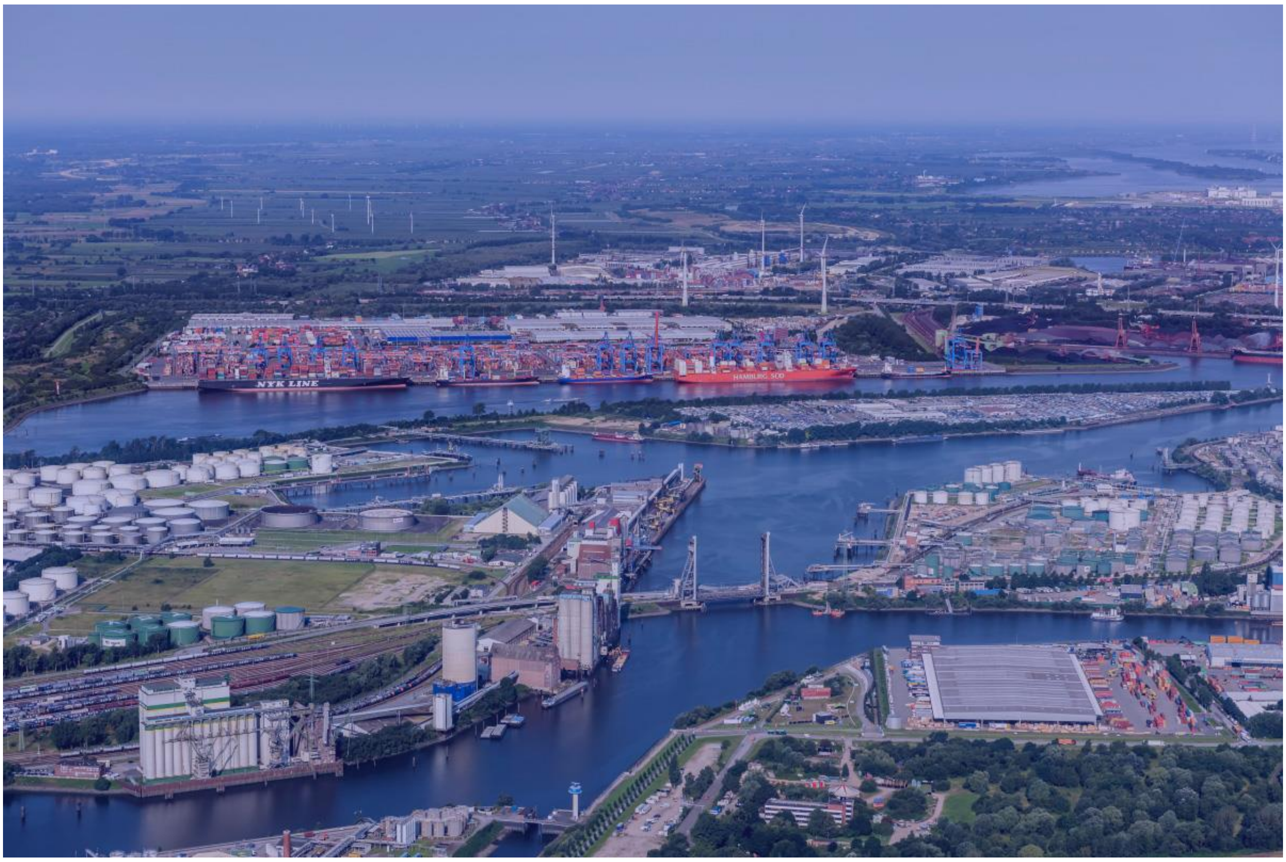
A LEAP TOWARDS SAE L4 AUTOMATED DRIVING FEATURES

A leap towards SAE L4 automated driving features

D4.2 Optimal Designs of Physical and Digital Infrastructures for Public Roads

20th December 2024



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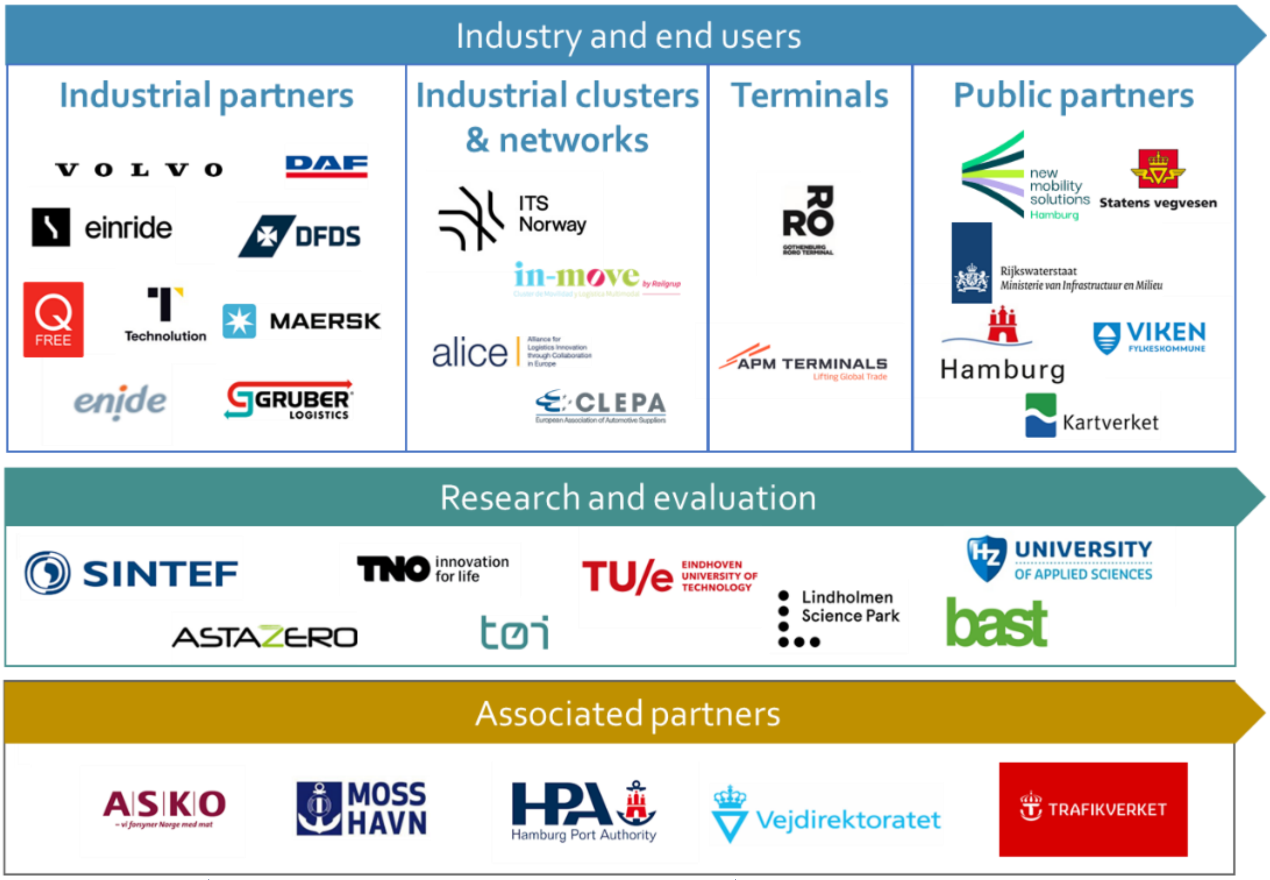

