that can be detected with simulations, or the effort needed for implementing the changed driving behaviour in the traffic simulation may be too high. However, for some of these use cases, the results from the safety impact assessment might provide qualitative insights into the indirect impacts on E&E.

In order to study differences in the driving behaviour of human drivers, EADF, and BADF, detailed driver models are needed to accurately describe the behaviour. Given that traffic simulation models such as Vissim have been developed to reproduce traffic phenomena rather than accurately describe the movements of vehicles, the behaviour may not be detailed enough for all purposes. For example, lane change behaviour is generally difficult to model, and the differences between the lane changing processes of manual vehicles, BADF, and EADF would need to be implemented in detail. The use case of hazard notification would require modelling of hazards, their detection, and message relaying from infrastructure to vehicle. This is beyond the possibilities within the project.

The enablers not addressed in the efficiency and environmental impact assessment are:

- V2V for speed adaptation

- I2V for hazard notification
- Driver monitoring
- External HMI
- V2V for overtaking
- Lane exiting

3.3.4 Scenarios

As described above, the efficiency and environmental impact assessment is built on traffic scenarios. Two major traffic scenario types are considered: enabler-centric and road-type-centric traffic scenarios.

Enabler-centric traffic scenarios are needed for assessing the impacts of use cases and related enablers in environments very close to those for which they were designed. Thus, they provide an indication of the impacts of certain use cases within their target scenarios. By varying the conditions such as fleet characteristics and traffic volumes, criteria can be defined for conditions where the enablers provide benefits, negative impacts, or even no effects. Four enabler-centric scenarios are considered in the E&E impact assessment. Two of these are relevant for the motorway ADF and the other two for the urban ADF. If found relevant for efficiency or environmental impacts, the use case for an enabler will be included in the simulation of the road-type specific scenarios and the scaling-up process.

Road-type-centric, representative traffic scenarios, on the other hand, are used when assessing impacts of EADF and its enablers on different types of roads and at European level. These scenarios are small network parts that represent the most important elements of real motorway and urban networks in Europe. Simulations in these scenarios provide information on the impacts of the EADF on different types of urban streets and motorway sections. They help to identify on what kind of roads and in which kind of traffic situations benefits and disbenefits can be expected for efficiency and environmental impacts.

These two types of scenarios are described in the following two chapters.

3.3.4.1 Enabler-centric traffic scenarios

Cooperative merging

The simulated traffic scenarios will consist of a motorway section with two or three lanes and an on-ramp. The traffic volumes and composition of automated and manually driven vehicles will be similar to the road-type-centric motorway traffic scenarios. Figure 3.7 is a sketch of the network for simulating the V2V for cooperative merging in the efficiency and environmental impact assessment.

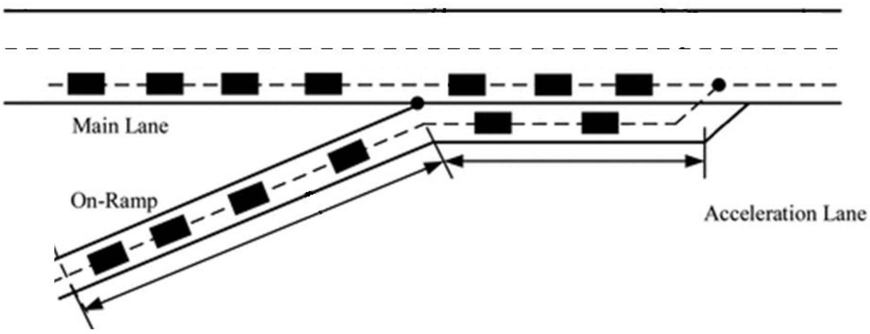

Figure 3.7: Sketch of the traffic scenario for simulating the V2V for cooperative merging.

The efficiency and environmental impact assessment will investigate two distinct scenarios of V2V-enabled cooperative merging: (1) a "passenger car" scenario with traffic consisting solely of passenger cars and (2) a "heavy truck" scenario with a traffic mix of heavy trucks and passenger cars in specific proportions. The two scenarios will be synchronized in terms of road network, traffic volumes, penetration of ADF and enablers, and coordination mechanisms, but will vary in the physical and dynamic attributes of the heavy- and light-duty vehicles. This setup will reflect the impact patterns of varying traffic compositions and provide further insight into how different types of ADF may affect future traffic differently.

GLOSA

For estimating the impact of GLOSA on traffic performance, a sufficiently long section is needed before an intersection, so that the effects of advisory information can be evaluated within the broadcasting range and on the upstream traffic approaching the intersection. Therefore, the simulated section should be long enough to provide space for the possible formed congestion, as well as for the transition range of the information transmitted by the V2I technology. Accordingly, each leg of the intersection will include two main sections in this enabler-centric scenario: one section representing the broadcasting range of the GLOSA system, and one relatively long section to allow the formation of congestion and studying the shockwaves when queues of vehicles are formed and spillbacks occur.

The designed road segments should have at least two or three lanes to account for the lane changes needed to follow the recommended speed by the GLOSA system. Different volumes of traffic, traffic signal cycle lengths and phasings, and penetration rates of AD systems will be simulated. A diagram of the scenario is depicted in Figure 3.8.

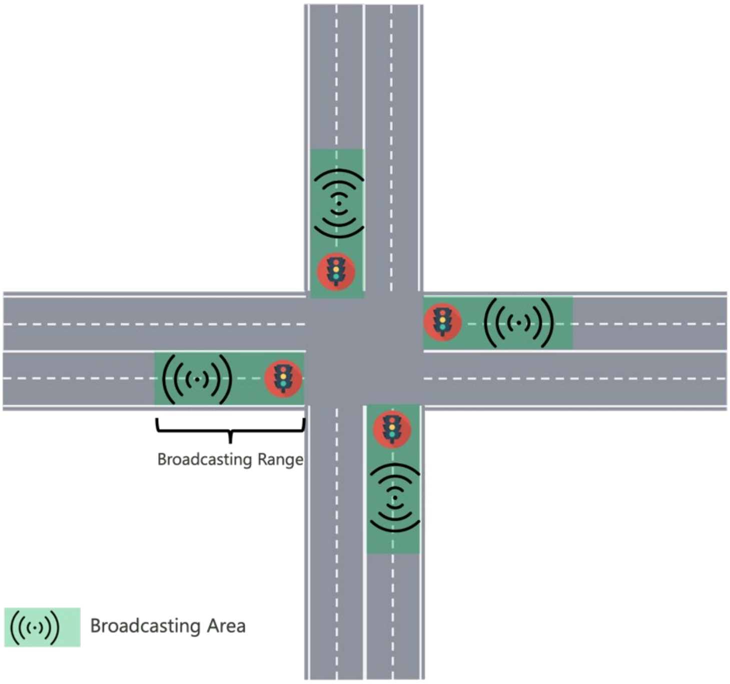

Figure 3.8: Schematic example of the GLOSA use case.

I2V for Dynamic Road Signage

For estimating the impact of an I2V solution for communicating dynamic road signage, a motorway with dynamic speed limits will be simulated. The dynamic speed signs are visible on matrix signs above the road. In the I2V scenario, vehicles receive the speed information directly in the vehicles and the vehicles immediately respond to it, while the human drivers and the BADF without I2V see the information and respond with a certain compliance, which is less strict than with EADF vehicles. In both cases also inaccuracies in the perceived/received speed information are possible.

The proposed motorway network is a motorway with multiple lanes. The traffic demand is medium or high such that congestion occurs and the dynamic speed limits are activated with speeds ranging from 90 km/h to 50 km/h.

Adding Infrastructure Elements – Cooperative non-signalized intersection

For estimating the impact of handling complex infrastructure elements, a traffic network involving an unsignalized intersection will be simulated. A sufficiently long section is needed before the intersection, for both the secondary and the main roads, to create space for possible formed congestion and for data to be exchanged between vehicles via cooperative messaging. Therefore, an unsignalized intersection is selected consisting of four segments. The designed road segments will consist of two lanes per direction on the main road and one lane per direction on the secondary road. Different volumes of traffic and penetration rates of AD will be simulated. A diagram of the scenario is depicted in Figure 3.9.

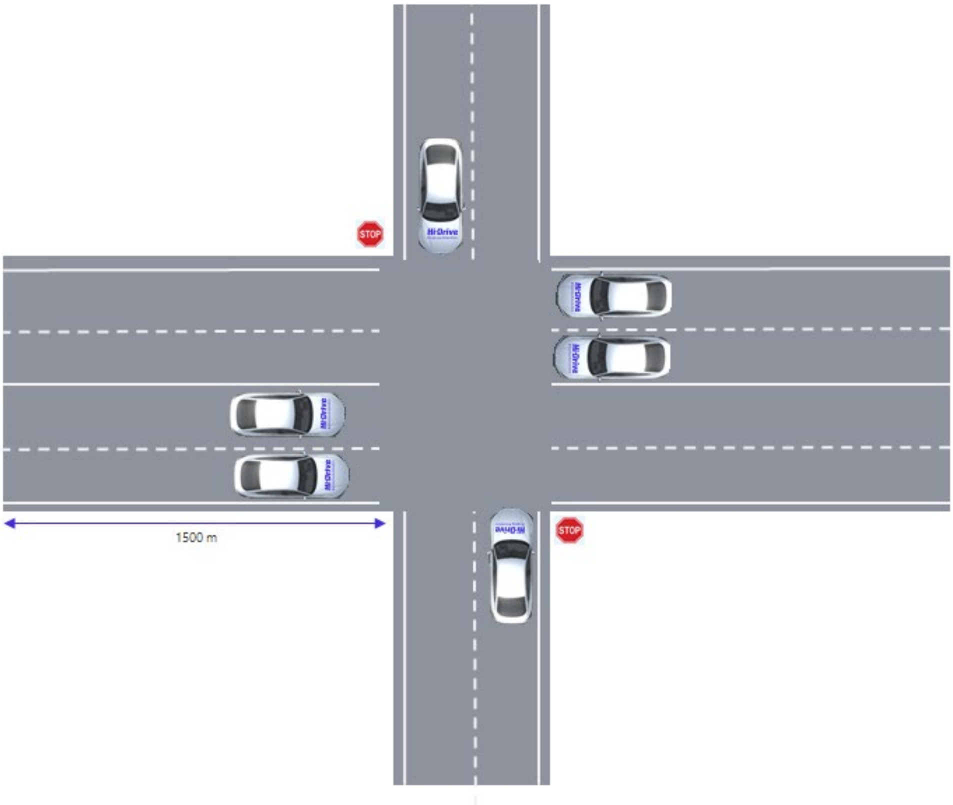

Figure 3.9: Schematic example of the use case Adding Infrastructure Elements - Cooperative non-signalized intersection.

3.3.4.2 Road-type-centric traffic scenarios

Motorways

Analysis results for the European motorway network, similarly as done in L3Pilot (Bjorvatn et al., 2021), will be used for creating traffic scenarios for simulation. These traffic scenarios will be designed to represent the European motorway network and will include different numbers of lanes, speed limits, and traffic volumes. Segments with and without on- and off-ramps will be considered. Heavy-duty vehicles and passenger cars will be included in the flow. An example of a motorway segment with three lanes per direction and an on- and off-ramp is shown in Figure 3.10.

Figure 3.10: Schematic example of a motorway section for traffic simulation. The section extends beyond the figure for about 1.5 km in both directions.

Urban areas

To cover the European urban network as much as possible, representative scenarios will be set up based on analysis of OpenStreetMap (OSM) data and the available traffic volume data.

Urban areas have higher complexity than motorways. In addition to traffic volumes, speed limits, and proportion of heavy-duty vehicles, other dimensions such as presence of pedestrians and cyclists, public transport, different intersection types, and infrastructural ODD need to be considered. For this reason, an analysis of urban networks will be made using OSM to find out the most prevalent road types. The road type selection for road-type-centric traffic scenarios will reflect attributes such as the category of roads in OSM (e.g., primary, secondary, tertiary roads), speed limit, intersection type, and typical link length. The selection of road types for simulation takes into account VKT on different types of roads. An example of an urban network is shown in Figure 3.11.

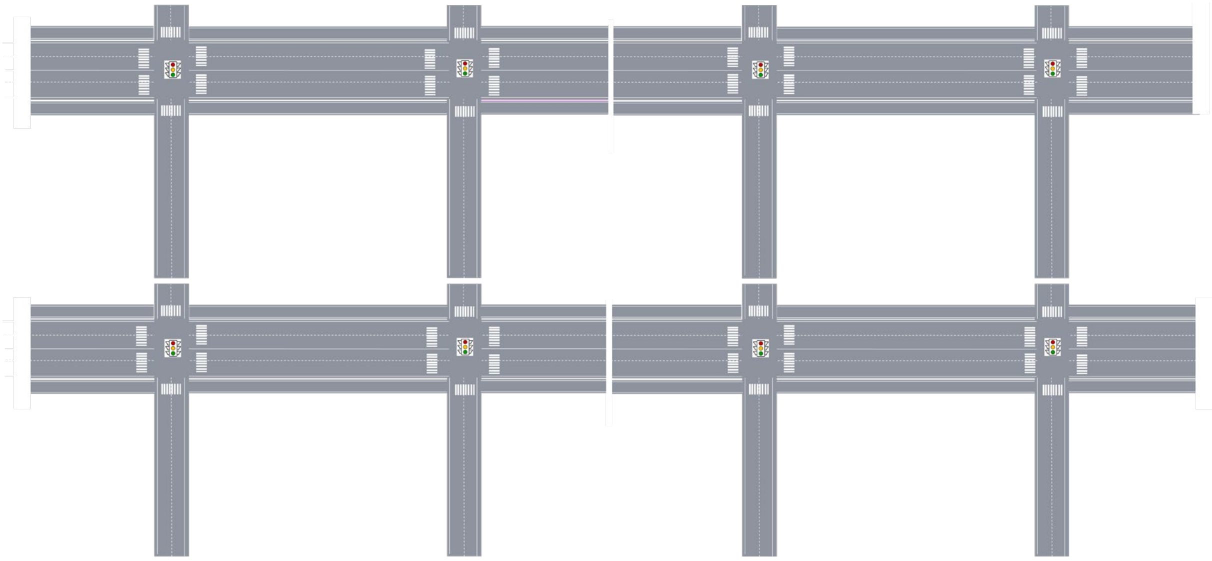

Figure 3.11: Schematic example of an urban network for traffic simulation.

3.3.5 Evaluation plan per research question

There are three main medium-level questions for each E&E impact area: energy demand, emissions, and traffic efficiency. The evaluation plan is set below for each of them.

3.3.5.1 What is the impact of AD and its enablers in different scenarios?

This research question will be answered by simulating two types of traffic scenarios: enabler-centric scenarios specifically built for testing the use cases and related enablers specified in the project, and road-type-centric scenarios. The scenarios are detailed in chapter 3.3.4.

The enabler-centric scenarios are built around four use cases: Cooperative merging, dynamic road signage, GLOSA, and complex infrastructure elements. In addition, road-type centric scenarios are used to determine the impacts of EADF and the enablers on the different network types most common in the EU.

First, relevant data for creating the enabler-specific and road-type centric traffic scenarios are collected. The process for designing the enabler-centric scenarios involves modelling the intended environment where the enabler will be used. This includes both the infrastructure required (e.g., roads, lanes and traffic lights) and the necessary traffic conditions to fully explore the impacts of the EADF. For the road-type-centric scenarios, map data will be analysed to specify the target network in terms of length per relevant attribute including speed limit, number of lanes, and intersection type. Based on the findings, several road networks will be built into Vissim, forming a set of representative networks per road environment. The traffic scenarios for each network type will be defined, varying the traffic volume among a set of typical levels. Both assessments will use the overall study design for baselines and treatments (from chapter 3.1.3.2), which will enable the comparison of human driving and BADF with EADF.

Next, the simulations will be performed for the manually driven baselines, with different penetration rates of BADF and EADF, with several repetitions per traffic scenario. Emissions and energy demand will be calculated based on vehicle trajectories from the simulations.

Finally, the effect sizes (average effect) per VKT will be calculated for each traffic scenario and network type combination. This link to VKT is necessary because some data are available on the total VKT on different road environments (urban areas and motorway) in Europe, but not on the total time spent travelling, total emissions, or total energy demand per environment.

3.3.5.2 What are the indirect impacts of AD and its enablers?

Indirect impacts refer to the impact mechanisms presented in chapter 3.1.3.1. They will be assessed qualitatively using the results from the safety, mobility, and transport system impact assessments and the literature where available.

The assessment of indirect impacts focuses on the impact mechanisms IM3, IM4, and IM6–IM9 (for details see chapter 3.1.3.1), as the simulations cover mechanisms related to the direct impact of modifications in driving behaviour and the influence of the physical and digital infrastructure, as well as the interaction between vehicles equipped with ADF and other road users.

Similar to the corresponding research question in the safety impact assessment, the process starts with the identification of relevant questions for the indirect impacts of ADF and its enablers under each mechanism. Hi-Drive results, especially on safety, mobility, and transport system impact assessment, are reviewed on these chosen focal topics. The literature is also reviewed to supplement the Hi-Drive results. Finally, a qualitative assessment of these findings is performed to assess the direction and magnitude of their effects on the overall impact on E&E.

3.3.5.3 What is the impact of AD and its enablers at the European level?

The results on the impacts of EADF, and on the contribution of enablers to these impacts, will be scaled up to EU27 level using the results from the traffic simulations in the road-type centric traffic scenarios and additional traffic and weather data. The process is similar but separate for both environments considered, motorway and urban. It follows the process set for motorways in L3Pilot (Bjorvatn et al., 2021).