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Terms and Abbreviations

Term / Abbreviation	Description
3GPP	3rd Generation Partnership Project, a global standards organization for mobile networks
ADAS	Advanced Driver Assistance Systems
AD	Automated Driving
ADS	Automated Driving System
AI	Artificial Intelligence
APM	APM Terminals
BASt	The Federal Highway Research Institute
C-ITS	Cooperative Intelligent Transport Systems
CAV	Connected and Automated Vehicle
CCAM	Connected, Cooperative and Automated Mobility
CPOS	Norwegian network RTK-service
DATEX	A European standard for traffic and travel data exchange
DENM	Decentralized Environmental Notification Message
DOP	Dilution of Precision
DSRC	Dedicated Short-Range Communications
ETA	Estimated Time of Arrival
ETSI	European Telecommunications Standards Institute
EV	Electric Vehicle
FAIR	Findable, Accessible, Interoperable, Reusable
FKB	Felles KartdataBase (a Norwegian national geospatial database)
Galileo	European global satellite navigation system
Galileo HAS	Galileo High Accuracy Service
GDPR	General Data Protection Regulation
GIS	Geographic Information System
GLOSA	Green Light Optimal Speed Advisory
GNSS	Global Navigation Satellite System
HD map	High-definition map
HGV	Heavy Goods Vehicle
IMU	Inertial Measurement Unit
IPR	Intellectual Property Rights
ISA	Intelligent Speed Assistance
ITS	Intelligent Transport Systems
ITS G5	A short-range wireless communication technology tailored for vehicle-to-vehicle communication
L2	SAE Level 2
L4	SAE Level 4
Lidar	Light Detection and Ranging
MAP	Map message [SAE J2735 2016-01]
METR	Mobility, Energy, and Transport Research
ML	Machine Learning
MRM	Minimum-risk manoeuvre
NMA	Norwegian Mapping Authority
NMIW	Ministerie van Infrastructuur en Waterstaat, Rijkwaterstaat
NMSH	New Mobility Solutions Hamburg
NPRA	Norwegian Public Roads Administration

NVDB	Nasjonal Vegdatabank (Norwegian National Road Database)
OADF	Open Autonomous Driving Forum
OBU	Onboard Unit
ODD	Operational Design Domain
OEM	Original Equipment Manufacturer
PDI	Physical and Digital Infrastructure
RA	Road Authority
RSU	Roadside Unit
RTK	Real-Time Kinematic, a GPS correction method for high-accuracy positioning
RTTI	Real-Time Traffic Information
SAE	Society of Automotive Engineers
SENSORIS	Sensor Interface Specification for IoT and autonomous driving
SIN	SINTEF, a Norwegian research organization
SPAT	Signal Phase and Timing
SRTI	Safety-Related Traffic Information
Sub-UC	Sub Use Case; a smaller, distinct scenario within a larger Use Case
SWEPO	Swedish network RTK-service
TEN-T	Trans-European Transport Network
TN-ITS	Transport Network Intelligent Transport Systems (a European standard for exchanging ITS spatial data)
TRA	Transport Research Arena
UC	Use Case
UNR	United Nations Regulation
V2I	Vehicle-to-Infrastructure communication
V2V	Vehicle-to-Vehicle communication
V2X	Vehicle-to-Anything communication
VMS	Variable Message Signs
VRU	Vulnerable Road User
WP	Work Package

Executive Summary

Deliverable D4.2, "Optimal Designs of Physical and Digital Infrastructures at Public Roads," assesses infrastructure needs for implementing SAE Level 4 automated freight transport along the MODI corridor, connecting the Netherlands to Norway. This evaluation draws on prior studies, input from key stakeholders—including road operators, vehicle manufacturers, and industry experts—and insights from MODI research, data collection, and Use Cases.

The supporting literature review spans 139 academic articles and 45 project deliverables, providing a comprehensive understanding of existing infrastructure along the MODI corridor. Additionally, semi-structured interviews and workshops with experts in transport infrastructure, vehicle automation, and logistics were conducted. These interactions enabled the research team to refine infrastructure requirements critical for L4 CCAM deployment.

Through case studies and stakeholder feedback, the report examined physical and digital infrastructure needs along complex MODI corridor sections, including tunnels, bridges, and toll plazas. A workshop with European authorities and industry experts further enriched the analysis, emphasizing national strategies for infrastructure adaptation. This collective input shaped the report's final recommendations on infrastructure priorities.

Based on the main findings of the literature review, a semi-structured interview guide was created for an extensive interview series with relevant stakeholders. The interview series, covering a wide range of stakeholders across the industry and public authorities concludes that large-scale physical infrastructure upgrades are most likely not necessary for L4 CCAM deployment. Current road markings, signage, and other elements meet most requirements, though minor improvements in road markings and the availability of safe harbour areas may be beneficial. Instead, the focus is on robust digital infrastructure to support automated driving.

Each of the four elements of the PDI (Physical Road Infrastructure, Connectivity, Positioning services and High-Definition Maps) are interdependent, but mature and develop according to traffic density, available funds, regulations, and vehicle demands and developments. Understanding the complexity and uncertainties imposed by the different development timelines in various locations is important to understand how MODI help bring about L4 operations.

The report emphasizes the importance of collaborative standardisation across both physical and digital infrastructures to support safe and efficient L4 CCAM vehicle operations. I.e., alignment and implementation of standards for road markings, signage, connectivity protocols, HD map formats, and positioning technologies that is vital for a harmonized framework that enables consistent and efficient CCAM features.

These findings are fundamental to MODI's overarching goals to accelerate automated freight transport in Europe. The recommendations presented lay the groundwork for infrastructure enhancements, preparing both physical and digital systems to support safe and effective operation of L4 freight vehicles across European corridors.

1 Introduction

Chapter 1 provides a brief outline of the objectives of the specific MODI Deliverable D4.2 Optimal Designs of Physical and Digital Infrastructure at Public Roads, and how those are aligned and relevant with the overall project, and what was the approach followed to achieve them.

1.1 MODI Project Background

MODI Ambitions: A leap towards SAE L4 automated driving features

The MODI project aims to accelerate the introduction of highly automated freight vehicles through demonstrations and by overcoming barriers to the rollout of automated transport systems and solutions in logistics. The logistics corridor from the Netherlands to Norway has been chosen for demonstration activities as the Netherlands, Germany, Denmark, Sweden, and Norway are expected to be among the first movers to implement fully automated vehicles in Europe.

MODI comprises five use cases, each describing a part of the logistics chain in confined areas and on public roads. It identifies what is already possible on an automated driving level without human interaction and what is yet to be developed. The MODI objectives are to:

- Implement new technology within the CCAM spectrum.
- Define recommendations for the design of physical and digital infrastructure.
- Demonstrate viable business models for connected and automated logistics.
- Perform technical and socio-economic impact assessments.

Major challenges include regulatory aspects and standardisation, border crossings, access control, charging, coordination with automated guided vehicles, loading/unloading and handover from the public to confined areas.

MODI test sites include a CCAM test corridor from Rotterdam to Oslo with specific use cases at Rotterdam (The Netherlands), Hamburg (Germany), Gothenburg (Sweden), and Moss (Norway).

The ambition of MODI is to take automated driving in Europe to the next level by demonstrating complex real-life CCAM use cases while:

- Showing the local, national, and international context of freight transport with CCAM vehicles, both in confined areas and on public roads.
- Cooperating and co-creating with logistics companies, road operators, vehicle OEMs, providers of physical and digital infrastructure and other stakeholders to bridge the gap between R&D and market readiness.
- L4 solutions for long-distance operational design domains.
- Creating innovative business models and improved business models across the logistics chain.
- Proving that the technology can soon deliver on promised benefits at relatively high speeds and medium traffic complexity, including a coordinated CCAM system to support smart traffic management.

- Paving the way to enable highly automatic transport on important corridors, connecting main ports across Europe.
- Accelerating CCAM in Europe by setting examples of business-wise CCAM integration in logistics.

1.2 Aim of the Deliverable

Deliverable D4.2, *Optimal Designs of Physical and Digital Infrastructure on Public Roads*, is presented in this report. It examines the infrastructure needed for safe and efficient SAE Level 4 freight transport, addressing both physical and digital road requirements. The deliverable reflects results from stakeholder input and considerations concerning requirements for the physical and digital infrastructure for automated driving. More input is expected through experiences from the completed Use Cases and deliverables in WP1, WP2 and WP5.

The study focuses on:

- Identifying general requirements: The study outlines the essential requirements for the physical and digital infrastructure necessary for CCAM freight vehicles on SAE L4 to operate safely and efficiently on the MODI corridor. These requirements are detailed for special road sections and for MODI's Sub-Use Cases
- Providing a foundation for future development: This study lays the groundwork for future infrastructure requirements for automated freight transport relevant to the MODI corridor on other European freight corridors.

What this study does not cover:

- Detailed quality and condition requirements: Specific quality or condition requirements for the infrastructure are not addressed.
- Implementation responsibilities: The focus is on what is needed, not who will implement these requirements.

1.3 Relation to MODI Output

The requirements described in this deliverable play a crucial role in the gap analysis presented in **D2.6 Gap Analysis Report on Technology and Societal Readiness** (Lead: SIN). The insights gained from the optimal design of physical and digital infrastructure provide essential input for the Sub-Use Cases conducted at public roads. The work on assessing the readiness of the MODI corridor has been closely coordinated with Task 5.5 (Lead: SIN), with **D5.5 Assessment of CCAM-implementation along MODI-corridor** set to add further detail to this section of the deliverable. Additionally, this deliverable will contribute to the **D1.5 Book of Recommendations (**Lead: BAST**)** on optimal infrastructure design for public roads.

Output:

- D1.5 Book of Recommendations

- D2.5 Gap Analysis Report on Technology and Societal Readiness
- D5.5 Assessment of CCAM Implementation along the MODI Corridor

The content referenced from various MODI deliverables is outlined in the literature review, see Annex I. These inputs have primarily shaped the overall infrastructure requirements, while also informing our approach to the required investments and optimal infrastructure design. Below are the key deliverables we have utilized:

- D1.1 User and Stakeholder Requirements
- D1.2 Safety and Security Requirements
- D1.3 Report on Border Processes
- D2.1 Report on UC Details
- D3.1 Report on Connectivity Requirements
- D3.2 Report on Automation Requirements

D1.2, D2.1, D3.1, and D3.2 are sensitive MODI deliverables. The full reports are available only to MODI partners.

1.4 Terms and Definitions

The following definitions apply to terms used in this report:

Physical Road Infrastructure: The road body with its geometric design, extent and paving, including physical road safety equipment, physically visible signs, and road markings.

Digital Road Infrastructure: All infrastructure for digital communication, positioning and digital representation of the real world, including but not limited to road equipment (sensors, signs and other RSUs) for communication; vehicles; digital maps, traffic rules and regulations; and positioning services.

Note: Some road equipment may be physical and digital, such as visual signs set up with digital communication. In principle, with complete digital maps that include digital rules and regulations, the complete physical infrastructure will be represented in the digital infrastructure.

For the most, the digital infrastructure is divided into three subtypes:

- **Connectivity services:** The infrastructure for sending and exchanging signals for digital communication, used for connecting vehicles, roadside equipment, authorities and traffic managers.
- **Positioning services:** The infrastructure for accurate global and relative positioning of vehicles.
- **High-definition (HD) Maps:** Detailed, accurate and up-to-date digital representations of the real world, including traffic rules and regulations.
    - *Note: Several different terms for digital representations have been used in academic literature, reports, and media for the digital representation of the real world need for*

automated driving. Widely used terms besides HD Maps are ADAS Maps, ADS Maps, AV Maps, HAD Maps, Digital Dynamic Maps, and Electronic Horizon. The products defined by these terms have different levels of content and the accuracy of the digital representations and are used for different levels of automation. For simplicity, this report uses the term HD Maps as a general term for the digital representation needed for any level of automation. Further discussions on the terms and their definitions can be studied in, for example, Elghazaly, Frank et al. 2023 [1], and Yang, Jiang et al. 2024 [2].

Operational Design Domain (ODD): Defined by SEA as “the 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” Knowledge of the conditions is dependent upon connectivity and dynamic environment descriptions in HD Maps [3].

Several terms are used to refer to the CCAM solutions and vehicles in the project (e.g. L4 CCAM vehicles, L4 CCAM automated vehicles, CCAM vehicles, CCAM Avs, CAVs, L4 vehicles, L4 freight vehicles, L4 features). To ensure coherence in the deliverable, the term "CCAM vehicles" (which in this project refers to either L4 or L2 automated electric vehicles) is used throughout the document. When applicable, the term L4 is specified. The term CCAM solutions or technologies refers to systems and advancements that facilitate higher levels of automation, surpassing those of conventional vehicles.

1.5 Structure of the Report

This report is organized to outline the infrastructure requirements for implementing SAE Level 4 freight transport on public roads on the MODI corridor, while also proposing optimal designs for both physical and digital infrastructure. It aims to ensure the reader gains a clear understanding of both the general principles and specific applications of these infrastructure elements.

Chapter 2 General Requirements to Public PDI for SAE L4 - This chapter summarizes general requirements of the PDI needed to accommodate SAE L4 CCAM vehicles on the MODI corridor and other transport corridors in Europe. The requirements for physical and digital infrastructure are based on the state of the art, available literature, and stakeholder input. Generally, this chapter sets out a frame that introduces the fundamental infrastructure components that will be necessary for enabling L4 CCAM vehicles in Europe.

Chapter 3: Stakeholder Input and Considerations for Optimal PDI Design - Chapter 3 presents practical insights from stakeholders, which inform the design considerations for Physical and Digital Infrastructure (PDI). These insights, gathered through interviews and literature reviews, provide a foundation for the general requirements outlined in Chapter 2. They also offer a forward-looking perspective, reflecting stakeholders' views on what is needed to create optimal infrastructure for the future.

Chapter 4: Detailed Requirements for the MODI Use Cases - Chapter 4 demonstrates how the general requirements are detailed to fit the needs of specific MODI Use Cases. This section also discusses the necessary adaptations to infrastructure solutions according to different logistics scenarios along the MODI corridor, along with relevant research activities on the future of PDI on public roads.

Chapter 5: Optimal Design of Physical Infrastructure - Chapter 5 highlights necessary physical improvements, including road markings, signage, and safety features essential for accommodating Level 4 vehicles. It also provides justification for the selected enhancements to ensure both operational safety and efficiency.