Available traffic data will be collected and combined with map data for the specified level of aggregation (e.g., NUTS3 classification) over one year. In addition, information on the total VKT in EU27 urban areas and motorways for the target year will be collected.

Next, an estimate will be made of how much of the VKT accumulates inside and outside the ODD (nominal ODD of the BADF and extended ODD of the EADF). The VKT in each traffic scenario, including the share of VKT inside and outside the ODD per aggregation level (e.g., NUTS3), will be estimated. The ODDs of the BADF and EADF will be considered separately.

Next, the effect sizes per VKT will be combined with VKT estimates in each traffic scenario. In line with the snapshot approach, we assume in this step that the VKT does not change with the introduction of the ADFs. The result of this step is an estimate of the direct efficiency and environmental impacts of the EADF and the contribution of enablers on the European level.

In a final step, these estimates will be adjusted, where feasible, with indirect impacts derived from the safety, mobility, and transport system impact assessments, for example to account for potential changes relevant to efficiency or environmental impacts due to changes in accident-induced congestion or the amount of VKT by passenger cars on different road types.

3.4 Mobility impact assessment plan

3.4.1 Methodology and research question

The mobility impact assessment focuses on the impacts of AD on personal mobility from the perspective of individual travellers or traveller segments. The mobility impact assessment answers the research question:

What is the impact of AD and its enablers on travel patterns?

Travel patterns cover the number of trips, their destinations, durations and timing, and mode choices on those trips.

The starting point of the analysis is that AD will change the travel experience on board the vehicles. Changes in the travel experience are expected to influence how the travelling by car and travel time on board an automated vehicle is perceived, affecting travel patterns (Lehtonen, Malin et al., 2022; Lehtonen, Wörle et al., 2022) (Figure 3.12).

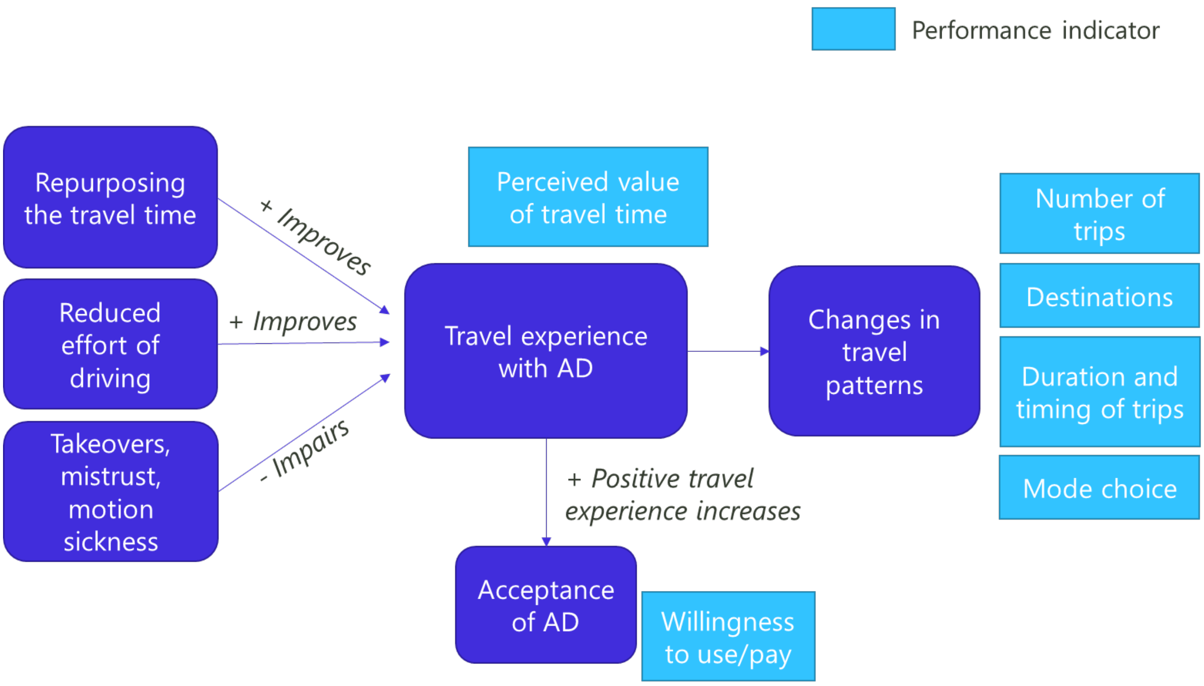

Figure 3.12: Conceptual model on how AD may influence travel experience and cause changes in the travel patterns and acceptance of AD together with performance indicators.

Three kinds of AD-related impacts on the travel experience will be considered: 1) AD should free the drivers to repurpose the driving time for work, leisure, or relaxation, and 2) decrease the effort of driving. 3) On the other hand, take-over requests or mistrust of automation may create new kinds of sources of stress. Passengers on board an automated vehicle may also experience car sickness, which they would not experience if driving themselves. Individual and contextual factors are expected to be important for shaping the impacts of AD and its enablers. The individual factors include things such as attitudes towards automation, ownership of a driver's licence, or what kind of trips an individual needs and wants to perform. An important example of an individual-level factor is acceptability/acceptance of AD: Only those travellers who start using ADFs will be exposed to the aforementioned AD-related changes in their travel experience and change their travel patterns in response. In the long term, AD-related changes in the transport system may also influence the travel patterns of non-users, but such indirect impacts are not caused by the AD-related changes in the travel experience. On the other hand, improvements in the travel experience may also increase acceptance of AD. Contextual factors entail, for example, what kind of travel modes are available and how well those travel modes can serve the individual travel needs.

Mobility impacts assessment in Hi-Drive focus on describing the impact mechanisms and identifying different kinds of travel pattern changes, while the transport system impact assessment focuses on system-level changes.

3.4.2 Assessment tools and input data

The basis of the mobility impact assessment is identifying the individual and contextual factors influencing the travel patterns and how these factors are interlinked. The impact mechanisms of AD on personal mobility will be described with causal loop diagrams. Causal loop diagrams visualize how different elements influence each other either directly or via other elements.

The impact mechanism descriptions will be based on the literature review and analysis of user questionnaires and surveys collected within the Hi-Drive project. In addition, the questionnaire data from L3Pilot will be utilized.

Mobility impacts of AD are likely to be different based on the current travel behaviour, travel needs, acceptance of AD, and socio-demographics. Traveller segmentation based on individual and contextual factors will be used to identify groups of travellers which are affected by similar factors.

3.4.3 ADFs and enablers covered

The mobility impact assessment relies heavily on the users' or survey respondents' subjective expectations on how AD could change their travel patterns. The combined impact of motorway and urban ADFs will be considered. The impact of specific enablers on travel patterns cannot be assessed. A single enabler may affect only a fraction of the trip, and it is not realistic to expect the respondents to be able to assess its influence on travel patterns.

The importance of different enablers or technologies on the acceptability of AD will be assessed within WP6.3 *User acceptance and awareness* and reported in D6.1 *User acceptance and awareness results*. Because the acceptance of AD is very important to the impact, the enabler contribution to acceptability will be used to assess how important the enablers could be for realizing the mobility impacts.

3.4.4 Scenarios

Mobility impact assessment considers travelling at the level of individual travellers and their trips. Consequently, analyses at the level of driving scenarios or traffic scenarios are not applicable.

3.4.5 Evaluation plan per research question

<u>What is the impact of AD and its enablers on travel patterns?</u>

The research question of the mobility impact assessment will be answered by refining the conceptual model (Figure 3.12) into a causal loop diagram describing the impacts and impact mechanisms.

Causal loop diagram of the impact pathways on travel patterns

The construction of the causal loop diagram will begin by listing the influencing individual-level and contextual factors for each of the AD-related changes in the travel experience. Then the inter and feedback linkages among factors, driving forces, and outcomes will be constructed. The initial construction of the causal loop diagram will be based on the literature review. After that, the direction of the impacts will be verified based on the questionnaire and survey data when available.

The causal loop diagrams will identify the impact pathways of the following travel pattern performance indicators: the number of trips, their lengths and durations, their destinations, and timing. The relevant scales for the performance indicators will be defined. For example, for the number of trips, a qualitative scale ‘decrease’, ‘stay the same’, or ‘increase’ would show the direction of the impacts. For timing of trips, the relevant scale can be ‘outside rush hour’ or ‘during rush hour’. Quantitative scales for the performance indicators might not be appropriate at the mobility impact assessment, because transforming changes in the travel experience into the number of trips, for example, will require transport-system-level modelling of the impacts. Mobility impact assessment will support this by providing an estimate on the perceived value of travel time with AD to be used in the transport system impact assessment.

Transport system level results will be reflected back to the mobility impact assessment when available. For example, AD can make it easier for a single traveller to travel by car, but if many travellers decide to do so, the resulting traffic jams may force some of the new car users back to other travel modes.

Traveller segments

Not all the identified impact pathways will be relevant for all travellers, depending on their individual level and contextual factors. For example, if a person is not working, they will not be able to use the time on board an automated vehicle for working.

Traveller segmentation will be done based on the survey data collected in the Hi-Drive and L3Pilot projects. Clustering methods, such as hierarchical clustering or latent class analysis, will be used to identify groups of travellers with similar travel mode patterns, sociodemographic traits, or attitudes towards AD.

Separate causal loop diagrams for different types of trips (e.g., commute, everyday leisure, long-distance travel) and traveller segments will be constructed if the impacts are different.

Importance of enablers

Acceptance of AD is highly relevant for the realization of its mobility impacts. One of the key aspects of acceptance is usefulness of the system for daily mobility. The mobility impact assessment will assess what kind of capabilities potential users expect AD vehicles to have and will reflect those capabilities against the enablers developed within Hi-Drive—for example, how important it is that an automated vehicle can merge onto a motorway in automated mode. If it is important, then an automated vehicle may need V2V for cooperative manoeuvring to perform it. The importance of capabilities will be analysed based on the Hi-Drive Global survey (*Annual Survey*). The results will be discussed against the identified impact pathways and traveller segments.

Perceived travel time

Based on the user questionnaires, WP6.3 *User acceptance and awareness* will report on how AD can influence perceived travel time. This analysis will be elaborated within the mobility impact assessment by considering the results from L3Pilot and other projects. The estimates will be validated against the causal loop diagram and traveller segments to create estimates of the changes in the value of travel time due to AD within Hi-Drive.

3.5 Transport system impact assessment plan

3.5.1 Methodology and research questions

The objective of the transport system impact assessment relies on understanding the effects of ADFs and their enablers on mode choices and travel patterns. For this purpose, the modal split after the introduction of AD for different penetration rates will be estimated using macroscopic travel demand-modelling software. Calculating the modal split implies calculating the VKT per mode. The methodology used in Hi-Drive relies on the methodology developed in the EU Project CoEXist (Sonnleitner et al., 2020).

The first step will be to state the assumptions for the macroscopic modelling that reflect the impacts of AD and its enablers on supply and demand. The parameters defined for the driving logics (Olstam 2020) and the results of microscopic traffic flow simulations will form the basis for the assumptions for the supply side of the macroscopic travel demand model. This will entail updating network capacities and capacity-restraining functions (i.e., links and nodes). For this purpose, the results of the traffic flow simulations will be extracted as fundamental diagrams. In traffic flow theory, these diagrams show the relationship between traffic volume, density, and speed. Here, the diagrams will be used to estimate volume-delay functions for links and nodes, enabling the results to be generalized for application in macroscopic travel demand models.

Automated driving travel time corresponds to the time during which the vehicle has control of the driving task. Car drivers in an automated vehicle of level 3 and higher may use some of their driving time for non-driving activities. This may decrease the perceived travel time of a car trip and improve the benefits of car usage leading to changes in route choice, mode choice, and destination choice. Then, the results from the mobility impacts combined with travel surveys will be used to estimate perceived travel times.

In the second step, macroscopic modelling of defined scenarios reflecting different penetration rates of driving automation will be performed.

The outcomes of modelling will be analysed. The results will on the one hand be used to answer the research questions related to transport systems (D4.1 *Research questions* by Metz et al., 2023):

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

On the other hand, they can also be used for upscaling the results of efficiency and environmental impact assessment. Therefore, the results of the macroscopic model, for example on the impacts on emissions and energy demand, can contribute to answering the research question assigned to Efficiency and Environmental impacts (see part chapter 3.3):

- What is the impact of AD and its enablers on energy demand, emissions, and traffic efficiency at European level?

The process is summarized in Figure 3.13 and described in detail in the evaluation plan presented in chapter 3.5.5.

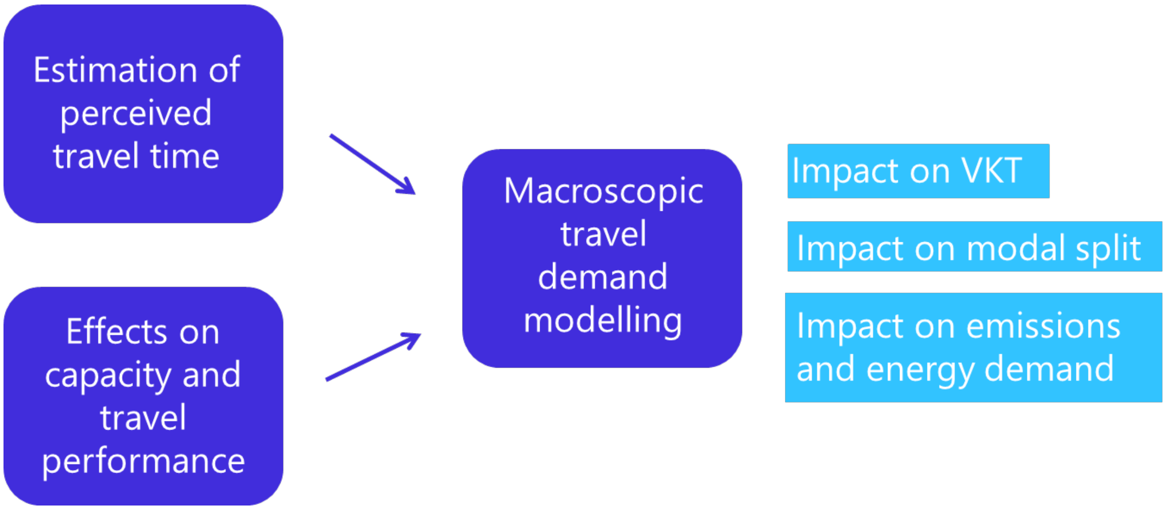

Figure 3.13: Simplified methodology for transport system impact assessment.

3.5.2 Assessment tools and input data

Transport system impacts will be investigated using the macroscopic travel demand modelling software PTV Visum with the Handbook Emission Factors for Road Transport module (HBEFA 4.2) used to calculate emissions and energy demand (HBEFA 2022).

The required inputs are:

- A macroscopic travel demand model including supply and demand—external to the project.
- Kilometres travelled per vehicle category per type of road per year (needed for emissions and energy consumption calculations)—will be estimated from travel surveys.
- Perceived travel times—will be estimated from the results of the mobility impacts and travel surveys.
- Assumptions of microscopic driving behaviours—the effect on capacity and traffic performance will be estimated as part of the Hi-Drive project.

The outputs of the tool are:

- VKT for the area covered by the model (for example per mode, per road type, inside or outside the ODD, …)
- Vehicle-hours-travelled for the area covered by the model (per mode, per road type, inside or outside the ODD, …)

- Emissions (carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), hydrocarbon (HC), sulphur dioxide (SO_2), particle matters (PM)) for the area covered by the model and based on the HBEFA model
- Energy demand for the area covered by the model ADFs and based on the HBEFA model.

3.5.3 ADFs and enablers covered

In contrast to microscopic models that consider the interaction of individual vehicles**,** macroscopic models consider an aggregated behaviour of traffic flow. For this reason, the macroscopic modelling will rely on the results from microscopic simulations and will cover the ADFs and enablers covered in efficiency and environmental impact assessment (chapter 3.3.4) in an aggregated way as explained in chapter 3.5.1.

3.5.4 Scenarios

The scenarios will be modelled using a model provided by the Landesbaudirektion Bayern, which encompasses the whole Bavarian Region of Germany, and including the road types urban, rural, and motorway.

The evaluation of impacts using macroscopic travel demand modelling relies on comparing scenarios with a baseline. The baseline will be the calibrated model that is already available in the macroscopic travel demand model, and scenarios will then be based on the first results of the microscopic simulation and in consultation with the respective partners from the other impact assessment activities. Generally, if an ADF and its enablers do not have an impact on efficiency at the microscopic level, they will not do so at the macroscopic level. The results of the microscopic scenarios will be then treated in an aggregated way, in other words, translated into resulting capacity and traffic performance as described in chapter 3.5.5 in step 1.b.

The scenarios will cover:

- Different ODDs. Since all type of roads are modelled, it will be possible to look at the results per road type, inside and outside the ODDs.
- Different values of perceived travel time, according to the results of mobility impact assessment (chapter 3.4) on perceived value of travel time.
- Different penetration rates of AD (10%, 30%, 50%).

3.5.5 Evaluation plan per research question

The plan for setting up the macroscopic simulation is explained in three steps in chapter 3.5.1. The macroscopic model will, with the method described in chapter 3.5.2., provide the answers to both research questions:

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

These questions are related to each other, since the modal split will be calculated based on VKT per mode.