Chapter 6: Optimal Design of Digital Infrastructure - Chapter 6 addresses the optimal design of digital infrastructure necessary for effective SAE Level 4 automated transport, emphasizing advancements in positioning, connectivity, and HD maps. It highlights the critical role of digital services ensuring an efficient, safe and environmentally friendly transport system.

Chapter 7: Conclusions - Summarizes key findings and recommendations.

Chapter 8: References - Lists sources and cited materials.

Annex I: Literature Review - This annex collates a comprehensive summary of research findings produced in support of the PDI requirements for automated driving. The report summarises findings from a literature review of 45 project deliverables and 139 academic articles on topics such as the interaction of physical road features and digital support systems needed by SAE L4 CCAM vehicles.

Annex II: MODI Workshop on National Strategies for Automated Transport - Documents the outcomes of a workshop held on April 3rd, 2024, which gathered 46 participants from seven European countries, including public authorities, industry stakeholders, and researchers. The workshop provided a platform to discuss national strategies and collaborative needs for adapting infrastructure to support L4 automated driving. Insights from this session underscored the importance of harmonising standards and infrastructure requirements across borders to facilitate effective implementation of automated freight transport.

Annex III: MODI Workshop on HD Maps - This annex covers insights from an internal MODI workshop focused on HD maps and their role in CCAM. It details the collaboration between authorities, HD map providers, and industry stakeholders on defining standards, ensuring data accuracy, and handling dynamic updates required for real-time navigation and safety.

Annex IV: GNSS Accuracy and Reliability: DOP-Values - Explores the concept of Dilution of Precision (DOP) values and models GNSS coverage along the MODI corridor, identifying areas where signal limitations may impact vehicle positioning and suggesting supplementary technologies.

Annex V Geodetic Refence Frames for Cross-Border Applications - Explores the need for aligned geodetic reference frames to ensure accurate vehicle positioning across borders, recommending a unified approach to support seamless navigation along the MODI corridor

Annex VI: Corridor Assessment of Physical Infrastructure - This annex reports on how road authorities in the MODI project assess the MODI corridor's physical infrastructure readiness for SAE Level 4 freight transport.

Annex VII: Data Types for HD Maps - This annex provides an evaluation of essential data types for high-definition (HD) maps, prioritizing static and dynamic elements crucial for automated driving along the MODI corridor. The analysis relies primarily on insights and judgments from road authorities and lessons learned throughout the MODI project. These evaluations incorporate practical experiences, observed requirements, and anticipated needs. This evaluation serves as guidance for future public investment in digital infrastructure to support automated transport.

Annex VIII: Public Data Infrastructure in Norway - Examines available public data resources, using Norwegian databases as an example, and their applications in automated driving. The annex focuses on both static and dynamic data relevant to MODI Use Cases.

2 General Requirements to Public PDI for SAE L4

2.1 Introduction

This chapter provides a detailed overview of the general requirements for both physical and digital infrastructure (PDI) essential to supporting SAE Level 4 CCAM vehicles on public roads in the future. These requirements form the basis for safe and efficient automated freight transport, with the optimal design based on these requirements discussed in Chapters 5 and 6. The requirements for PDI are divided into four main categories: the first category relates to physical infrastructure, while the remaining three categories are linked to digital infrastructure:

1. Physical Road Infrastructure
2. Connectivity
3. Positioning
4. High-Definition Maps

The requirements reflect the findings from the comprehensive requirement-gathering process. This approach included an extensive literature review, summarising data from various project deliverables, reports, and academic articles to offer a broad perspective on requirements identified in previous studies. Additionally, semi-structured interviews with industry stakeholders were conducted to capture current insights and practical needs. The literature review is summarised in Chapter 3.2 and the full text is available in Annex I. The findings from the interviews are detailed in Chapter 3.3.

The study focuses on requirements for both physical and digital infrastructure but do not delve into detailed quality or condition requirements. The findings from this study are applicable to other European transport corridors, contributing to the broader development of automated freight transport systems.

2.2 Requirements to PDI on Public Roads

Table 2-1 shows the identified general requirements for PDI on public roads. Each requirement is assigned a unique ID using the format **MODI_PDI_D42_r.x.y,** where:

MODI_PDI_D42_r: Identifies the project (MODI), the type of requirements (PDI) and this deliverable (D4.2), and;

- **x**: Represents the general area of the requirement:
    1. Physical Road Infrastructure
    2. Connectivity
    3. Positioning
    4. High-Definition Maps
- **y**: Sequential number within each category of requirements.

Table 2-1: General Requirements to PDI on Public Roads

ID	Description	Comments/Examples
MODI_PDI_D42_r.1.1	**Road Marking Visibility**: Road markings are sufficiently visible for detection by vehicle sensors.	This is a basic requirement, as lane markings are crucial for lane-keeping and other driving tasks.
MODI_PDI_D42_r.1.2	**Signage Placement**: Road signs and signals are consistently placed, visible and readable.	Consistent placement and visibility are important for both human and automated vehicles.
MODI_PDI_D42_r.1.3	**Road Surface Quality**: Road surfaces are maintained to a certain standard.	This is important for both sensor accuracy and traffic safety.
MODI_PDI_D42_r.1.4	**Safe Harbour Availability**: There must be room for CCAM freight vehicles to perform MRMs safely and with as little interference with other traffic as possible.	The required extent and frequency of safe harbours must be found in collaboration between authorities and the industry.
MODI_PDI_D42_r.2.1	**Basic Connectivity**: Challenging areas have connectivity solutions to enable, at minimum, emergency communication for L4 CCAM vehicles.	This ensures that L4 CCAM vehicles can communicate, even in areas with limited cellular connectivity
MODI_PDI_D42_r.2.2	**Cellular Network Coverage**: Cellular network coverage is documented.	Cellular networks must have the necessary coverage along the road networks to support automated driving.
MODI_PDI_D42_r.2.3	**Data Transmission Capability**: Network capacity supports data transmission to and from L4 CCAM vehicles.	The network must be able to handle the volume of data needed for L4 CCAM vehicle operations.
MODI_PDI_D42_r.2.4	**Cybersecurity**: Communication-related systems for L4 CCAM vehicles have basic cybersecurity safeguards in place.	This is important for protecting L4 CCAM vehicles from cyberattacks and ensuring the integrity of communication data.
MODI_PDI_D42_r.3.1	**Positioning Services**: Publicly available and reliable positioning services, e.g. GNSS, are accessible.	This is important for providing L4 CCAM vehicles with accurate location information. Where GNSS signals are unavailable, other positioning services can be provided.
MODI_PDI_D42_r.3.2	**Reference Frame Definition**: Positioning data are provided within a defined geodetic reference frame.	This ensures consistency of positioning data across different systems and regions.
MODI_PDI_D42_r.4.1	**Situation Data**: Real-time information on traffic incidents, road closures, and other events affecting traffic flow are available.	This helps L4 CCAM vehicles to navigate safely and efficiently in dynamic traffic conditions.
MODI_PDI_D42_r.4.2	**VMS Data**: Data describing the position and messages from variable message signs (VMS) are available.	This provides L4 CCAM vehicles with information about upcoming traffic conditions and regulations.
MODI_PDI_D42_r.4.3	**Traffic Regulation Data**: Data representing traffic regulations, including speed limits, overtaking restrictions, and turning movements, are available.	This provides L4 CCAM vehicles with information on legal and safe driving practices.
MODI_PDI_D42_r.4.4	**Physical Infrastructure Representation Data**: Detailed and accurate geometric data representing road infrastructure elements, such as road markings, signage, structures, and other relevant features, are available, with precise position data provided for key features.	This type of data is essential for safe and efficient navigation, as it allows L4 CCAM vehicles to identify lanes, avoid obstacles, and follow traffic regulations. It also includes information on the location of important road features, such as toll plazas, charging stations, and rest areas.
MODI_PDI_D42_r.4.5	**Road Traffic Data**: Real-time and historical traffic flow data are readily available.	This helps L4 CCAM vehicles to avoid traffic congestion and plan routes efficiently.
MODI_PDI_D42_r.4.6	**Energy Infrastructure Data**: Data on the location and availability of charging stations and other energy infrastructure are available.	This type of data is essential for planning routes for electric L4 CCAM vehicles and ensuring access to charging stations. It is also highly relevant for the MODI corridor, as the use of electric L4 CCAM vehicles is expected to increase.