To answer the research questions, the following steps will be performed:

Step 1. Model preparation for automated driving

a. *Assumptions on capacity and traffic performance for the supply side of the model*

AD may change the capacity and performance of the road network. The performance, measured by the indicator delay time per vehicle, depends either on varying capacity values or on the ability of a given demand composition (driver/vehicle population) to use a given (constant) capacity.

Macroscopic route choice and assignment models for private transport apply volume-delay functions to determine travel time on the road network. For links, the travel time is computed by multiplying the free flow travel time with a factor that is determined by a volume-delay function (VDF). For nodes, a delay time is added to the free-flow travel time. The VDF factor depends on the volume-to capacity ratio, i.e., the saturation rate of a supply element, which represents either a link or a node.

The relationship between volume and capacity uses the concept of passenger car units (PCU) where capacity and vehicle volumes are converted into passenger car equivalents. If automated vehicles have a traffic performance that differs from conventional cars, and if the performance additionally depends on the type of supply element, the PCU concept must be extended to automated vehicles as well as to road and intersection types (motorway or urban road, grade separated or at-grade intersections, signalized or unsignalized intersections). Since in the macroscopic model the PCU factor will be multiplied by the volume of the related vehicle type, it is possible to model the impacts of different penetration rates of automated vehicles.

Traffic flow microsimulation on simple network elements, parametrized with the Hi-Drive driving behaviour and parameters, will be performed in efficiency and environmental impact assessment. These simulations are used to draw fundamental diagrams. PCUs will be derived from the fundamental diagrams with the help of the Van Aerde parameters (Van Aerde 1995).

b. *Estimation of perceived travel times*

Travel demand models replicate the decision-making process of individual travellers concerning the choice of destination, mode, and route. A utility function describes the utility of each choice considering the characteristics of the trip maker (user group) and the trip purpose (activity type). These functions consider various time components (access, egress, driving, waiting, parking search), cost and travel comfort. Each component is weighted with a specific factor. For current transport modes, these factors are usually estimated from mobility surveys and are already calibrated in the Bavarian model used in this study. For choices with automated vehicles, the functions, as well as the choice set, will be adjusted.

The perceived value of time experienced in an automated vehicle differs from the value of time spent in a conventional vehicle, because the driver can spend some of the trip time on other tasks than driving. Automated vehicles of level 3 and 4 can only drive automatically within their ODD, which probably has an impact on route choice as well as mode choice. Such behavioural changes can be integrated into existing travel demand models by adding an additional transport system for automated vehicles with a specific utility function for route choice.

This specific utility function resembles already existing functions for conventional vehicles but is supplemented by another factor smaller or equal to unity, which reduces the perception of travel time when travelling in an automated vehicle. Because AD is only possible within its ODD, the factor needs to be dependent on the road segment. For road segments that allow AD, the perception of time will be reduced, whereas for road segments that do not provide the necessary signals, there will be no reduced value of time for AD.

The estimation of the value of perceived travel time will be done in collaboration with the mobility impact assessment and may include the use of travel surveys. Figure 3.14 shows the sequences of a travel demand model (purple elements) and the assumptions that will be made on the impacts of AD and its enablers (blue elements).

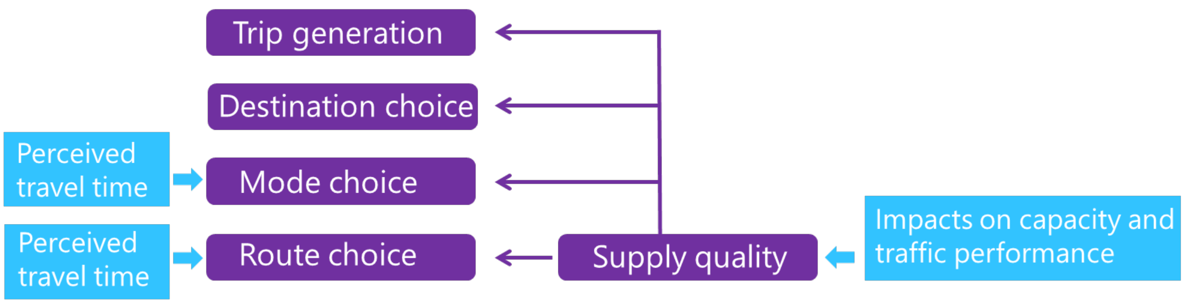

Figure 3.14: Method for modelling automated driving and its enablers with macroscopic travel demand models (adapted from Sonnleitner 2020).

<u>*Step 2. Modelling of the scenarios*</u>

In this step the transport model will be adapted to modelling automated vehicles as described in step 1: Model preparation for automated driving. The baseline will be either used as it is (last version of the calibrated model from Landesbaudirektion Bayern) or, if found necessary, adapted to align with the common baselines decided as part of the project. Then several scenarios as described in chapter 3.5.4 will be set and modelled.

Step *3. Analysis*

The results of macroscopic modelling are directly available on the graphic user interface of the software. This way, VKT, emissions, and energy consumption will be directly accessible without further treatment. However, consistency checks of the results will be performed, in order make sure that their changes compared to the base scenario are within a plausible range. Therefore, the results of other projects where AD has been modelled with macroscopic models will be taken into account (e.g., CoEXist), as well as general modelling knowhow from experts. The modal split will be calculated based on the VKT per mode.

The results needed for upscaling the efficiency and environmental impacts will be handled as described in chapter 3.3.5.3. The macroscopic simulations of transport system impact assessment will specifically provide an indication of the impacts of changes in modal split and VKT which cannot be covered directly with microscopic traffic simulations alone.

4 Socio-economic impacts

4.1 Scope

Socio-economic impact evaluations of any project or policy are concerned with the effects on welfare. Thus, the overall research task when evaluating socio-economic impacts in the Hi-Drive project is to investigate *how automated driving (AD) and its enablers in passenger cars affect welfare*.

The main approach chosen for the socio-economic impact evaluation relies on traditional cost-benefit analysis, which is a type of analysis often used in the appraisal of investment projects and policy reforms. The theoretical foundation for this approach is found in the *economics of welfare* (Boardman et al., 2018).

Before presenting the method chosen for the cost-benefit analysis and how it is applied in the Hi-Drive project, we discuss the research questions addressed when considering economic impacts of AD, and how such new transport technology more principally influences welfare. Then, the evaluation plan is discussed through a presentation of methods and data needs. The description starts by presenting the essence of cost-benefit analysis, assumptions made to facilitate the analysis, and the design of treatment scenarios and their baseline, which is essential for the analyses.

Defining these scenarios is necessary to detect and quantify the magnitude of impacts generated by AD with and without the technology enablers. After this description of the method, we specify our data needs. This concerns data input from the impact assessments and a clarification of standard unit costs needed to calculate the monetary value of estimated impacts.

4.1.1 Research questions

Socio-economic impact assessment may address different topics related to welfare. Welfare impacts may be investigated from the perspective of the society as a whole, and from the perspective of different groups, or stakeholders, in society, where the distribution of welfare impacts is an additional dimension. These three aspects of welfare impacts are reflected in the research questions outlined for the socio-economic impact evaluation of AD:

- What is the overall socio-economic impact (net welfare effect) of AD and its enablers?
- How does AD affect the welfare of different stakeholders in society?
- How does AD affect social equity?

Cost-benefit analyses are particularly relevant to quantify welfare impacts at the aggregate European level and for different stakeholders if relevant data can be provided. Data availability is expected to be sufficient for an economic evaluation in an aggregate European perspective. It is more uncertain with regard to economic analyses in a stakeholder perspective. As an example, for safety impacts, which are the ones of greatest economic importance, the simulations and upscaling of impacts cannot be modelled to distribute impacts across different types of travellers (e.g., cyclists, pedestrians).

Cost-benefit calculations are in principle also possible when addressing social equity issues, which consider the distribution of benefits between different groups of stakeholders, according to gender or socio-economic status. The access to relevant data is, however, extremely challenging. When exploring equity with respect to how AD may improve the capability of people who face severe obstacles, which prevent them from fulfilling their travel needs, more qualitative approaches are the most likely approach.

4.1.2 Transport technology and welfare

The aggregate welfare effect is the sum of net gains (benefits minus costs) for all individuals in society, as they are directly involved or indirectly affected by the application of AD technology and its enablers, measured in monetary terms. Welfare is derived from the consumption of goods and services, leisure, good health, etc. Travelling does not contribute to welfare directly. On the contrary, travelling implies costs caused by the need to move geographically and in time between activities that contribute to welfare more directly, taking place at home, at work, at different marketplaces, etc. The more costly travelling is, the less resources remain for welfare generating activities. Thus, the welfare impacts of new transport technology are derived from how it affects costs of travelling, including road traffic incidents. Based on a recent study of level 3 ADFs, welfare impacts were mainly derived from expected reductions in traffic accidents and lower unit cost of travel time (Bjorvatn et al., 2021). We expect that impacts in these areas also will be the major contributor to welfare impacts from AD and its enablers. In addition, welfare impacts are considered regarding travel efficiency, the environment, and mobility impacts.

The basis for our economic analysis is that travelling is a risky activity in the sense that delays and accidents may happen. Individuals do not like being exposed to such risks; they are risk averse. When deciding on what trips to undertake, how to travel, etc., they are assumed to choose the option giving the highest risk-adjusted welfare (expected utility), which is equivalent to the lowest risk-adjusted travel cost. In transport economics this is referred to as generalized travel cost. Due to risk aversion, the risk-adjusted travel cost will be higher than the expected travel cost.

From the individual traveller's perspective, we expect that AD technology will reduce the risk of becoming involved in traffic accidents, which will reduce negative welfare consequences of travelling. AD may also impact other aspects of travelling such as effective travel time and CO_2 emissions.

Possible welfare impacts may be analysed with an insurance and prevention-related perspective. Then, the extra capital and maintenance costs required to have AD equipment installed can be considered as an extra monetary prevention and insurance premium. This will, in turn, affect other prevention-related activities, especially the time-consuming ones. For example, if the likelihood of delays decreases, the need for time buffers, i.e., time added to ensure that a destination is reached on time, is reduced. Furthermore, if the likelihood of accidents decreases, average speed may be increased because of less "careful" driving. If so, both should materialize in a reduction in expected effective travel time and an increase in travel time efficiency.

A welfare-maximizing traveller will also value any reductions in ex-ante perceived risks of delays and accidents, which should result in reduced uneasiness and increased comfort/reduced discomfort. In addition, there may be benefits of AD related to increased possibilities for drivers to relax and/or engage in productive work or other non-driving related tasks and activities. In monetary terms, such benefits may be considered as a reduction in the unit cost of travel time.

Flügel et al. (2022) argue that lower cost of travel time may be ascribed to what they include in a wide definition of driving comfort: a) increased productivity (more useful use of travel time), b) increased driving pleasure (positive driving experience), and c) reduced perceived insecurity (negative driving experience). From a theoretical point of view, these factors differ quite significantly, where the latter two may constitute various aspects of driving comfort. The opportunity to engage in productive work is, however, different from driving comfort. It lowers the alternative cost of travelling and lowers the willingness of travellers to pay for reductions in travel time.

Individuals are primarily stakeholders as travellers, where it is essential to distinguish between travellers who travel with AD and those who do not. Travellers may be specified further according to mode of travelling. Individuals may, however, also be affected as taxpayers, victims of pollution, workers, and/or capital owners. These groups may also be analysed as stakeholders, if there are reasons to expect that they will experience welfare impacts of AD and that relevant data and resources are available.

4.2 Plan

The primary goal for the evaluation plan is to address all three research questions. The evaluation plan builds on two pillars. One is the evaluation method that will be applied, while the other is specification of data that is needed to undertake a socio-economic evaluation. The data for the analysis will originate from scaling up of impacts of AD and its enablers, which are conducted in the different impact assessment areas, namely safety, efficiency and environmental, mobility, and transport system (see chapter 3). To assess the value of the potential impacts in each impact area, proper standard unit costs must be defined and applied to calculate the value of benefits and related costs.

Figure 4.1 illustrates how the potential impacts of AD and its enablers are captured in the socio-economic impact evaluation. The figure provides a simplified picture of the overall evaluation plan. More details are presented in the following chapters, which elaborate on the evaluation method and data needs for the analysis.

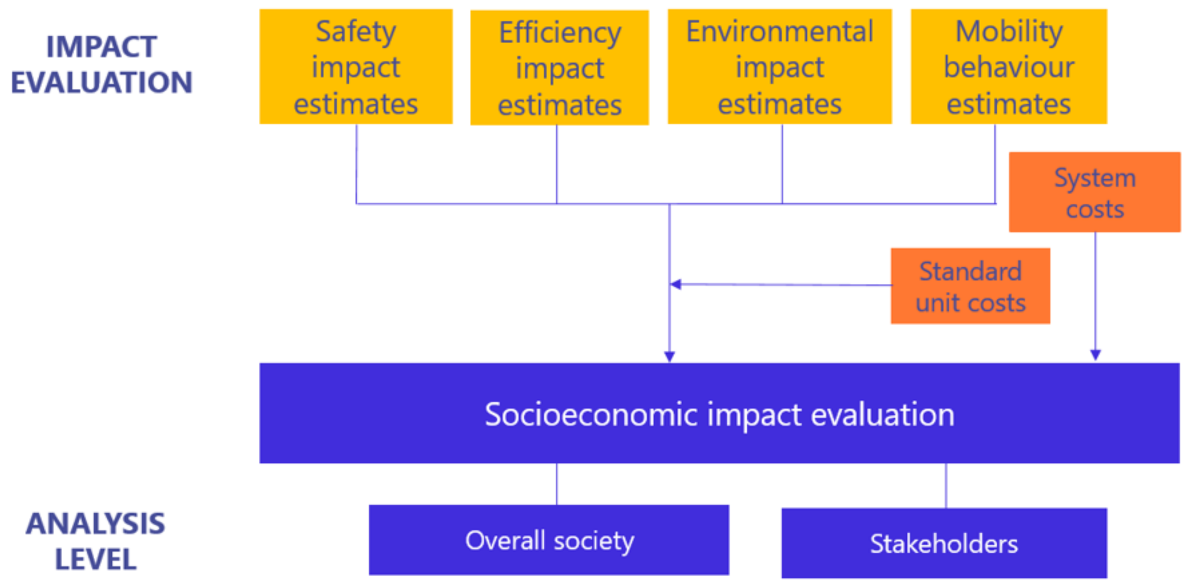

Figure 4.1: Socio-economic impact evaluation plan summary.

4.2.1 Method

The method applied for the socio-economic impact evaluation contains cost-benefit analysis designed to consider the impacts of a technology at a specific stage of an ongoing development towards fully automated driving technology. After presenting the chosen approach, we clarify assumptions made to facilitate the economic analyses, and how the treatment scenarios and baseline are operationalized to assess the impacts of AD and its enablers.

4.2.1.1 Cost-benefit analyses

As already spelt out, the impacts are estimated by focusing on the differences in outcomes between treatment scenarios containing the AD technology and its enablers with a relevant baseline scenario. By ascribing economic values to the different impacts that are estimated, the magnitude of benefits and costs in monetary terms can be calculated, and if the relevant data on impacts can be provided, conclusions can be drawn on how beneficial the AD is for the society and for specific stakeholders. For the social equity impact, a traditional cost-benefit analysis is more difficult. This is because it is unlikely that relevant data can be provided for quantification in monetary terms, implying that a qualitative approach is more suitable.

In socio-economic impact evaluations, the standard way is to construct scenarios which unfold over a time period resembling the lifetime of the investigated project. Alternatively, the focus can be on the situation in a specific year in the future when all impacts of the project investigated have been realized, which is compared to what the situation that year would have been without the project in question. In either case, the timeframe applied must be the same for the treatment scenarios and the comparable baseline scenario. However, as AD in our study relates to a certain stage of an ongoing development of highly automated vehicles, it does not make sense to construct a baseline scenario that does not contain this technology at all for the next 10–20 years.

Instead, we apply what we have called a *snapshot approach*, where the time perspective is narrowed down to consider the impacts of the technology at a specific point in time. The essence of this approach is that the current traffic situation, where AD has not been implemented yet, is regarded as the baseline. Then, the treatment scenarios estimate what the current traffic situation would have looked like if a certain fraction of the passenger car fleet had been replaced by vehicles with AD and its enablers.

Thus, the overall research question for the socio-economic impact assessment may be formulated more precisely as follows:

> *How much higher (or lower) would the annual welfare have been if AD had been implemented in a given fraction of passenger cars, with and without enablers, in the current traffic situation?*

In economics, this way of addressing a problem is referred to as comparative statics. It is a comparison of two different economic outcomes before and after a change in an underlying exogenous parameter, and it is static as it compares two different equilibrium states, i.e., with and without AD.

Applying comparative statics means that we assume that the society is in a steady state, where nothing happens except for the inclusion of different fractions of vehicles equipped with AD. This means that the introduction of AD and its enablers is treated as an exogenous change.

4.2.1.2 Assumptions underlying the analyses

We find it justified to consider the impacts of introducing AD and its enablers as investigated in Hi-Drive as relatively small compared to the total European economy. AD is not expected to cause changes in labour markets. This facilitates the analysis in the sense that we do not have to consider huge, groundbreaking impacts on the economy.

To be able to focus directly on the main research questions regarding welfare impacts, and to avoid unnecessary complications in the analysis, we further make two assumptions about the working of the economy. These assumptions are often made in economic analyses of long-term steady states, which is a prerequisite for the snapshot approach:

1. The economy is characterized by *sufficient competition* among all businesses involved and by well-functioning markets. This implies that the price of scarce resources, like labour and capital used in the production of goods and services, reflects their shadow value to society—i.e., their opportunity cost. As a result, the producer prices of goods and services reflect their shadow cost to society, i.e., the value of goods and services forgone when resources are used in their production. This further implies that there is no unemployment and that capital earns a normal risk-adjusted return.
2. There are *constant returns to scale* in production, which means that the unit cost of production is constant, independent of the level of production. This means that when firms or industries scale up or down, the unit price of whatever they produce is constant.

In combination, these assumptions imply that any restructuring of car manufacturing or of other industries caused by the introduction of AD technology may take place at no additional cost (or benefit) to society. It is, however, possible to relax on the assumption of constant returns to scale when discussing the sensitivity of findings, e.g., that unit costs for AD are reduced with increasing penetration rates.

In addition, we make two assumptions regarding the distribution of benefits and costs:

3. When it comes to *cost of public funds,* we consider the value of one Euro out of/into government coffers to be the same as the value of one Euro out of/into private pockets. This implies that the monetary value of impacts can be calculated by disregarding the distribution of costs and benefits between the government and the private sector, which is important as this distribution differs significantly between European countries.

4. We also disregard the question of *distribution of costs and benefits between the different private stakeholders*. This implies that the value to society of one Euro in benefit or cost does not depend on who the winner or loser is or whether they are rich or poor.

In discussion of results from the cost-benefit analyses, we may relax on the assumptions regarding the cost of public funding and the neglect of distributional impacts. It is generally accepted that the cost of public funds exceeds the cost of private funding because taxation distorts the functioning of an economy (Boardman et al., 2018; NOU 2012:16), which makes it interesting to go deeper into how the distribution of costs and benefits between government and the private sector may affect welfare. Furthermore, we may also consider what distributional effects would imply if one Euro in benefit or cost for rich households should count less than for poor. There may also be a *gender* aspect involved, especially if the subjective perception of accident risk differs between males and females.

4.2.1.3 Baseline and treatment scenarios

One of the most crucial tasks for any impact evaluation is to describe the baseline scenario. The clue is to define an adequate reference, with which the treatment scenarios can be compared with, in order to estimate relevant impacts of the project under consideration. This is also the case when investigating the impacts of installing AD technology, where all driving tasks are performed by the vehicle within the technology's ODD.

The baseline and treatment scenarios needed to assess the economic impacts of ADF and its enablers are described in more detail below. The purpose is to establish baseline and treatment scenarios where reliable estimates can be provided, revealing the magnitude of expected impacts of AD and its enablers. The snapshot approach implies that this is done by replacing fractions of the current car fleet with new cars equipped with ADF.

4.2.1.3.1 Baseline to elaborate on economic impacts of AD

The baseline for the economic impact assessment is the traffic situation of today, where AD has not been implemented. Data regarding traffic volumes, traffic accidents, and traffic flows, which describe the current traffic situation, will be from the most recent year with reliable statistics on traffic in Europe, presuming that the traffic situation does not change significantly over a couple of years.

The traffic situation of today does, however, also contain safety regulations by public authorities. These must be taken into account, and incorporated in baseline, to the extent they can be expected to generate significant shifts in the current traffic situation. In our view, this is the case with EU's General Safety Regulation of July 6, 2022, which makes several ADAS mandatory from 2024 for all new vehicles in the EU. This is stated in the Fact sheet from the

European Commission on *New rules on vehicle safety and automated mobility* (European Commission, 2022). The mandatory ADAS components are:

- Lane keeping assistance
- Advanced emergency braking
- Intelligent speed assistance
- Reversing detection with camera or sensors
- Attention of warning in case of driver drowsiness
- Emergency stop signal
- Cyber-security measures
- Event data records

These mandatory ADAS components are integrated in the ADFs, and as ADFs will not be introduced prior to 2024, the impacts of the mandatory ADAS equipment on traffic outcomes should be considered as a part of the baseline. Then, in the socio-economic impact assessment, the impacts of ADFs, which generate economic value, should be estimated as impacts beyond what is achieved with the mandatory ADAS components.

Based on previous studies, we expect that the ADAS components in particular will contribute to a reduction in traffic accidents (see e.g., Bjorvatn et al., 2021). For the economic analyses, such safety impacts of mandatory ADAS should be included in the baseline. As the ADAS components also are expected to reduce traffic accidents outside the ODD of the ADFs, estimation of safety impacts of ADF outside its ODD should only measure expected impacts of ADAS components that are additional to those that are mandatory.

This means that to elaborate on the economic impacts of ADF and its enablers, the socio-economic impact assessment requires a baseline containing an ADAS adjustment of the current traffic situation. In principle, this ADAS-adjusted baseline should be constructed as if all vehicles at baseline were equipped with mandatory ADAS. This will comply with the underlying theoretical premises for the snapshot approach, which is an economy in steady state reproducing the same situation over many years.

In order to take account of mandatory ADAS as an integral part of the baseline, current knowledge on the safety impacts of each of the relevant mandatory ADAS systems has been examined. These findings have been incorporated in the simulations that are conducted to detect the effects of ADF and its enablers, so that the effects are compared to a baseline scenario reflecting almost full penetration of mandatory ADAS in the current traffic situation. This baseline is referred to as BADAS. These effects feed into the upscaling of safety impacts to the European level. This complies with the request from the socio-economic impact evaluation to measure impacts relative to an ADAS-adjusted baseline.

In the simulations, effects are also assessed relative to a baseline with the current car fleet, i.e., today's traffic, which we refer to as BTTS (Baseline Today's Traffic Situation). These are also applied to estimate impacts upscaled to the European level. The difference between the upscaled impacts relative to BTTS and to BADAS measures the estimated impacts of mandatory ADAS. As it is not obvious what the impacts of mandatory ADAS actually are, but this information is essential for anyone who critically wants to examine the results of the economic impact assessment. Furthermore, it is needed to calculate the economic values of ADAS generated impacts, which will be done in exactly the same way as when calculating the economic value of impacts generated by AD and its enablers.

4.2.1.3.2 Treatment scenarios and estimation of impacts

The basic treatment scenario for the impact assessments is the scenario including ADF and its enablers, which is referred to as EADF. The enablers are expected to increase the impacts of ADF by extending the ADF's ODD and improve the performance of ADF within its ODD. This means that the ADF and its enablers capture the impacts of two different types of treatments. One is the impacts of the ADF, the other is the impacts of technology enablers expanding the efficiency of the ADF.

Impacts are detected as the difference in traffic outcomes between a treatment scenario and its relevant baseline. For the treatment scenario of ADF and its enablers (EADF), the baseline for the economic impact evaluation is the one discussed in the previous chapter, i.e., a baseline where the current traffic situation is adjusted with full penetration of mandatory ADAS (BADAS). This captures the impacts of both the ADF and its enablers.

The simulations and upscaling also quantify the contribution of enablers to achieving these impacts. The baseline scenario for these calculations is ADF with no enablers, called Baseline ADF (BADF). Hence, the impacts of the enablers are the difference between the EADF and BADF scenarios (EADF - BADF).

The difference between these two sets of impacts, (EADF - BADAS) - (EADF - BADF), quantifies the impacts of ADF without enablers. In this respect, BADF is also the treatment scenario to detect the impacts of ADF (i.e., BADF - BADAS), which the simulations and upscaling do not estimate separately.

Impacts of ADF and its enablers are also detected by comparing the treatment with a baseline of today's traffic situation, i.e., a baseline with the current car fleet, BTTS. The difference between these impacts and the ones detected when comparing ADF and its enablers with a baseline adjusted for the implementation of mandatory ADAS, (EADF - BTTS)

- (EADF - BADAS), provides an estimate of the impacts generated by the decision to make certain ADAS components mandatory for all new cars. However, it is not within the scope of the Hi-Drive project to assess the impacts of mandatory ADAS in isolation.

The way impacts are detected is shown in Figure 4.2.

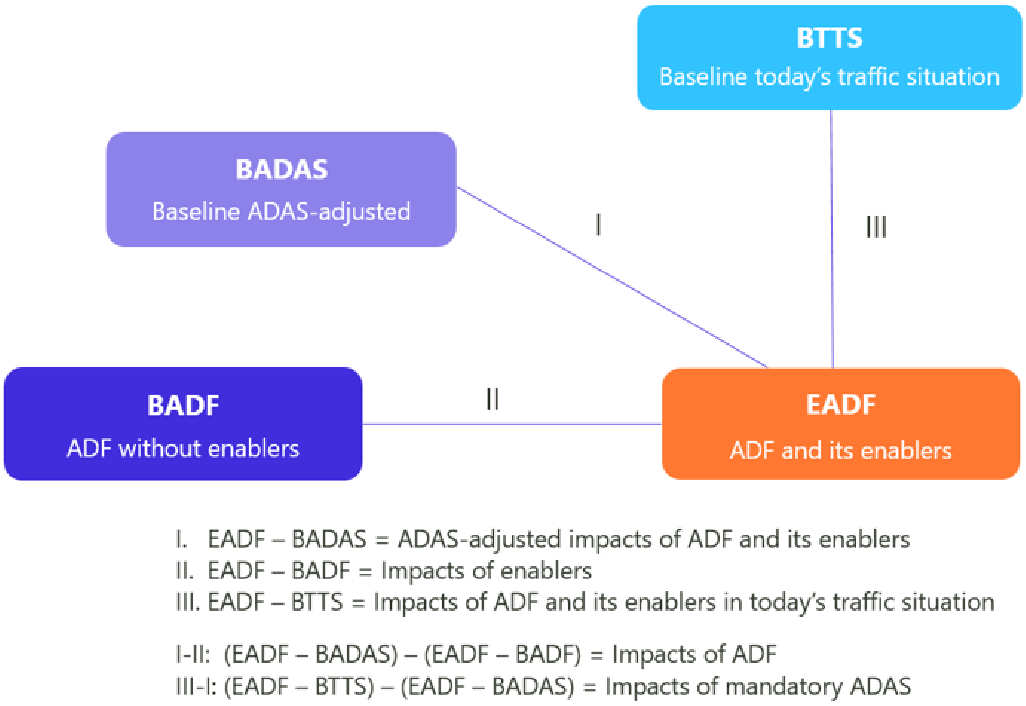

Figure 4.2: Baseline and treatment scenarios in the socio-economic impact assessment.

4.2.1.3.3 Penetration rates

Simulations will be used to assess the effects of ADF and its enablers for different fractions, or penetration rates of passenger cars being equipped with ADF. These effects will feed into models scaling up impact estimates to the European level for the same penetration rates.

For ADF and its enablers related to the ADAS-adjusted baseline, it has been decided that simulations and upscaling will be conducted for two penetration rates, 30% and 50%. The two penetration rates serve no particular purpose for the evaluation of economic impacts except for specifying at what rates of penetration the value of benefits and costs are calculated. A 100% penetration scenario would capture the full value of the technology, but practical problems prevent such simulations. This is due to the complexity of urban and motorway scenarios causing computational challenges, and to the lack of detailed statistics related to all traffic scenarios.

The impact assessments on safety, efficiency, and environment will also calculate the impacts of ADF and its enablers relative to a non-ADAS adjusted baseline, resembling the composition of the current car fleet, BTTS. This will be done for the same treatment scenario, EADF, with penetration rates of 10% and 30%. The 30% scenario is similar for the two different impact estimations using BADAS and BTTS as the baseline, and it may serve as a link to consider how the estimated impacts of EADF are linked to increasing penetration rates up to 50% (10%, 30% and 50%). Then, it might also be possible to extrapolate at what interval there might be any thresholds, which the implementation of ADF must pass for impacts to really set out.

The impacts estimated with BTTS as a baseline will be larger than those that are estimated relative to the ADAS-adjusted baseline, BADAS. The difference between the two is, as already mentioned, an estimate of the impacts of mandatory ADAS. The economic benefits of mandatory ADAS do not, however, have any economic value for our analyses since the costs and benefits of mandatory ADAS are part of the baseline in the evaluation of economic impacts.

4.2.1.4 Impacts from a stakeholder perspective

As the most important impacts cannot be distributed across different stakeholders, the stakeholder perspective has to be addressed by a more qualitative approach. Important stakeholders for transport economic analyses are different types of travellers, where it is essential to have the impacts distributed between travellers with and without AD, and where non-AD travellers may be grouped in greater detail, as travelling with non-AD vehicles, as pedestrians, bicycles, with public transport, etc. It is, in particular, the expected reduction in the number of traffic accidents that may also concern other travellers than those with AD. The impacts of AD regarding travel cost savings due to lower unit travel time cost will only concern those who are AD travellers. Impacts on travel efficiency will presumably affect all types of travellers more evenly.

By making assumptions of this kind, it is possible to use the aggregated macro impacts to investigate impacts for different types of travellers from a stakeholder perspective. The distribution of economic benefits and costs among stakeholders can then be analysed by calculating the share of European standard unit costs from the aggregated macro impact analyses that the stakeholders internalize. Hopefully, a decomposition of these unit costs is possible and useful for analysis of impacts in a stakeholder perspective.

Reductions in traffic accidents, as well as the funding of road infrastructure for AD and its enablers to work, also affect public budgets and hence all citizens as taxpayers. We will not have detailed information on government involvement in all these respects, but it is possible to have a theoretically based discussion and indicate in what direction impacts for the government, or taxpayers, may be expected to occur. In this discussion, it is also possible to discuss how the magnitude of impacts are affected if we relax on the assumption that the cost of funding is the same for private and public spending. It is generally accepted that the cost of public funding exceeds the cost of private funding because taxation distorts the functioning of an economy (Boardman et al., 2018; NOU 2012:16.).

From a stakeholder perspective, it is also reasonable to argue that AD has no net impacts on employees or on the business owners. This follows from the assumptions that are made to facilitate analyses based on the snapshot approach. The key assumption in this respect regarding the competitive environment should, however, also be considered realistic. This means that any restructuring of car manufacturing or of other industries caused by the introduction of AD technology may take place at no additional cost (or benefit) to society.

Another matter worth pursuing is the possibility to calculate to what extent we can expect reductions in generalized travel costs for travellers with AD. In particular, it offers an opportunity to compare such reductions with information on willingness to pay. In theory, travellers' willingness to pay for AD should reflect expected reductions in generalized travel costs originating from AD.

4.2.1.5 Investigating equity issues

The work description of Hi-Drive states that "social equity relates to equal access to car use by disabled, sick, elderly and those with no driver's license". Furthermore, it is mentioned that the socio-economic impact assessment will address "equity for gender and socio-economic", which we interpret as gender and socio-economic status.

When addressing equity issues, we are relaxing on the assumption that the distribution of benefits and costs is disregarded when estimating the economic value for society. The impact assessments cannot provide data which allow us to include such concerns in the quantification of net welfare gains. Instead, these issues are approached by qualitative assessments, indicating how AD may affect the equity issue in question.

Equity impacts for gender and socio-economic status will depend on who is actually most likely to acquire cars with AD, and consequently harvest the benefits of the technology. This may be elaborated further by discussing how this may change with increasing penetration rates, and to what extent different groups may value benefits differently. There may, for instance, be gender differences in how one values the expected impact of lower accident risk.

When it comes to how AD affects social equity and travel demand, we will use information from the surveys in mobility impact assessment (gender, income, self-reported disability) in order to address this properly. More detailed information is definitely required to understand the obstacles that the disabled, sick, and elderly face which prevent them from fulfilling their travel needs. Then, convincing arguments are needed to explain how these obstacles are overcome by AD and its enablers. However, the AD investigated in Hi-Drive is not fully automated, which means that the technology cannot provide equal access to car use for those with no driver's licence. Thus, this technology cannot solve the mobility issues of those without a driver's licence.

4.2.2 Data needs

The way impacts are measured and their economic value is calculated differs for the different perspectives that are applied, even if cost-benefit analyses should be the preferred methodology for all perspectives. In analyses of aggregated macro impacts, it is essential to incorporate all impacts that follow from the introduction of AD and its enablers, directly and indirectly. In the stakeholders' perspective, travellers and other groups of stakeholders will only include impacts that directly concern themselves. This will also be the case for the social equity perspective. However, the sum of adding together the monetary value of all impacts for all different stakeholders shall in theory give the aggregated macro impacts.

It is clear that no estimates are made regarding the disaggregation of macro impacts to specific stakeholders or social groups for social equity considerations. Thus, the details on data needs are only specified for impacts on the aggregate European level. That is also the reason why the specific data needs from a stakeholder or a social equity perspective are not described, or why their relevant standard unit costs to calculate the economic value of such impacts are not addressed.

Estimates on the expected impacts of AD and its enablers will by and large be provided by the different impact assessments in Hi-Drive (see chapter 3). Estimated impacts should as much as possible be estimated in absolute terms at the European level (EU27). This will serve the purpose for the aggregate macro impact analyses. As major impacts cannot be distributed across stakeholders, we do not specify data needs in this respect. Neither do we elaborate on how standard unit costs relevant for the different stakeholders should be calculated.

For the same reason, the standard unit costs that would be relevant from a social equity perspective is not considered. It is yet uncertain whether impacts can be measured as expected outcomes per a standard travel distance. Thus, it is still a possibility that welfare impacts may be considered for different prototypes of travellers.

Before we specify the data needs regarding impacts, we clarify the data required to understand the project under consideration—AD and its enablers—in economic terms.