2.3 Detailed Requirements for Special Road Sections

While the general PDI requirements outlined in Section 2.2 apply to all road sections within the MODI corridor, certain areas pose unique challenges for SAE L4 freight transport and require additional considerations. These sections, referred to as "special road sections," demand further adaptation to ensure safe and efficient operation of L4 CCAM vehicles in logistics.

Table 2-2 presents an overview of the specific requirements for these road sections. By examining tunnels, bridges, and toll plazas, the table highlights how the general PDI elements need to be tailored to address issues such as limited visibility, infrastructure restrictions, and complex layouts. In the table, each challenge is paired with detailed requirements, ensuring that L4 CCAM vehicles navigate these sections safely and smoothly.

Table 2-2: Detailed requirements to Special Road Sections

Road Section	Challenge	Detailed Requirements
Tunnels	Limited visibility, potential for congestion, lack of cellular network coverage, height and width restrictions, specific positioning and communication requirements, potential need for longer safe harbours for heavy vehicles, lighting requirements, overtaking restrictions, lane restrictions, and cargo restrictions.	**MODI_PDI_D42_r.1.1**: Increased emphasis on clearly visible road markings. **MODI_PDI_D42_r.1.4**: Adequate safe harbour availability, accounting for potential vehicle weight and length. **MODI_PDI_D42_r.2.1**: Enhanced connectivity solutions, including dedicated communication systems, to ensure emergency communication. **MODI_PDI_D42_r.3.1**: Improved positioning services or alternative solutions due to limited GNSS availability. **MODI_PDI_D42_r.4.5**: Real-time information on traffic flow and incidents, especially in case of congestion or accidents. **MODI_PDI_D42_r.4.3**: Data on tunnel height and width limitations. Information on cargo restrictions.
Bridges	Weight limits, wind gusts, potential for congestion, lack of safe harbours, height and width restrictions, and increased risk of slippery conditions.	**MODI_PDI_D42_r.1.4**: Adequate safe harbour availability, accounting for potential vehicle weight and length. **MODI_PDI_D42_r.4.3**: Data on bridge weight limits and other relevant structural information. **MODI_PDI_D42_r.4.5**: Real-time information on potential congestion and accidents. **MODI_PDI_D42_r.4.1:** Information on wind speed and slippery conditions
Toll plazas	Complex layout, stopping and paying tolls, communication with toll booths, high traffic density, need for automated payment	**MODI_PDI_D42_r.1.1:** Increased emphasize on clearly visible road markings for keeping lane discipline and correct navigation. **MODI_PDI_D42_r.4.4**: Data on toll plaza layout, toll booth locations, and available payment options,

Road Section	Challenge	Detailed Requirements
	solutions, communication interference, vehicle identification, and lanes dedicated to different vehicle classes.	including automated payment systems and lane restrictions. **MODI_PDI_D42_r.4.5**: Real-time information on queue length and traffic flow to optimise route planning and minimise delays.
Energy stations	Finding available energy stations, ensuring a safe and efficient refuelling or charging process, communicating with the energy station system, availability of fuel types, user interface, organisation of energy stations, payment solutions, queue management, availability of waiting areas, and potential for robotic arms or contactless refuelling/charging.	**MODI_PDI_D42_r.4.1:** Detailed information on the location and availability of energy stations, including fuel types, charger types, and power ratings, possibly including real-time information on station availability and wait times. **MODI_PDI_D42_r.4.6:** Data on the energy station layout and access points, as well as information on payment systems and waiting areas.
Ferry stops	Coordinating the loading and unloading process, ensuring a smooth and safe transition between road and ferry, communicating with the ferry system, different lanes for different vehicle types, queue organisation, booking systems, payment solutions, weight, width, and height restrictions, and specific requirements for ferry cargo.	**MODI_PDI_D42_r.4.1**: Real-time information on ferry departures and arrivals. **MODI_PDI_D42_r.4.4**: Data on ferry stop layout, boarding areas, and ferry schedules, including data on designated lanes for different vehicle classes. **MODI_PDI_D42_r.4.3**: Data on weight, width, and height restrictions for the ferry. Information on permitted cargo types.
Customs	Providing necessary documentation, interacting with customs officers, complying with relevant regulations, potential for delays, digital customs solutions, and identification procedures.	**MODI_PDI_D42_r.2.1:** Connectivity solutions for secure, real-time communication with customs systems.

Road Section	Challenge	Detailed Requirements
Border crossings	Varying regulations and vehicle requirements, need for secure and reliable communication, and differences in geodetic reference frames for positioning.	**MODI_PDI_D42_r.2.1:** Connectivity solutions to ensure secure communication at border crossings. **MODI_PDI_D42_r.3.2:** Risk of different geodetic reference frames for map and positioning data, with adjustments needed for accurate vehicle positioning.
Complex intersections	Multiple lanes, conflicting traffic flows, limited visibility, and the need for precise manoeuvring.	**MODI_PDI_D42_r.1.1**: Enhanced road markings to clearly define lanes and traffic flow. **MODI_PDI_D42_r.2.1**: Short-range communication support precise manoeuvring and collision avoidance. VRU protection. **MODI_PDI_D42_r.4.4**: Accurate positioning data of landmarks and intersections.**MODI_PDI_D42_r.4.1**: Real-time information on traffic flow and potential conflicts. **MODI_PDI_D42_r.4.3**: Data on traffic regulations and allowed turning movements.

3 Stakeholder Input and Considerations for Optimal PDI Design

3.1 Introduction

The general requirements for PDI on public roads, as outlined in Section 2.2, are derived from the findings in this chapter. This task began with a literature review, from which we prepared statements to be explored in semi-structured interviews. This approach allowed interviewees to discuss our initial assumptions and, in some cases, explore future needs for this part of the infrastructure. Additionally, a MODI workshop titled *National Strategies for Automated Transport* held in Oslo on April 3rd, 2024, served to validate and deepen these insights. This chapter presents general observations across all three activities in Section 3.2, with detailed findings from each in Sections 3.3, 3.4, and 3.5.

Through this research, we engaged with four key stakeholder groups:

- **Public authorities:** Agencies responsible for the construction, operation, and maintenance of the physical and digital infrastructure.
- **PDI solution providers:** Companies specialising in the technologies, systems and services that make PDI work.
- **Logistics companies:** Organisations planning to use SAE L4 freight transport.
- **Regulatory bodies:** Agencies overseeing the safety and rules of autonomous vehicles.