4.2.2.1 Data on ADF and its enablers

From the impact assessments we will receive information on the details regarding the content of the ADFs and their enablers. Information on both is necessary to calculate the magnitude of costs required for the estimated impacts to occur.

The costs required to equip cars with ADF will be variable, increasing with the number of cars. The cost of providing the enablers investigated will be variable for some of the enablers and fixed for others. Enablers which are sensors, radars, or software programs can be installed with the ADF, and the costs will be variable.

Improvements of road infrastructure and telecommunication, which also are among the enablers, represent a public good. In economic terms, they are fundamentally different from enablers that can be acquired when needed. It is essential to make this distinction between these two types of enablers, as the public good will be a fixed cost independent of the number of vehicles making use of it, while the latter will be a variable cost increasing with the number of vehicles equipped with them.

4.2.2.2 Impact estimates regarding safety

We will make use of impact estimates provided by the safety impact assessment on how AD and its enablers, for different penetration rates, are expected to affect traffic accidents on the European level, and the contribution of the enablers in that respect, regarding:

- Number and severity of traffic accidents
- Fatal accidents
- Serious injury accidents
- Slight injury accidents
- We will also provide estimates on to what extent crashes with material damage only are affected.
- Impacts are measured as the change in the number of accidents by accident severity. To undertake risk considerations, the gross number of accidents for the relevant treatment and baseline scenarios is needed. If only the change in the number of accidents by accident severity is provided, the gross figures must be inferred from what is considered to be the empirical basis for the current traffic situation.

4.2.2.3 Impact estimates regarding efficiency

From the efficiency impact assessment we will receive estimates on how AD affects expected travel time at the European level for the different penetration rates, where travel volumes and mix of travel modes are the same as at baseline:

- Total hours driven and vehicle kilometres travelled with motor vehicles within the ODD over a year
- Change in travel time from baseline
- Change in expected time to travel a standard distance for motor vehicles
- Standard deviation in expected travel time for the same standard distance

4.2.2.4 Impact estimates regarding environmental impacts

From the Environmental impact assessment, we will receive annual estimates for the different penetration rates on how AD affects pollution and energy demand at the European level, where the energy mix is the same as at baseline:

- Tonnes of CO_2 emissions
- Energy demand

The environmental impact assessment can also provide estimates for changes in energy demand and travel times for passenger cars and heavy-duty vehicles.

For the economic analysis, change in energy demand is primarily a component of how costs of driving cars are affected. It is calculated as part of the environmental impact assessment, but not treated as an environmental impact in our economic perspective.

4.2.2.5 Data on unit cost of travel time

Based on the findings and discussions in L3Pilot (Bjorvatn et al., 2021), the benefit derived from the lowering of travel time costs when driving automated vehicles is a major contributor to the welfare gains of AD. There are several factors related to AD which may be expected to cause the unit travel time cost to decrease, thereby generating travel time cost savings. It is an opportunity for those with driving responsibility to engage in productive work and other non-driving activities while travelling. AD may further affect the perception of risk associated with travelling, as traffic accidents can be reduced and the predictability of expected travel time increased, which theoretically should lower the travel time costs. This is also the case if travel comfort increases, as AD may make travelling less stressful, or because car sickness may be reduced.

Information on these matters may be attained from questionnaires in WP6.3 *User acceptance and awareness* and will be elaborated on in the mobility impact assessment. The specific questions to be constructed within Hi-Drive are yet to be decided. It is important that these questions should address expected impacts compared to the traffic situation resembling the baseline for the estimation of economic values regarding safety, efficiency, and environmental impacts.

As already mentioned, such questions capture changes in the alternative cost of spending time travelling. These are factors that should materialize in a reduction of the unit cost of travel time. Results of analyses in this area based on questionnaires may be compared with the results from other studies based on more sophisticated modelling, such as the route choice experiments presented by Flügel et al. (2019).

4.2.2.6 Data on social equity impacts

The questionnaires in WP6.3 *User acceptance and awareness* are essential to provide information which can serve as input when considering potential social equity impacts. To the extent that benefits will accrue among drivers of automated vehicles, information on who is likely to acquire such cars is of relevance. Therefore, questions on willingness to pay for AD are essential, as the distribution of willingness to pay relative to the respondents' socio-economic status or income will reveal to what extent those better off are likely to benefit the most.

Equity with regard to gender will depend on whether there are gender differences in how the benefits of AD are perceived. To the extent that WP6.3 *User acceptance and awareness* can provide information on to what extent there are gender differences in the subjective feeling of uncertainty regarding traffic accidents, the gender expressing the strongest uncertainty can be expected to value the safety impacts of AD more highly and hence benefit the most from expected reductions in traffic accidents. To what extent this is realized with AD is far from fully understood and can be clarified with information on willingness to pay for AD by gender.

Information that can shed light on social equity issues related to how AD can be expected to facilitate equal access to car use by the disabled, sick, and elderly, is not easily available, and it is uncertain whether it can be provided. Knowledge is needed on the different factors that actually prevent people from fulfilling their travel needs, and to what extent AD can be expected to make driving so much easier that these obstacles are overcome.

4.2.2.7 Standard unit costs

The impact assessments on safety, efficiency, and environment will provide quantified estimates of impacts expressed in some physical unit. The monetary value of these impacts is calculated in the socio-economic impact evaluation,.

The unit costs applied to calculate the monetary value of expected impacts will differ between the different types of impact. They will also differ depending on the analytical perspective in the analyses, i.e., between the society as a whole and each group of stakeholders.

Standard unit costs at the European level are needed to calculate the monetary value of these impacts. The challenge is that authoritative standard unit costs for transport economic analyses are only available for each European country, and their quality differs significantly because they are calculated with different methods and not necessarily in accordance with sound theoretical principles. This means that it is essential to document the basis for the choice of standard unit costs.

Standard unit costs will also differ between the analytical perspectives. In the aggregate macro perspective, all costs must be included when costs are considered, and taxes must be excluded to calculate costs from the society's point of view. In a stakeholder perspective, only impacts that directly concern the stakeholders are of relevance, and the costs considered must include taxes. These principal differences should be borne in mind also when addressing stakeholder issues qualitatively.

The standard unit costs applied will be based on historical data. It has however, already been discussed that AD may affect the unit cost of travel time. In the analyses, this will be addressed in two steps. The monetary value of AD-induced changes in travel time will be calculated based on historical figures for all vehicles. Then, the magnitude of travel time cost savings based on a lower unit travel time cost for travellers in AD-equipped cars will be calculated separately.

AD may also change unit costs in other areas than for traffic accidents. Safety impacts are estimated by showing how AD and its enablers may be expected to reduce the number of traffic accidents for each category of accident severity. However, it is uncertain how AD and its enablers may change the composition of human injuries and material damages for the different categories of accident severity. Thus, we will have to rely on unit costs based on historical data.

Impacts are estimated on an annual basis. The standard unit costs needed to conduct the economic analyses establishing the economic values of these impacts must be calculated for:

- Unit accident costs for each category of accident severity
- Unit travel time costs
- Unit CO_2 emission costs
- Unit energy costs

In addition, standard unit costs have to be calculated on an annual basis to provide relevant cost data for the investments needed to achieve these impacts:

- Annual unit costs for equipping passenger cars with AD

- Annual costs of enablers

The calculation of standard unit costs is not straightforward. The principal guidelines for these calculations, and the methods applied, will be covered in detail in D7.5 *Socio-economic effects* presenting the results of the socio-economic impact evaluation.

4.2.3 Summary of the evaluation plan

The different stages in the evaluation plan for assessing the socio-economic impacts of AD and its enablers are summarized in Figure 4.3. The first stage is to ensure that the impacts, which are provided by the impact assessments on safety, efficiency, environment, and mobility, are estimated and upscaled to match the needs of the socio-economic impact evaluation. We expect that impacts regarding safety, efficiency, and environment will be quantified, while mobility impacts to a larger extent will be based on qualitative elaborations.

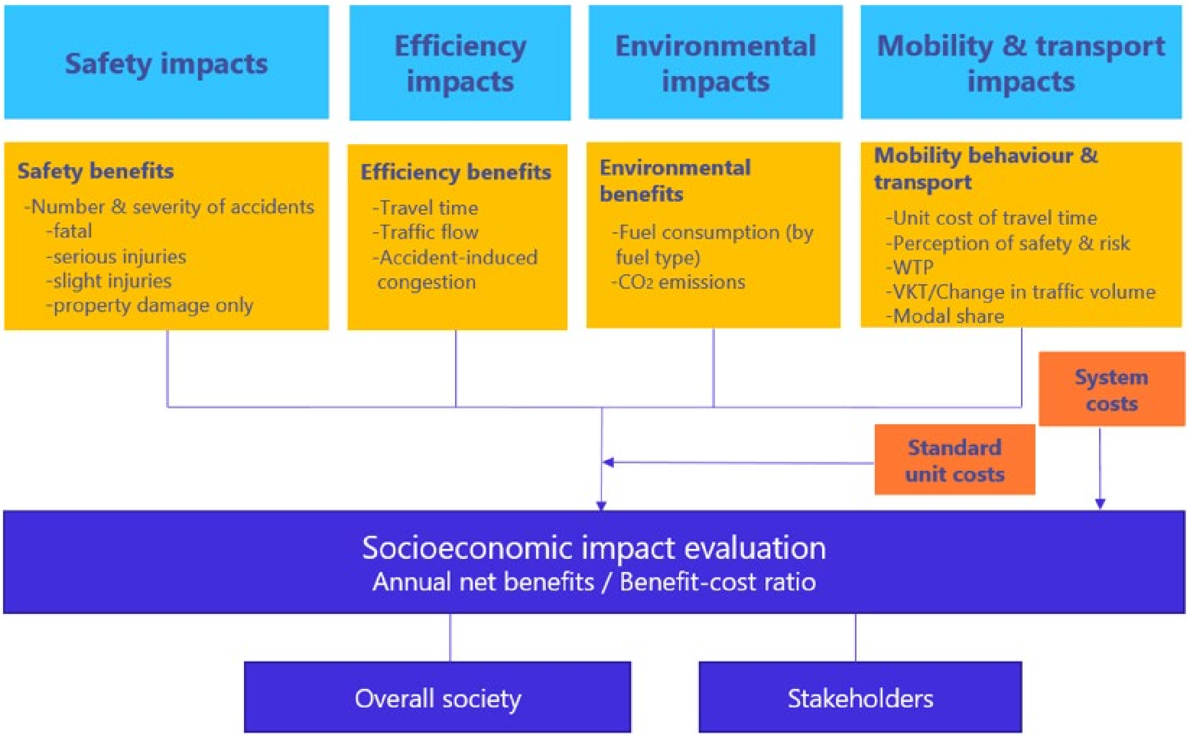

Figure 4.3: Detailed socio-economic evaluation plan.

The second stage is to provide relevant and well documented unit costs to calculate the monetary value of the detected impacts. As authorized unit cost data at the European level are missing, we have to build on the work of other studies and on standard unit costs established for transport economic analyses at national level. We should be aware that national recommendations do not always comply with guidelines derived from economic theory.

The third stage is to provide realistic system cost data regarding production, installation, and maintenance of AD and its enablers. This is a challenging task as producers, for many legitimate reasons, are reluctant in sharing cost data with outsiders.

The fourth and final stage is to carry out the cost-benefit analyses of AD and the enablers that enhance the functioning of this technology. The cost-benefit considerations will primarily deal with impacts detected regarding safety, efficiency, environment, and mobility. Impacts regarding the traffic systems, based on macroscopic modelling, will address how AD can be expected to change the traffic situation at baseline, which is outside the scope incorporated in the snapshot approach. Hence, such impacts will be included in the discussion of reliability and validity of the findings from the cost-benefit analyses, and how the findings should be interpreted.

5 Conclusions and outlook

This deliverable defines the methods and evaluation plans for the following three assessment areas: the technical evaluation, the impact assessment, and the socio-economic impact assessment.

For the technical evaluation plan, the available information from previous and parallel work packages was systematically analysed to establish the methods and the plan for assessing the effect of enablers on the availability and driving behaviour of AD. The evaluation plan is based on a driving scenario concept and performance indicators. However, not every research question is relevant to every use case and not each driving scenario will happen in each use case. This complexity and multi-layered structure were the biggest challenge for setting up the plan. The challenge has been met through a systematic approach and continuous exchange with all relevant experts in the project.

In the impact assessment, the impacts of AD and especially its enablers on different aspects are estimated and scaled up to the European level. The impacts on safety, efficiency, the environment, the transport system, and the mobility are considered separately. In each area, different methods and tools are needed and used to estimate the impacts. This made the development of the methodology and plan particularly challenging, as a high level of expertise is required in each area. Furthermore, not all enablers developed and tested in the project have the same expected impact in every impact area. The selection of the enablers covered in each of the assessments has been a key point in the preparation of the plans.

In the socio-economic impact assessment, the focus is on the welfare benefits of AD and its enablers from the society's point of view. For this purpose, a cost-benefit analysis will be carried out. In addition to various external data sources, simulation results from the impact assessment that are scaled up to European level are considered.

The evaluation plans presented in this deliverable will be implemented and carried out in SP7 *Effects* to get the results. Finally, details of the evaluations will be developed and agreed upon during implementation of the evaluation plan. The results of the technical evaluation will be reported in D7.1 *Technical evaluation results*. The results of the impact assessment will be reported in D7.2 *Effects*, which combines D7.3 *Effect on safety* and D7.4 *Effects on mobility, efficiency and environment*. The results of the socio-economic impact assessment will be reported in D7.5 *Socio-economic effects*.

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List of abbreviations and acronyms

Abbreviation	Meaning
ACC	Adaptive cruise control
AD	Automated driving
ADAS	Advanced Driver Assistance System
ADF	Automated driving function
AV	Automated vehicle
BADF	Baseline ADF (without enablers) in impact assessment
CAD	Connected and automated driving
CAV	Connected and automated vehicle
CDB	Consolidated database
CDF	Common data format
CoP	Code of Practice
EADF	ADF with enablers in impact assessment
EU	European Union
E&E	Efficiency and environmental
GLOSA	Green light optimal speed advisory
HDV	Heavy-duty vehicle
HBEFA	Handbook Emission Factors for Road Transport
I2V	Infrastructure to vehicle
IRF	Injury-risk function
ISA	Intelligent speed assistance
L3	SAE level 3 (driving automation)
ODD	Operational design domain
OSM	OpenStreetMap
PCU	Passenger car unit
THW	Time headway
TOR	Take-over request
TTC	Time to collision
V2I	Vehicle to infrastructure
V2V	Vehicle to vehicle
V2X	Vehicle to everything

Abbreviation	Meaning
VDF	Volume-delay function
VHT	Vehicle hours travelled
VKT	Vehicle kilometres travelled
VRU	Vulnerable road user

Annex 1 Templates for setting up the technical evaluation plan

Task for Table A1.1: "*Which research question is relevant for which use case?*"

Table A1.1: Template for the mapping between use cases and research questions.

	Medium-level research question 1	**Medium-level research question 2**	**...**	**Medium-level research question 17**
Use case 1	*Yes/no*	*Yes/no*	...	*Yes/no*
...	...	...	...	...
Use case 36	*Yes/no*	*Yes/no*	...	*Yes/no*

Task for Table A1.2: "*Which driving scenarios occur in the use cases?*"

Table A1.2: Template for the mapping between use cases and driving scenarios.

	Driving scenario 1	**Driving scenario 2**	**...**	**Driving scenario 36**
Use case 1	*Yes/no*	*Yes/no*	...	*Yes/no*
...	...	...	...	...
Use Case 36	*Yes/no*	*Yes/no*	...	*Yes/no*

Task for Table A1.3: "*For the use case, which performance indicators are valid of meaningful within which driving scenario? Which performance indicators should be calculated per test scenario or per trip/test run?*"

Table A1.3: Template (for one use case) for the mapping between performance indicators and driving scenarios per use case.

Medium-level research question	Low-level research question	Performance indicator	Driving scenario X	...	Driving scenario Y	Per test scenario	Per trip/test run
Medium-level research question A	Low-level research question A.1	Performance indicator A.1.1	*Yes/no*	...	*Yes/no*	*Yes/no*	*Yes/no*
	Low-level research question A.1	Performance indicator A.2.1	*Yes/no*	...	*Yes/no*	*Yes/no*	*Yes/no*
		Performance indicator A.2.2	*Yes/no*	...	*Yes/no*	*Yes/no*	*Yes/no*
Medium-level research question B	Low-level research question B.1	Performance indicator B.1.2	*Yes/no*	...	*Yes/no*	*Yes/no*	*Yes/no*
...	...	...	...	...	...	...	...
Medium-level research question N	Low-level research question N.1	Performance indicator N17.1.1	*Yes/no*	...	*Yes/no*	*Yes/no*	*Yes/no*

Annex 2 Use cases, ADFs, and operations in the technical evaluation

The tables in this annex list the use cases covered in the technical evaluation and their corresponding ADFs and operations. The ADFs are divided in four categories according to their ADF group (motorway and inter-urban motorway, rural, urban, parking) and mapped to the ADF and operation IDs. The ADF and operation IDs are based on the anonymization processes for the ADFs and operations in the Hi-Drive project described in D3.1 *Use case definition and description* (Bolovinou et al., 2023) and D5.1 *Description of operations* (Sauvaget et al., 2023), respectively.

Table A2.1: Motorway use cases in the technical evaluation mapped to ADFs and operations.

ID	Title	Test enviroment	ADF IDs	Operation IDs
M1	Cooperative Overtaking via V2V with rear vehicle	Open road, test track	M.ADF4	6.1
M2	Cooperative Lane Merging on motorway entry via V2V [AV drives on the on-ramp area (2 actors)]	Test track, virtual	M.ADF1, M.ADF2, M.ADF3, M.ADF5	9.1, 7.1, 18.1, 10.3
M3	Cooperative Merging Awareness on Motorway entry via V2V [AV drives on the motorway (2 actors)]	Test track	M.ADF1, M.ADF2, M.ADF3, M.ADF5	9.1, 7.1, 18.1, 10.3
M4	Cooperative Lane Merging on Motorway entry with lead vehicle via V2V [AV drives on the on-ramp area (3 actors)]	Test track	M.ADF3	18.1
M5	Cooperative Merging Awareness on Motorway entry with lead AV vehicle via V2V – AV drives on the motorway (3 actors)	Test track	M.ADF3	18.1
M6	Cooperative Lane Exiting via I2V	Open road, test track	M.ADF4	6.3
M7	Cooperative Lane Merging and cyber-attack	Open road, test track	M.ADF4	6.6
M8	Cooperative Hazard Awareness and Avoidance (lane changing or speed adaptation required)	Open road, test track	M.ADF4, M.ADF5, M.ADF7	6.2, 10.1, 5.1

ID	Title	Test enviroment	ADF IDs	Operation IDs
M9	Cooperative Dynamic Signage Awareness (lane changing or speed adaptation required)	Open road, test track	M.ADF5, M.ADF7	10.1, 5.1
M10	Driving through a tunnel	Open road	M.ADF7, M.ADF8, M.ADF9	5.2, 1.1, 16.1
M11	Driving through a road construction zone	Open road, virtual	M.ADF8, M.ADF9	1.1, 16.2
M12	Support of a basic set of scenarios in lane keeping mode: Free Driving, Car following, Passive cut-in	Open road, virtual	M.ADF4; M.ADF7; M.ADF10	6.1, 6.2, 6.2, 6.4, 6.6; 5.1, 5.2; 8.2
M13	Lane change	Open road	M.ADF7, M.ADF10	5.1, 8.2
M14	Driving in lane under rain/fog/heavy rain	Open road	M.ADF4, M.ADF8	6.2, 1.1
M15	Approaching elevated bridge	Open road	M.ADF4, M.ADF8	6.4, 1.1
M16	Driving through areas affected by GNSS interruption or map inconsistencies or deteriorated lane markings	Open road, test track, virtual	M.ADF4, M.ADF7	6.4, 5.2
M17	Interchange from one motorway to next motorway (navigation system available)	Open road, test track	M.ADF10	8.2
M19	Passing motorway entry and allowing other vehicle to merge	Open road	M.ADF7, M.ADF10	5.1, 5.2, 8.2

Table A2.2: Urban use cases in the technical evaluation mapped to ADFs and operations.

ID	Title	Test environment	ADF IDs	Operation IDs
U1	Cooperative non-signalized intersection crossing via V2I	Test track	U.ADF2	10.2
U2	Cooperative non-signalized roundabout crossing via V2I (focus on conflicts between CAV and other vehicles)	Open road	U.ADF9	15.1
U3	Smart intersection crossing (RSU and connected vehicles)	Test track, virtual	U.ADF6	18.2

ID	Title	Test environment	ADF IDs	Operation IDs
U4	Smart traffic light crossing	Open road, test track	U.ADF1, U.ADF3, U.ADF4	8.1, 20.1, 20.3, 12.1
U5	Consecutive Traffic Light crossing	Open road, test track	U.ADF4	12.1
U6	Re-routing to avoid congestion or hazard in front	Open road test track, virtual	U.ADF5, U.ADF9	14.1, 15.1
U7	Cooperative speed adaptation applicable downstream via V2V	Test track	U.ADF5	14.1
U8	Signalized intersection crossing	Open road	U.ADF3, U.ADF7	20.1, 20.3 4.1
U9	Support of basic set of scenarios: Free driving / Car-Follow / Cut-in	Open road	U.ADF1, U.ADF3, U.ADF5, U.ADF7, U.ADF9	8.1, 20.1, 20.3, 14.1, 4.1, 15.
U10	Lane changing / Overtaking	Open road	U.ADF7	4.1
U11	Urban canyon driving	Test track	U.ADF4	12.2, 12.3
U12	Driving in rainy weather or with missing lane markings	Open road	U.ADF3, U.ADF7, U.ADF9	20.1, 20.3, 4.1, 15.1,15.2
U13	Pedestrian crossing (w/wo zebra crossing)	Open road	U.ADF7	4.1
U14	Crossing intersection with left or right turn	Open road	U.ADF3, U.ADF7, U.ADF9	20.1, 20.3, 4.1, 15.1

Table A2.3: Rural use cases in the technical evaluation mapped to ADFs and operations.

ID	Title	Test environment	ADF IDs	Operation IDs
R1	Urban-to-rural transition	Open road	R.ADF1	20.2
R2	AV-Truck Cooperative Overtaking on 2-directional road via V2V object info sharing from truck	Test track	R.ADF2	18.3
R3	(Cooperative) Arctic driving on road covered by snow	Open road	R.ADF3	19.1, 19.2, 19.3

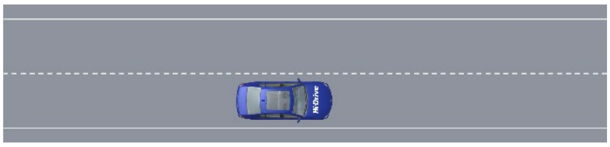
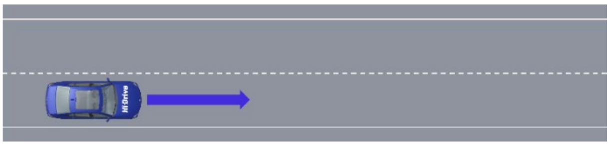
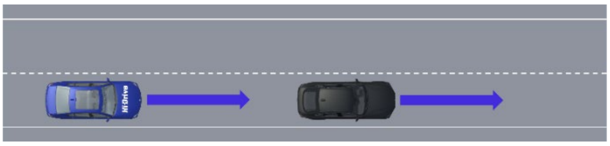
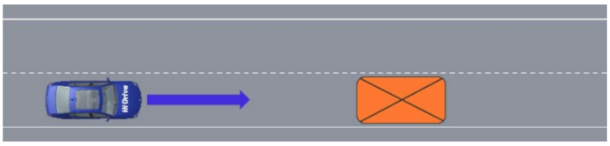
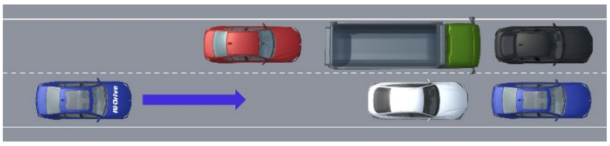
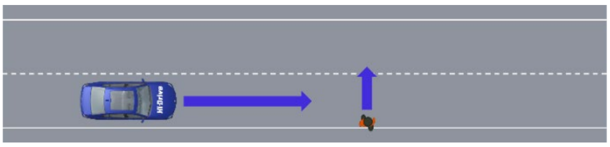
Table A2.4: Parking use case in the technical evaluation mapped to ADFs and operations.

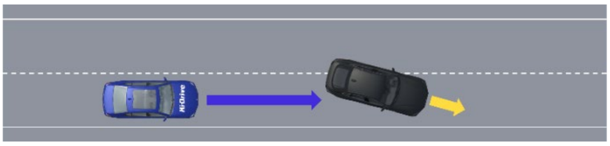
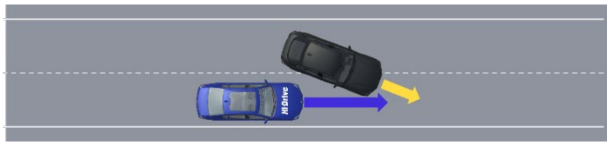
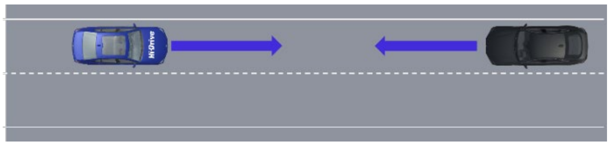
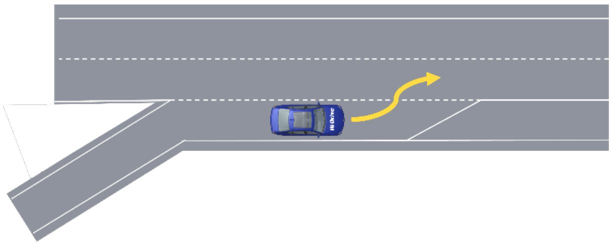
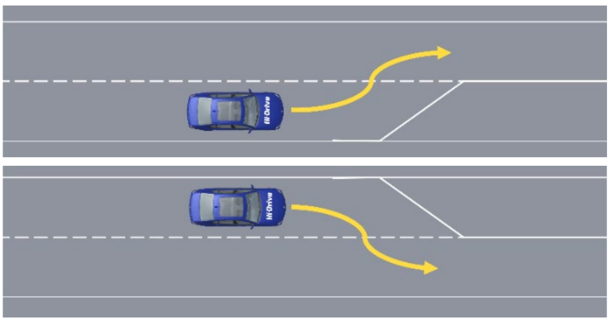
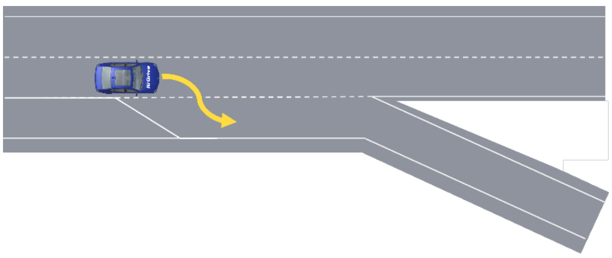
ID	Title	Test environment	ADF IDs	Operation IDs
P1	Automated Valet Parking via seamless positioning	Test track	P.ADF1, P.ADF2	8.3, 6.5

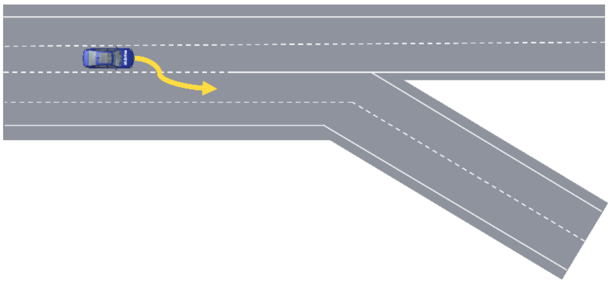
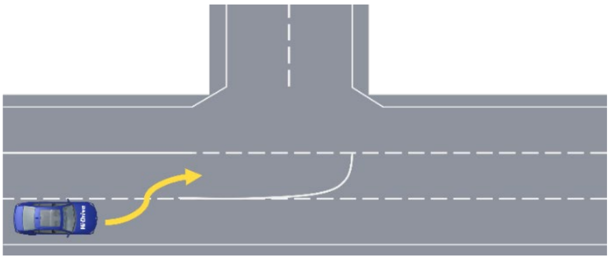
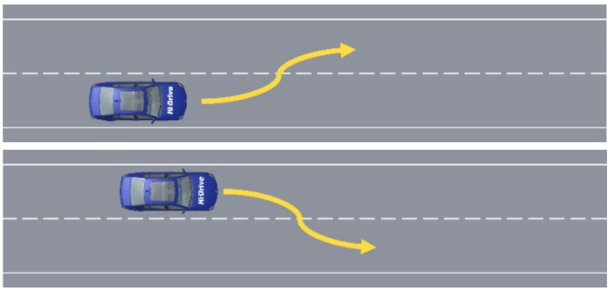
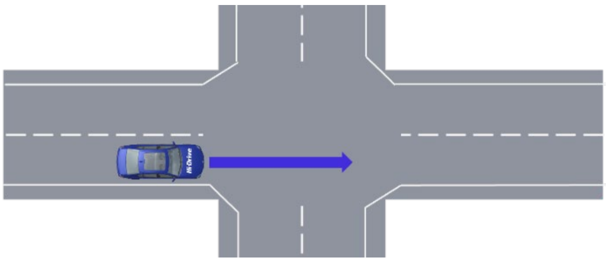
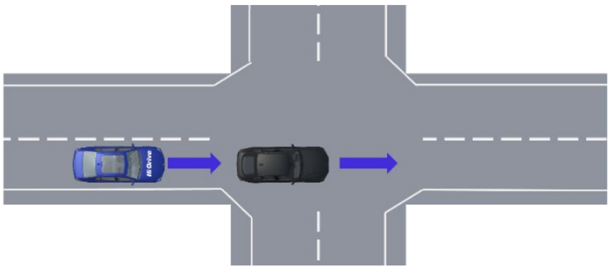
Annex 3 Driving scenarios for the technical evaluation

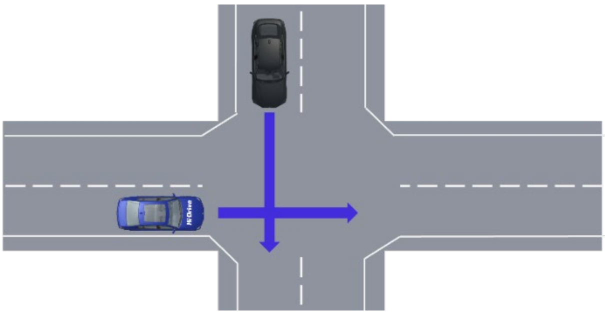
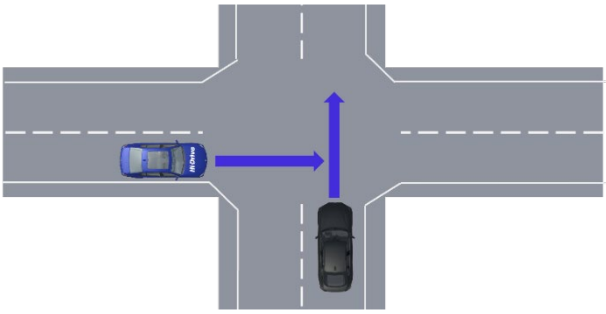
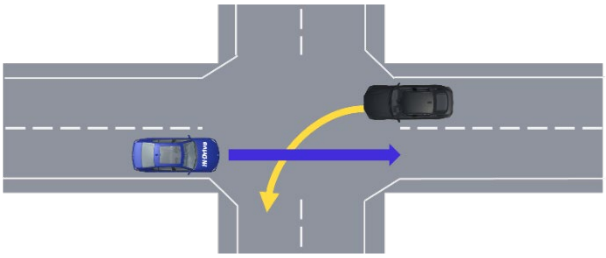
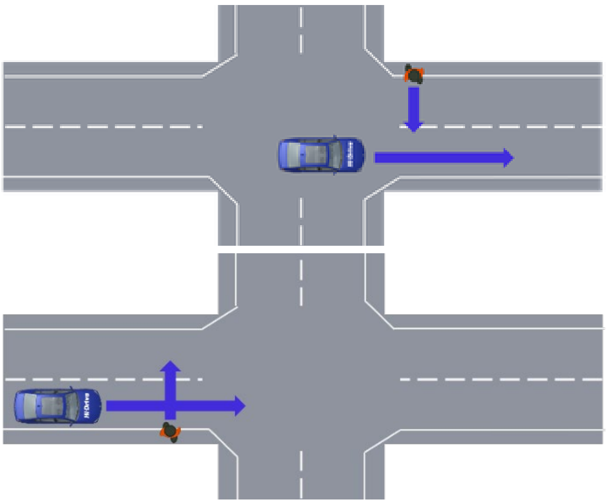
Detailed information on the driving scenario concept can be found in the corresponding publication (Sonntag et al., 2023).

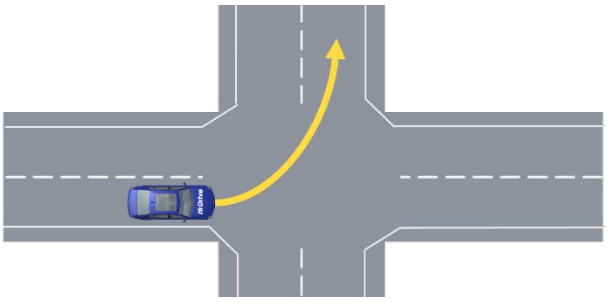
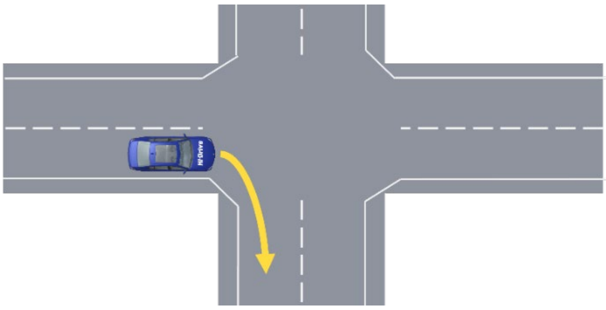
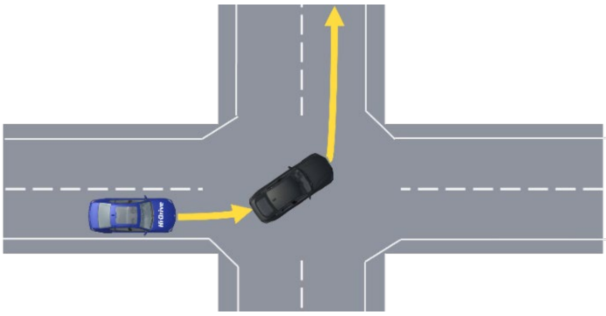
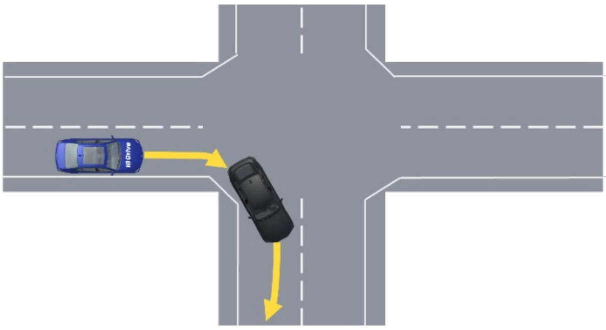
Table A3.1: List of all driving scenarios used in the technical evaluation.