3.2 General Observations

This section summarises general observations from literature, stakeholder interviews and the MODI workshop on infrastructure needs for automated transport, focusing on the balance between physical and digital upgrades. Statements from the studied literature are supported with references to examples where they can be studied further. Key topics include the adequacy of existing physical infrastructure, the importance of digital support, and the need for standardisation to enable the deployment of automated vehicles.

A general perception in the studied literature and from the interviews is that new requirements for automated transport concern the digital infrastructure more than the physical. For the most part, the support provided by the physical infrastructure to human-operated vehicles is also expected to be sufficient for automated vehicles, as the industry intends to produce automated vehicles capable of operating in the existing network rather than creating vehicles that can only function on certain roads. They consider the existing physical infrastructure not as a barrier but as an unavoidable reality [3-5]. Interviewees broadly agreed that significant physical infrastructure upgrades to accommodate CCAM vehicles are prohibitively expensive and likely unrealistic. Most believe investments will prioritise digital infrastructure over physical adaptations. In the short term, clearer lane markings and signage are important for both human drivers and CCAM vehicle perception systems; however, as CCAM technology advances, reliance on such markings is expected to decrease. The concept of dedicated lanes for CCAM vehicles was largely dismissed, although selective use of public transport lanes or other dedicated lanes for various types of transport was seen as a feasible early-stage option to support integration.

Furthermore, it is clear from the input that the physical infrastructure alone is not sufficient. Studies are clear in the statement that highly automated vehicles and advanced driver-assistance systems in human-driven vehicles need digital infrastructures to support their physical counterparts [3,5-8]. In the interviews, connectivity was viewed as essential for CCAM functionality. Still, stakeholders debated whether CCAM vehicles should be critically dependent on it, which would imply a need for near-perfect, stable network coverage. Most respondents favoured a balanced approach: connectivity should enhance, but not exclusively enable, CCAM operation, with onboard sensors as a fallback. The use of existing 4G and 5G networks was deemed sufficient, especially with edge processing managing local data, allowing connectivity to serve as a tool for real-time updates and safety information.

Positioning accuracy is another area of focus, with RTK correction seen as a promising solution to enhance GNSS signals, although external factors like weather can impact performance. Respondents supported sensor fusion, integrating multiple sensors such as cameras, LiDAR, and RADAR with GNSS and RTK to ensure robust positioning in challenging environments. While V2X communication (e.g., V2V, V2I) was noted as a valuable addition, it was not seen as essential for positioning, with most agreeing that CCAM vehicles should remain operational even when network connectivity is unavailable.

Finally, there is a general agreement that some form of digital maps will be important for CCAM vehicle navigation in the future. Many believe HD maps will be critical in this regard, providing detailed environmental data necessary for route planning and decision-making. Despite the high value placed on HD maps, the literature highlights a lack of standardised specifications for their content and structure, with various commercial actors producing proprietary products that limit data exchange [3-5, 8, 11, 13, 25]. Public authorities are expected to provide foundational, high-trust data, such as speed limits and landmarks, with private entities layering additional detailed mapping information. Privacy concerns were also addressed in the interviews, where respondents highlighted the importance of data protection measures, including pseudonymisation, to ensure compliance with regulations and allow positioning and navigation services to function without breaching user privacy.

The literature notes that standardisation is urgent for both physical and digital infrastructure before automated vehicles can be introduced in large numbers [6, 8, 10, 13]. Industry stakeholders and authorities need to work together towards this goal, and several studies recommend that authorities should lead such standardisation efforts [3, 6, 13, 14].

To validate and expand upon these findings, a workshop was held in Oslo, bringing together public authorities and industry stakeholders. The workshop aimed to confirm insights from the literature review and interviews while also exploring these requirements through the lens of national strategies for automated transport. This session provided additional perspectives that reinforced the study's findings and offered further alignment on the infrastructure needs and standardisation goals necessary for effective implementation. A detailed summary of the workshop's outcomes is presented in Section 3.5.

3.3 Literature Review

3.3.1 Introduction

This part of the report summarises the findings from the literature review, which also included input from other MODI deliverables. *Statements in this part come from the studied literature and are supported with references to the literature where they are found.* Given the large amount of literature used in the study, it cannot be guaranteed that all relevant sources are provided for all statements. The complete literature review is documented in Annex I.

3.3.2 Physical Infrastructure

Even though automated vehicles are expected to operate on current roads, the literature has considered some preparations to be required. For future road design, prominent studies have acknowledged that automated vehicles have heightened electromagnetic sensitivity and a wider field of view than human drivers. Differences in the height and perception of sensors, the dimensions of road features, and the reaction times need to be considered [3, 5, 15].

Automated vehicles have been described as more dependent than humans on the standardisation and visibility of signs and markings. Humans are expected to be more capable of understanding what markings or signs should have been there if they are missing or difficult to see. Standards are, therefore, seen as necessary for design; and especially for upgraded maintenance to ensure visibility [3-6, 8, 10, 13]. More and better edge lines have been suggested for complementing HD Maps with real-time observations [8]. Upgraded maintenance standards may also be necessary for pavement as sensors on automated vehicles may have difficulties interpreting pavement defects [3].

Safe harbours for minimum-risk manoeuvres (MRMs) have been discussed, either as specific emergency areas or on hard shoulders. It has been stated that authorities need to ensure the physical infrastructure is prepared for MRMs and parking in safe harbours without interfering with other road users [3, 11, 13, 16]. This may be particularly demanding for large and heavy vehicles requiring more space. It has been discussed whether dual carriageways should have broad hard shoulders on both sides to prevent vehicles from crossing the road when performing MRMs [16]. However, using hard shoulders as safe harbours might also clash with their role in traffic efficiency in some countries [13, 16, 17].

Complex intersections have been pointed out as a topic that poses challenges to the perception of automated vehicles and needs consideration in future road design. Current highways, expressways, and major urban roads with fewer complex intersections are seen as most prepared for automated vehicles [4, 6, 10, 11, 13]. Discussions have suggested dedicated lanes for automated vehicles to boost safety and efficiency, especially for freight vehicles. Yet, it has been stated that this impacts other road users and is not viable until more vehicles are automated [3, 4, 13, 18, 19].

3.3.3 Digital Infrastructure

Expanding the Operational Design Domain

It is widely recognised in the studied literature that the digital infrastructure will play a crucial role in successfully implementing CCAM vehicles. Private and public stakeholders have been urged to invest in the digital infrastructure to ensure that expectations and objectives for automated transport are met [13, 24]. The emphasis is on technologies for expanding the vehicle's Operational Design Domain (ODD) and enabling more consistent use of automated mode. Enabling technologies include roadside equipment, connectivity services, positioning technologies, and HD Maps [10, 13, 18, 25].

Several studies have identified and listed critical elements (attributes) to help define the ODD. They have emphasised the need for standardisation and close dialogue between authorities, traffic managers, developers, and fleet operators regarding how the ODD attributes should be described and shared. The standardisation of ODD-related information is seen as a necessity that must be done before CCAM vehicles operate in large numbers [4, 10, 13, 18, 21, 26-29]. NAPCORE and METR have been mentioned as crucial standardisation activities that may contribute to enhanced information sharing [4, 24, 25, 28].