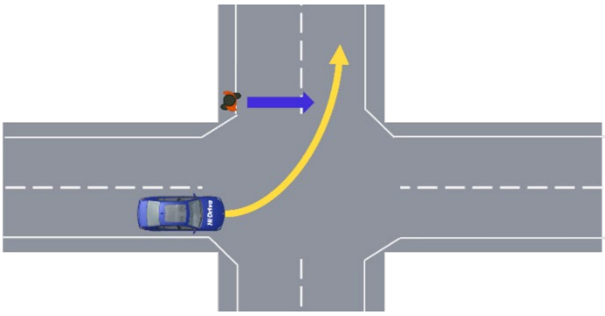
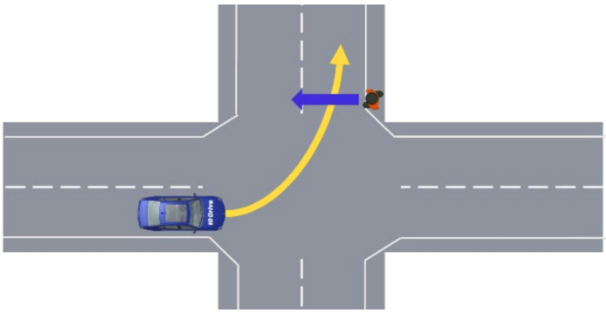
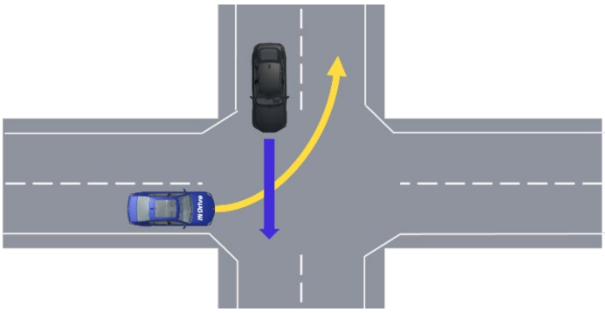
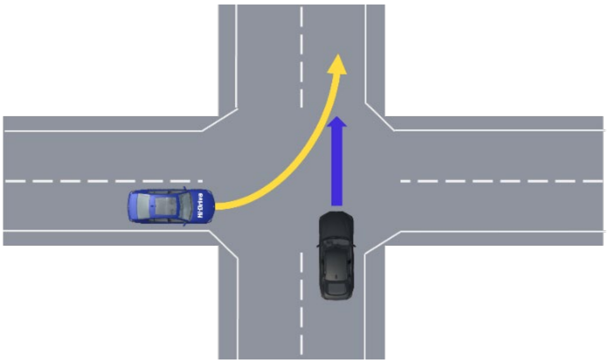
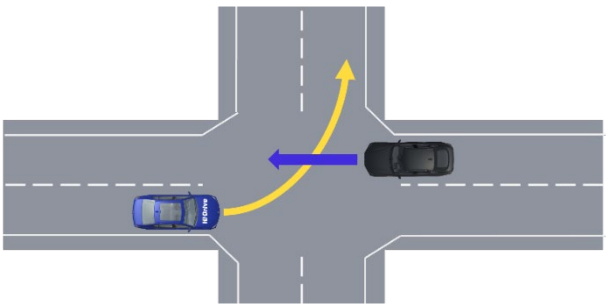
Name	Description	Pictogram
Standstill	The ego vehicle does not move for a period of time.	
Uninfluenced Driving	The ego vehicle is following a lane without being influenced by front objects.	
Following Object	The ego vehicle is following a lane and is following a dynamic object.	
Approaching Static Object	The ego vehicle is following a lane and is approaching a static object.	
Approaching Object in Traffic Jam	The ego vehicle is following a lane and is approaching an object in a traffic jam.	
Approaching Longitudinally Moving Object	The ego vehicle is following a lane and is approaching an object that is driving in the same lane.	
Approaching Laterally Moving Object	The ego vehicle is following a lane and is approaching a laterally moving object at a road section that is not near a crossing.	

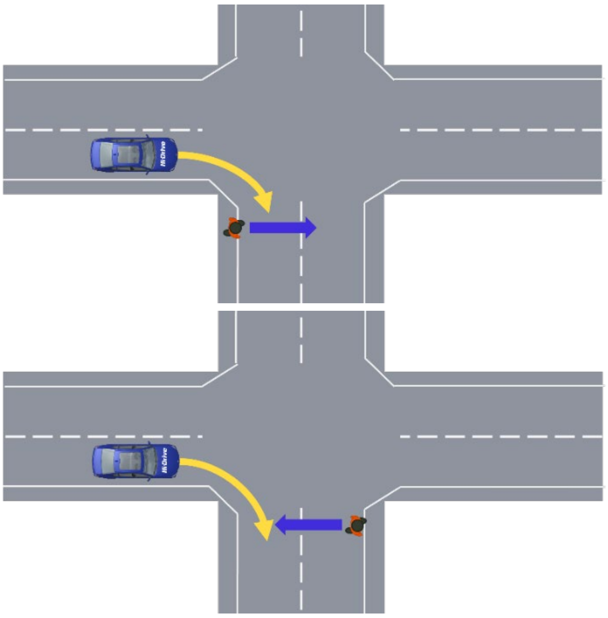
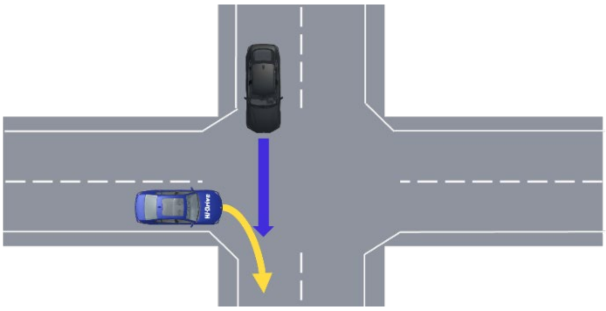
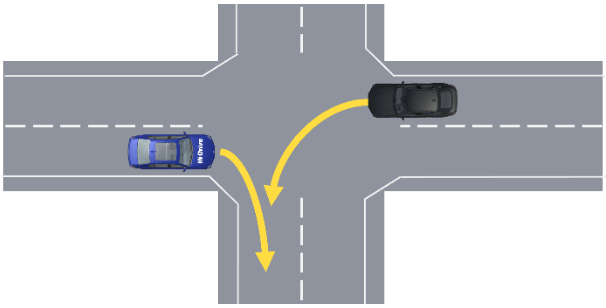
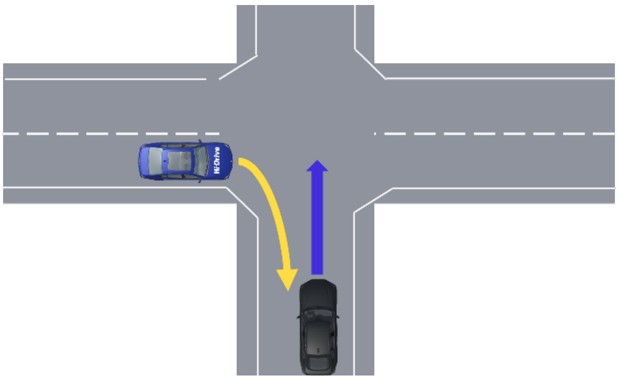
Name	Description	Pictogram
Cut-in with a Rear-End Conflict	The ego vehicle is following a lane and another object is doing a cut-in that results in a rear-end conflict.	
Cut-in with a Sideswipe Conflict	The ego vehicle is following a lane and another object is doing a cut-in that results in a sideswipe conflict.	
Oncoming Traffic in Lane	The ego vehicle is following a lane and in the same lane is oncoming traffic (happens e.g. when ego is overtaking).	
On-Ramp	The ego vehicle is changing lane. The lane change needs to be performed for routing as the ego vehicle is doing an on-ramp.	
Lane Change at Merging Lanes	The ego vehicle is changing lane. The lane change needs to be performed as lanes are merging.	
Off-Ramp	The ego vehicle is changing lane. The lane change needs to be performed for routing as the ego vehicle is doing an off-ramp.	

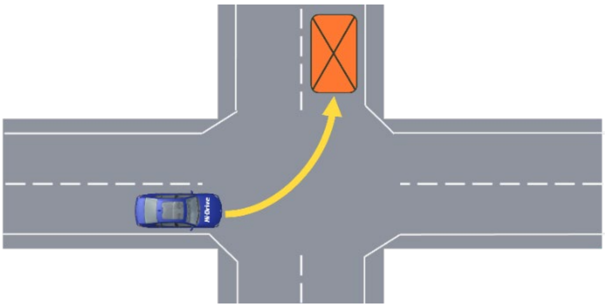
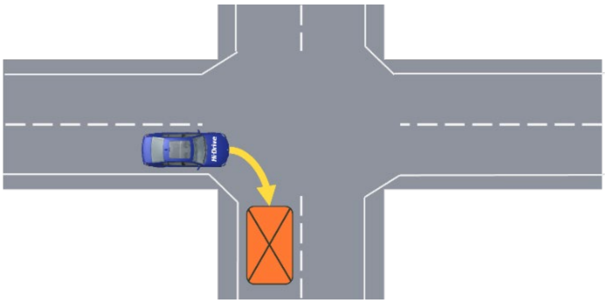
Name	Description	Pictogram
Lane Change at Interchange	The ego vehicle is changing lane. The lane change needs to be performed for routing as the ego vehicle is at an interchange.	
Lane Change at Intersection	The ego vehicle is changing lane. The lane change needs to be performed for routing as the ego vehicle needs to change its lane at an intersection.	
Discretionary Lane Change	The ego vehicle is changing lane. The lane change does not need to be performed but it optimizes speed, comfort etc.	
Crossing with no Interaction	The ego vehicle is crossing an intersection and does not interact with any other dynamic object.	
Crossing Interacting with a Lead Object	The ego vehicle is crossing an intersection and interacts with a leading vehicle or bicycle that is driving on the road.	

Name	Description	Pictogram
Crossing Interacting with a Vehicle/Bicycle Coming from Left	The ego vehicle is crossing an intersection and interacts with a vehicle or bicycle that is driving on the road and is coming from the left. The other vehicle can either turn or cross.	
Crossing Interacting with a Vehicle/Bicycle Coming from Right	The ego vehicle is crossing an intersection and interacts with a vehicle or bicycle that is driving on the road and is coming from the right. The other vehicle can either turn or cross.	
Crossing Interacting with an Oncoming Vehicle/Bicycle Turning Left	The ego vehicle is crossing an intersection and interacts with a vehicle or bicycle that is driving on the road and is oncoming and e.g. turning left.	
Crossing Interacting with a Pedestrian Crossing	The ego vehicle is crossing an intersection and interacts with a pedestrian crossing the road, who may cross the road right before or after the intersection from the right or left.	

Name	Description	Pictogram
Turning Left no Interaction	The ego vehicle is turning left at an intersection without interacting with any other road user.	
Turning Right no Interaction	The ego vehicle is turning right at an intersection without interacting with any other road user.	
Turning Left with a Lead Object	The ego vehicle is turning left at an intersection interacting with a dynamic lead object that is turning left as well.	
Turning Right with a Lead Object	The ego vehicle is turning right at an intersection interacting with a dynamic lead object that is turning right as well.	

Name	Description	Pictogram
Turning Left Interacting with a Pedestrian Crossing	The ego vehicle is turning left at an intersection interacting with a pedestrian crossing the road from the left or right.	 
Turning Left Interacting with a Vehicle/Bicycle Coming from Left	The ego vehicle is turning left at an intersection interacting with a vehicle or bicycle that is driving on the road coming from the left.	
Turning Left Interacting with a Vehicle/Bicycle Coming from Right	The ego vehicle is turning left at an intersection interacting with a vehicle or bicycle that is driving on the road coming from the right.	
Turning Left Interacting with an Oncoming Vehicle/Bicycle	The ego vehicle is turning left at an intersection interacting with an oncoming vehicle or bicycle that is driving on the road.	

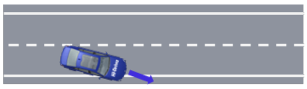
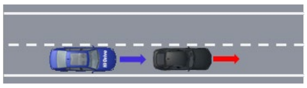
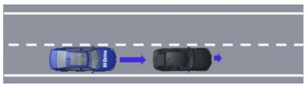
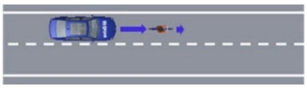
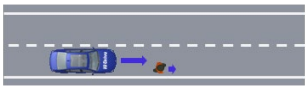
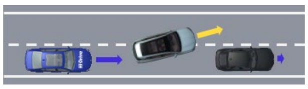
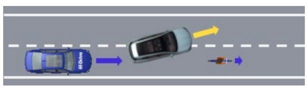
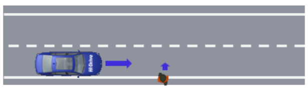
Name	Description	Pictogram
Turning Right Interacting with a Pedestrian Crossing	The ego vehicle is turning right at an intersection interacting with a pedestrian crossing the road from the left or right.	
Turning Right Interacting with a Vehicle/Bicycle Coming from Left	The ego vehicle is turning right at an intersection interacting with a vehicle or bicycle that is driving on the road coming from the left.	
Turning Right Interacting with an Oncoming Vehicle/Bicycle	The ego vehicle is turning right at an intersection interacting with an oncoming vehicle or bicycle that is driving on the road.	
Turning Right Interacting with a Vehicle/Bicycle Coming from Right	The ego vehicle is turning right at an intersection interacting with a vehicle or bicycle that is driving on the road coming from the right.	

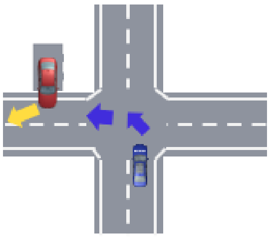
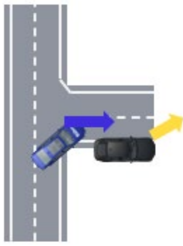
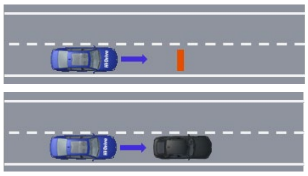
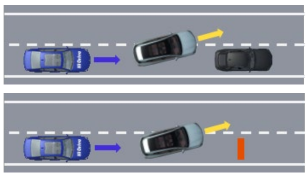
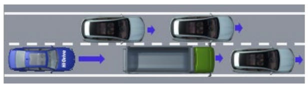
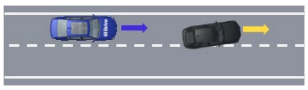
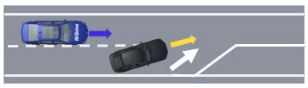
Name	Description	Pictogram
Turning Left Interacting with a Static Object on the Road	The ego vehicle is turning left at an intersection interacting with a static object on the road.	
Turning Right Interacting with a Static Object on the Road	The ego vehicle is turning right at an intersection interacting with a static object on the road.	

Annex 4 Driving scenarios for the safety impact assessment

The list of scenarios builds upon driving scenarios for the technical evaluation and the Hi-Drive driving scenario concept (Sonntag et al., 2023). The rightmost column indicates which road type is considered and the preliminary assignment of baseline approach to be used.

Table A4.1: Driving scenarios in the category Driving in lane.

ID	Scenario type	Conflict type	Pictogram	Considered road type (m = motorway, u=urban, r=rural) and assessment approach
01|01	Uninfluenced Driving (run-off road)	Run-off road conflict / Single vehicle conflict		Expert judgment: m, u & r
01|02	Following Object	Rear-end conflict		Approach B: m, u & r
01|03	Approaching – moving	Front / Rear-end conflict w. slower moving vehicle (Car)		Approach B: m, u & r
01|04	Approaching – moving	Front / Rear-end conflict w. slower moving vehicle (Cyclist, VRU)		Approach B: u & r
01|05	Approaching – moving	Front conflict w. pedestrian moving		Approach B: u & r
01|06	Approaching – moving (Vehicle or Object)	Cut-out collision		Approach C2 without traffic: m, u & r
01|07	Approaching – moving (VRU)	Cut-out collision		Approach C2 without traffic: u & r
01|08	Approaching – moving	Front conflict w. VRU moving laterally (left and right)		Approach C2: m Approach B or C2: u & r

ID	Scenario type	Conflict type	Pictogram	Considered road type (m = motorway, u=urban, r=rural) and assessment approach
01|09	Approaching – moving	Moving from private garage/alley, at left, conflict Rear-end; front/side collision		Approach C2: u & r
01|10	Approaching – moving	Entering/exit conflict (private lane/garage close to curve); Rear-end/front side collision		Approach C2: u
01|11	Approaching – standing still	Crash with vehicle, VRU, object		Approach C2: m & u
01|12	Approaching – standing still	Cut-out collision		Approach C2: m & u
01|13	Approaching – Object in traffic jam	Front / Rear-end conflict w. vehicle / truck		Expert judgment: m & u
01|14	Cut-in – rear-end	Front / Rear-end conflict w. vehicle / truck / MTW		Approach B: m & u
01|15	Cut-in – rear-end (infrastructure related) (Truck)	Front / Rear-end conflict w. vehicle / truck / MTW		Approach C2: m
01|16	Cut-in – side swipe	Side swipe		Approach B: m & u

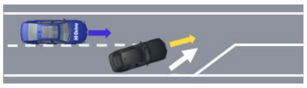
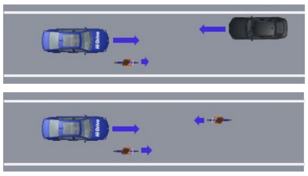
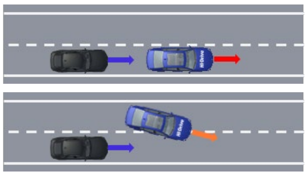
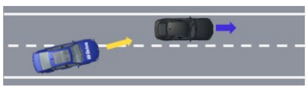
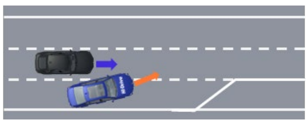
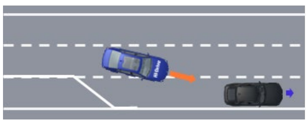
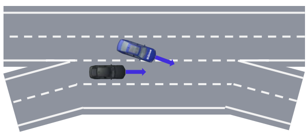
ID	Scenario type	Conflict type	Pictogram	Considered road type (m = motorway, u=urban, r=rural) and assessment approach
01|17	Cut-in – side swipe (infrastructure related)	Side swipe		Approach C2: m
01|18	Oncoming traffic in lane	Front-Front conflict		Expert judgment: m & r Approach B: u
01|19	Minimum Risk Manoeuvre	Rear-end conflict (ego: front vehicle), lane change conflict (ego-lane change)		Approach C: m & u

Table A4.2: Driving scenarios in the category Lane change.

ID	Scenario type	Conflict type	Pictogram	Considered road type (m = motorway, u=urban, r=rural) and assessment approach
02|01	Discretionary – to left	Front-/rear-end conflict		Approach C2: m & u
02|02	Discretionary – to right	Front-/rear-end conflict		Approach C2: m & u
02|03	Mandatory – for routing- on ramp	Cut-in conflict		Approach C2: m
02|04	Mandatory – for routing- off ramp	Rear-end conflict		Not considered in safety impact assessment
02|05	Mandatory – interchange	Front-/rear-end conflict, Cut-in/out conflict		Expert judgement:

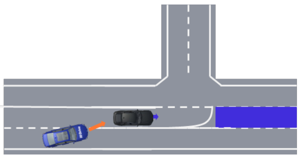
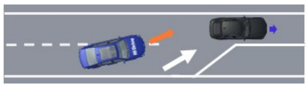
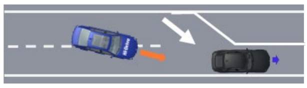
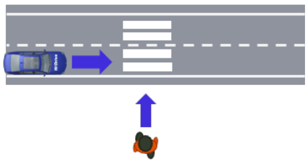
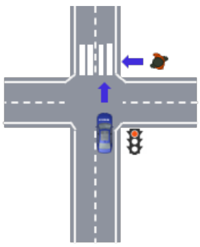
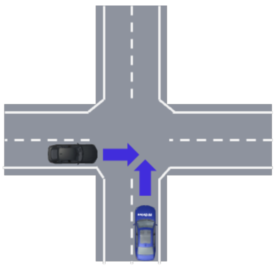
ID	Scenario type	Conflict type	Pictogram	Considered road type (m = motorway, u=urban, r=rural) and assessment approach
02|06	Mandatory – intersection	Front-/rear-end conflict, Cut-in/out collision		Not considered in safety impact assessment
02|07	Mandatory – merging lanes to left	Front-/rear-end conflict, Cut-in collision		Approach C2: m & u
02|08	Mandatory – merging lanes to right	Front-/rear-end conflict, Cut-in collision		Approach C2: m & u

Table A4.3: Driving scenarios in the category Crossing.

ID	Scenario type	Conflict type	Pictogram	Considered road type (m = motorway, u=urban, r=rural) and assessment approach
03|01	Interacting – VRU crossing (at a dedicated area such as a zebra crossing)	VRU conflict		Expert judgment: u
03|02	Interacting – VRU crossing (at crossing -> red light)	VRU conflict		Expert judgment: u & r
03|03	Interacting – Vehicle – from left straight	Cross-traffic/sideswipes		Approach C2 (potentially B): u & r

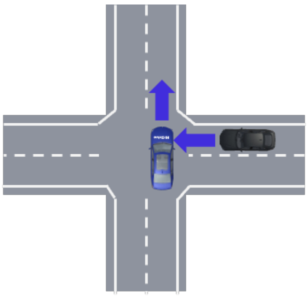
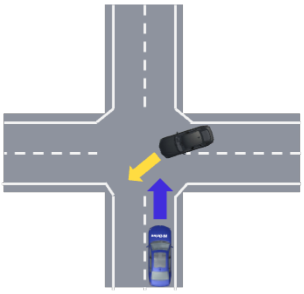
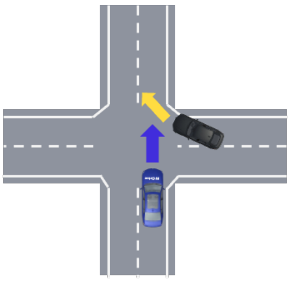
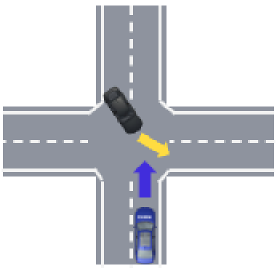
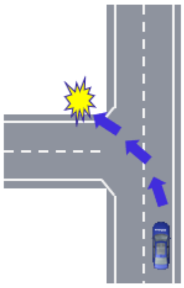
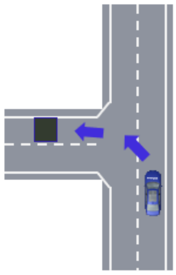
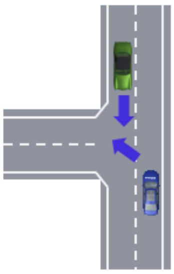
ID	Scenario type	Conflict type	Pictogram	Considered road type (m = motorway, u=urban, r=rural) and assessment approach
03|04	Interacting – Vehicle – from left turning left			Approach C2 (potentially B): u & r
03|05	Interacting – Vehicle – from right straight	Cross-traffic/sideswipes		Approach C2 (potentially B): u & r
03|06	Interacting – Vehicle – from right turning left	Cross-traffic/sideswipes		Approach C2 (potentially B): u & r
03|07	Interacting – Vehicle – from right turning right	Weave conflicts | cross-traffic/sideswipes		Approach C2 (potentially B): u & r
03|08	Interacting – Vehicle – turning left in the opposite direction	Cross-traffic/sideswipes		Approach B or C2: u & r

Table A4.4: Driving scenarios in the category turning left.

ID	Scenario type	Conflict type	Pictogram	Considered road type (m = motorway, u=urban, r=rural) and assessment approach
04|01	Not Interacting	Run off-road conflict (single vehicle / speed, road surface, visibility, ...)		Expert judgment: u & r
04|02	Interacting – Lead object	Rear-end conflict type (slower vehicle ahead)		Approach C2: u & r
04|03	Interacting – Lead object EGO turns left when VRU (PTW, cyclist) is leaving a parking slot	Moving from parking slot conflict | Rear-end/front side collision		Expert judgment: u & r
04|04	Interacting – static object	Rear-end conflict type (stopped vehicle or bicycle, PTW ahead)		Expert judgment: u & r

ID	Scenario type	Conflict type	Pictogram	Considered road type (m = motorway, u=urban, r=rural) and assessment approach
04|05	Interacting – static object	Front conflict (accident /object/animal in front of …) (front collision)		Expert judgment: u & r
04|06	Interacting – VRU crossing – from right	Pedestrian/Cyclist conflict (front collision)		Approach B or C2: u & r
04|07	Interacting – VRU crossing – from left	Pedestrian/Cyclist conflict (front collision)		Approach B or C2: u & r
04|08	Interacting – Vehicle – oncoming left (two lanes in opposite direction)	Oncoming traffic conflict (Head on collision)		Approach B or C2: u & r
04|09	Interacting – Vehicle – oncoming left (two lanes in opposite direction)	Oncoming from left traffic conflict (head-on collision)		Expert judgment: u & r

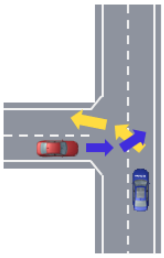
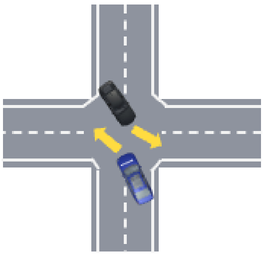
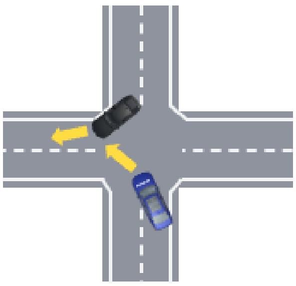
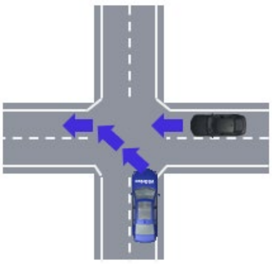
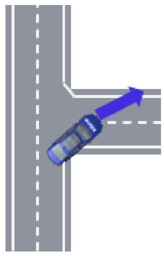
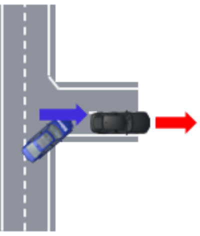
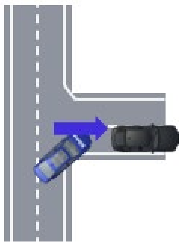
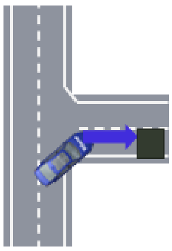
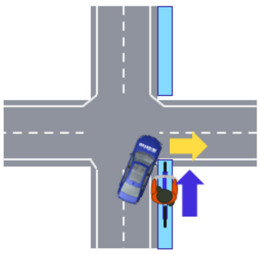
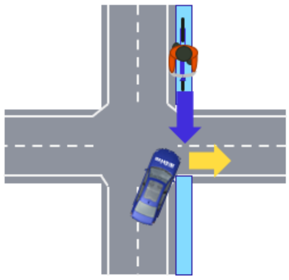
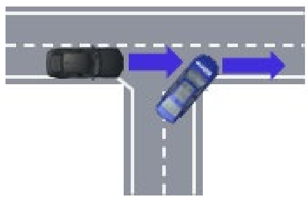
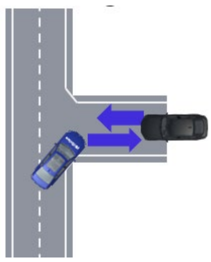
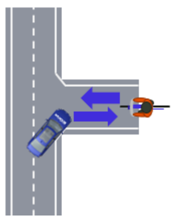
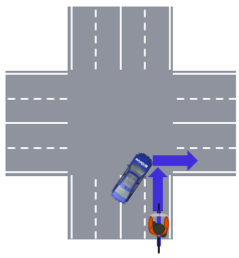
ID	Scenario type	Conflict type	Pictogram	Considered road type (m = motorway, u=urban, r=rural) and assessment approach
04|10	Interacting – vehicle overtaking at left when turning left (two lanes in the same direction)	Overtaking traffic (PTW) (front/side; sideswipe collision)		Approach B: u
04|11	Interacting – vehicle turning left when the other vehicle turning left as well	Crossing traffic (front/side; head-on collision (corner); rear-end)		Expert judgment: u
04|12	Interacting – Vehicle – oncoming left (both turning)	Oncoming traffic conflict (head-on collision)		Expert judgment: u
04|13	Interacting – Vehicle – oncoming left (both turning)	Cross-traffic/sideswipes; head-on collision		Expert judgment: u
04|14	Interacting - vehicle turning left when other vehicle going straight			Approach B: u Expert judgment: r

Table A4.5: Driving scenarios in the category turning right.

ID	Scenario type	Conflict type	Pictogram	Considered road type (m = motorway, u=urban, r=rural) and assessment approach
05|01	Not Interacting	Run off-road conflict (single vehicle / speed, road surface, road geometry, visibility, ... issue in curve)		Expert judgement: u
05|02	Interacting – Lead object	Rear-end conflict type (slower/braking vehicle ahead)		Approach C2 (potentially B): u & r
05|03	Interacting – Lead object	Rear-end conflict type (stopped vehicle, VRU ahead)		Approach C2 (potentially B): u & r
05|04	Interacting – static object	Front conflict (accident /object/animal in front of ...) (front collision)		Not considered in the safety impact assessment
05|05	Interacting – VRU crossing – from right	Pedestrian/Cyclist conflict (front collision) (side collision)		Approach B: u Expert judgment: r

ID	Scenario type	Conflict type	Pictogram	Considered road type (m = motorway, u=urban, r=rural) and assessment approach
05|06	Interacting – VRU crossing – from left	Pedestrian/Cyclist conflict (front collision) (side collision)		Approach B: u Expert judgment: r
05|07	Interacting – Vehicle – from left	Front/side or Side/front collision		Approach C2: u & r
05|08	Interacting – Vehicle – oncoming	Front collision (head-on)		Expert judgment: u
05|09	Interacting – VRU – oncoming	Front collision (head-on) PTW conflict		Expert judgment: u
05|10	Interacting – VRU coming from behind	RR-end Side impact		Approach B: u Expert judgment: r

Annex 5 Use cases covered in the efficiency and environmental impact assessment

Table A5.1 shows the selection of enabler use cases for efficiency and environmental impact assessment. The hypothesis for significance and direction of impact within the scenario addressed by the use case (compared to situation without enabler) is indicated using the following scale:

- +++ large positive,
- + small positive,
- 0 negligible,
- - small negative,
- --- large negative.

Positive meaning: increase in efficiency or decrease in emissions. Negative meaning: decrease in efficiency or increase in emissions.

Table A5.1: Selection of enabler use cases for efficiency and environmental impact assessment.

Use case grouping for impact assessment	Impact mechanism	Presumed direction and size of impact within the scenario	Difficulty of modelling	Consideration in Efficiency and Environmental Impact Assessment
Cooperative Merging	Reduce disturbance upstream	Efficiency: ++ Emissions: +	High	Simulation: yes Scaling up: yes
Non-cooperative merging	Enable (safe) merging without reducing disturbances, increase the ODD	Unknown	Very high	Not covered
V2V for speed adaptation	Extend ODD, reduce disturbance	Unknown	High	Not covered
GLOSA	Reduce delay and number of stops at traffic lights.	Efficiency: ++ Emissions: ++	Medium to high	Simulation: yes Scaling up: yes

Use case grouping for impact assessment	Impact mechanism	Presumed direction and size of impact within the scenario	Difficulty of modelling	Consideration in Efficiency and Environmental Impact Assessment
I2V for Hazard notification	Early reaction to road hazards enables smoother deceleration or a timely avoidance manoeuvre.	In congested conditions: Efficiency: + Emissions: 0/+/-	Medium to high	Not covered
I2V for dynamic road signage	Lower number of lane changes, smoother braking, and timely reactions.	In congested conditions: Efficiency: + Emissions: 0/+/-	Moderate	Simulation: yes Scaling up: yes
Driver Monitoring	Small changes in speed at TOR	Small	Moderate	Not covered
Adding infrastructure elements – Driving through tunnel	Extend ODD	n/a	n/a	Simulation: no Scaling up: yes
Adding infrastructure elements – Approaching elevated bridge	Extend ODD	n/a	n/a	Simulation: no Scaling up: yes
Adding Infrastructure Elements – Cooperative non-signalized intersection crossing via V2I	Faster driving through intersection.	Efficiency: ++ Emissions: 0/-	High	Simulation: yes Scaling up: yes
Adding Infrastructure Elements – Urban canyon driving	Extend ODD	n/a	n/a	Simulation: no Scaling up: yes

Use case grouping for impact assessment	Impact mechanism	Presumed direction and size of impact within the scenario	Difficulty of modelling	Consideration in Efficiency and Environmental Impact Assessment
Adding Infrastructure Elements – Crossing intersection with left or right turn	Faster driving through intersection.	Efficiency: + Emissions: -	High	Not covered
Adding Infrastructure Elements – Driving through road construction zone	Extend ODD	n/a	n/a	Simulation: no Scaling up: yes
External HMI	Faster crossing of road by pedestrians at unsignalized zebra crossings	Efficiency: 0/+ Emissions: 0	High	Not covered
V2V for overtaking	None		High	Not covered
Lane exiting	None			Not covered
Challenging ODD	Extend ODD	n/a	n/a	Simulation: no Scaling up: yes