It has been claimed that road authorities and operators are responsible for providing ODD-related information and that they need to improve their registries and get better at sharing and exporting information. The current data flow has been described as slow and inefficient [3, 4, 8, 13, 26].

Roadside Equipment

Infrastructure-based perception using roadside units (RSUs) like cameras and radars aims to improve CCAM vehicles' situational awareness through Vehicle-to-Infrastructure (V2I) communication. Despite the advancements in sensor technology for onboard units (OBUs), it has been observed that automated vehicles struggle to achieve full awareness, especially concerning occlusions in complex intersections and extreme weather conditions. Besides, the traffic managers' need for RSUs to monitor traffic and the environment, as well as advise and control automated and human-driven vehicles, has been described. Protecting vulnerable road users in mixed environments is particularly important [11-13, 26, 27, 30-34].

Most studies have focused on single-sensor systems, but there has been a shift towards multi-sensor systems [35]. The synchronisation of these systems has been described as crucial for addressing occlusion issues. Nevertheless, as OBUs become more affordable and efficient, the need for infrastructure nodes may also decrease [35].

It is expected that significant investments in roadside equipment may be needed to ensure that CCAM vehicles have the required situational awareness. Several studies have stated that road authorities and industry stakeholders need to collaborate on the investments, operation and maintenance of such equipment. However, as road owners, road authorities have been pointed out as responsible for ensuring the required coverage of roadside equipment independent of vehicle technology [4, 6, 11-13, 26, 30, 34, 36, 37]. Fortunately, tools have been developed to optimise the placement of roadside sensors, particularly in complex intersections where onboard sensors struggle with occlusions [35, 38, 39].

Connectivity Services

Connectivity services have been considered a necessary part of a safe road [3, 13, 30] to ensure seamless, stable, and secure communication between vehicles, roadside equipment, and traffic managers through vehicle-to-everything (V2X) communication. It is widely accepted that vehicles need communication to get information from roadside equipment and traffic managers for oversight over traffic and situations nearby and on a planned route. Similarly, traffic managers require oversight and communication to direct vehicles, control road accessibility, set maximum speed limits and orchestrate traffic flows flexibly. This requirement concerns automated as well as human-driven vehicles [3, 8, 12, 13, 30].

A future high number of connected vehicles has been expected to require communication networks scaled for large data traffic; and remote assistance of automated vehicles will require especially high bandwidths [3]. For cellular communication, 5G technology is described as increasingly crucial in terms of capacity, speed, and coverage [3, 13, 40]. Short-range communication with Cooperative Intelligent Transport Systems (C-ITS) is seen as instrumental in enabling platooning – and necessary to ensure road safety, especially in intersections in dense areas, areas without mobile coverage, and tunnels [3, 6, 12].

Standardisation of connectivity services regarding protocols, content, and format is seen as critical, whether the communication is based on regular cellular networks or special C-ITS networks. Studies have stated that communication services must be available and understood independently of the vehicle manufacturer and across borders [4, 11, 13]. Cellular (mobile) connectivity in border areas has been identified as a potential challenge [41, 42]. For C-ITS, standards and an organisational structure are already in place [3].

Road authorities are not expected to own or operate cellular networks. However, as road owners, it has been stated that they should play a role in ensuring the necessary coverage of their road networks to support automated driving [8].

Positioning Technologies

Positioning technologies for accurate global and relative positioning have been considered one of the most crucial information needs for automated vehicles [3, 10]. Most automated driving systems depend upon accurate positions that can be matched with accurate HD Maps. Several studies have suggested required accuracy levels for specific tasks, but common, standardised, and explicit measures were not found. The required accuracy has been described as dependent upon the complexity of the environment and the task. Complex tasks in intersections and urban areas require higher accuracy than lane-keeping on dual carriageways. While the latter may be handled with the accuracy that can be provided by today’s Global Navigation Satellite Systems (GNSS) combined with onboard sensors, the more complex tasks are expected to require higher accuracy than what can be achieved without supporting positioning services [3, 8, 26, 27, 40, 43-46].

Improved positioning accuracy can be achieved through positioning services based on, e.g., GNSS and 5G-based technologies [16, 27, 40, 45-48]. Services are and can be provided by governments and commercial actors [3, 40, 46]. As precise geolocation is critical for automated vehicles, complete and stable coverage and protection against vulnerabilities like spoofing, interference, and cyberattacks are seen as crucial [3, 6, 45-48]. Positioning services are expected to be designed for high volumes of vehicles and use standardised interfaces and content descriptions [25, 27, 40-42].

Explicit descriptions of reference frames for global positioning have been identified as critical when crossing borders and operating in different countries [16, 25, 41, 46].

Even with improved and stable accuracy from positioning services, relying on one single technology is still vulnerable. It has been stated that vehicles must combine complementary approaches for positioning. Besides positioning services for global positioning, local positioning can be improved by navigation based on point clouds and accurately known positions of landmarks. Consequently, precise data on roadside landmarks have been considered essential information [3, 4, 13, 26, 43, 49].

HD Maps

HD Maps are expected to play a crucial role in route planning, navigation, and positioning of automated vehicles. These maps provide a detailed and up-to-date representation of the real world and reference what the vehicle's sensors can and cannot observe. Prior knowledge of the infrastructure ahead allows the automated driving systems to make better decisions.

Despite several studies and descriptions of HD Maps, open and internationally standardised specifications for what they should contain and how they should be structured have not been found. Various commercial actors produce their own vendor-specific HD Maps with little or no standardisation, leading to differences in the content and structure of the proprietary products and low possibilities for exchanging information [3-5, 8, 11, 13, 25, 28, 43].

HD Maps must be frequently updated with precise and accurate information regarding static and dynamic situations. Dynamic changes such as road works have been stated to pose a particular challenge. The processes for collecting data and maintaining the maps are described as costly, time-consuming and vendor-specific [3, 5, 13, 14, 18, 21, 50, 51]. Although studies have investigated technologies for more efficient data collection for HD Maps [52-54], it has been argued that HD Maps are unlikely to cover the entire road network due to the costs involved [3, 6].

Road and mapping authorities and road operators have been pointed out to play a significant role in the production processes of HD Maps. Road authorities and road operators are described as the authoritative sources for rules and regulations for navigation, road works and events. Public authorities collect accurate geospatial information such as base maps, point clouds, and the position of landmarks. It is not expected that the authorities will own or operate HD Maps. Still, authority data may provide better coverage and lower the production costs of commercial HD Maps, besides giving them a higher authoritativeness. For this purpose, it has been stated that the information must be provided to the producers of HD Maps in standardised machine-interpretable form. It has been described as essential to evaluate what data can be provided by authorities and commercial actors, respectively, in an ecosystem for HD Map production and that such an ecosystem will require a standardisation of the content and structure of HD Maps and the interfaces for sharing them. Besides, it is widely accepted that the authorities' data will need to be better prepared for the requirements of automated vehicles in terms of content and quality, and authorities will need to get far better at sharing information [3-5, 8, 11, 13, 14, 16, 43, 51].

3.4 Semi-Structured Interviews

3.4.1 Introduction

Based on the main findings of the literature review, a semi-structured interview guide was created for an extensive interview series with relevant stakeholders.

The aim of the interview series was twofold; first, to hear the respondents' assessment of the main findings and secondly; to move beyond the results towards solutions and development of recommendations and best practices that can inform authorities and the industry across borders. The interview guide was structured as follows: The first section was focused on the potential *1) Changes in physical infrastructure*, before moving over to the digital infrastructure where *2) connectivity services* and *3) Positioning and navigation technologies* were discussed, before wrapping up with a final section on *4) HD Maps*.

The interview series, conducted by researchers from SINTEF and BASt at the end of 2023, comprised of 19 interviews covering a wide range of stakeholders across the industry and public authorities detailed in Table 3-1 below:

Table 3-1: Interview respondent overview

1	Industry consultant
2	Research / Road Authority
3	Road Authority
4	Interest organisation
5	HD Map provider
6	Industry consultant
7	OEM
8	OEM
9	Public Authority
10	Road Authority
11	Telecom industry
12	OEM / industry
13	Research / industry consultant
14	HD Map provider
15	Research / industry consultant
16	Road Authority / industry consultant
17	Interest organisation
18	Research
19	Research / public authority

3.4.2 Changes in Physical Infrastructure to Accommodate CCAM vehicles

The emergence of CCAM vehicles that are equipped with automated driving systems (ADS) and utilise communication network systems to monitor other road users and connect with distant sources[1] may lead to changes in the physical properties of roads and related physical infrastructure. Changes to the physical infrastructure depend on several key factors such as constraints related to public budgets for infrastructure and the future demands and requirements from the CCAM vehicles themselves, which are rapidly developing. Future changes to the physical infrastructure also need to consider and balance aspects of human drivers, which will share the roads with CCAM vehicles for the foreseeable future.

Public financing of the physical infrastructure

Road authorities today are signalling that the cost of upgrading or adapting existing roads to any significant degree to specifically accommodate CCAM vehicles would be prohibitable expensive. Likewise, the industry intends to develop automated vehicles that can operate on the current road network. CCAM vehicles are therefore generally expected to conform to the existing infrastructure requirements and fit into the current requirements for infrastructure for human drivers.

Overall, the respondents suggested that investments should benefit both today's human drivers and CCAM vehicles and that most likely efforts going forward will be on the digital side.

Most respondents agree that significant upgrading or adaptation of the infrastructure for automated vehicles is unlikely due to financial constraints, and it is not feasible to maintain near-perfect road conditions at all times. The responsibility, therefore, is on vehicle manufacturers to ensure that automated vehicles can cope with the existing infrastructure. This is also the general expectation from the respondents. Safety is also raised as a major concern, as their perception is that society has higher expectations for CCAM vehicles to make fewer mistakes than human drivers. Although major changes to the physical infrastructure are deemed unlikely, the respondents broadly believe that there will be developments in the digital infrastructure to support connected and automated driving.

General considerations related to physical infrastructure for CCAM vehicles

For CCAM vehicles, inconsistency or deterioration of lane markings and signage has been seen as problematic. Harsh weather conditions, especially in the winter, can also pose problems for readability.

In the short term, lane markings and signage are important for current perception systems in CCAM vehicles and are also important for human drivers and would therefore benefit from improved markings. In the long term however, CCAM vehicles will likely not rely heavily on lane markings.

While major investments are seen as unlikely, many respondents mentioned the possibility of minor changes such as improved road markings or machine-readable traffic signs. There is also an expectation of future improvements to the infrastructure, particularly in relation to safety. But there is a consensus that maintaining clear lane markings is both physically challenging and costly. However, lane markings are essential for both human drivers and current automated driving systems. Some respondents suggest that the importance of lane markings may decrease as technology progresses and might not even be necessary at all for advanced automated vehicles in

[1] Lee, D., & Hess, D. J. (2022). Public concerns and connected and automated vehicles: safety, privacy, and data security. *Humanities and social sciences communications*, 9(1), 1-13.

the future. However, as long as human-operated vehicles and "lower-level" automated vehicles share the road with these advanced vehicles, the lane markings need to be maintained at a certain level.

There is also a concern that increased automation could lead to more wear and tear on roads, as current automated vehicles primarily follow the same path, leading to uneven road wear. This could potentially increase maintenance costs. There were also discussions about balancing the wear and tear by guiding groups of vehicles to slightly different paths, but the practical implementation of such a solution remains unclear. Others simply do not believe this is a problem at all.

There is a need for standardisation, particularly in relation to road works and road operators are currently considering what changes might be needed. It is also unclear what the standards for maintenance would be in an era of increased automation.

Some suggest that dedicated lanes for CCAM vehicles could be useful, but the OEM and CCAM vehicle manufacturers have so far made few such expectations on the grounds of limitation of the full utility of CCAM vehicles.

Generally mixed responses but it is highly unlikely with "dedicated lanes for CCAM vehicles" however, there might be a case for the CCAM vehicles *being allowed to drive in a dedicated lane e.g., similarly to public transport lanes today.*

The concept of dedicated lanes for CCAM vehicles is seen as interesting but not universally applicable. It's considered more feasible for large highways with multiple lanes. However, the economic implications and the limited number of automated vehicles make this idea less attractive. Some respondents suggest that dedicated lanes could be more beneficial for public transport or electric vehicles, or that CCAM vehicles could be given access to the public transport lanes to make the early development easier.

Others propose the necessity of having dedicated safe zones or emergency bays for CCAM vehicles in case the CCAM vehicle is required to stop.

Although these zones and bays would benefit the early rollout of CCAM vehicles, there is little to suggest that the road authorities can and will accommodate these at any meaningful intervals or critical points, therefore solutions such as remote management are more likely.

The idea of dedicated safe zones or emergency bays is seen as potentially necessary, especially for performing minimum risk manoeuvres. However, the practicality of having long stretches of safe zones is questioned due to space and economic constraints. Some respondents suggest alternative solutions such as remote management as a potential remedy for the lack of these safe zones or bays.

In general, the respondents also highlighted the significant potential of digital infrastructure solutions. This includes the creation of a digital twin or HD Map of the road network, provision of precise and up-to-date digital traffic rules such as speed limits, and the use of RTK data for positioning and measures to ensure stable connectivity.

3.4.3 Connectivity Services

Connectivity is seen as a critical component for the operation and advancement of CCAM vehicles. Since most of these vehicles could rely on seamless communication with other cars, traffic systems, networks and roadside units, enhanced connectivity infrastructure is rapidly emerging as a priority.

There are multiple aspects related to connectivity for CCAM vehicles, most notably represented by the term V2X (vehicle-to-everything).

In terms of future demands for connectivity, there is broad agreement that it will play an important role. But there is a significant debate among the respondents on whether connectivity should be labelled as critical, as it would imply being fully dependent on a stable connection and near-perfect coverage at all times.

The respondents believe that the future of communication for CCAM vehicles will be shaped by the need for a balanced approach that leverages current network capabilities while preparing for more sophisticated systems. Current 4G and 5G networks are deemed sufficient for CCAM vehicles, with edge processing reducing the need for high bandwidth communication. The transition to 6G is not considered immediately required, but rather part of a long-term natural evolution of the system. Generally, the respondents believe that connectivity is an enhancing element for the CCAM vehicles and that it is problematic to require a critical level of connectivity at all times, hence they should be able to operate independently using onboard sensors.

A diverse ecosystem of communication methods, including V2X, both long and short range, and cloud-based systems is anticipated to support various CCAM services and functionalities. The potential for interconnected clouds and data sharing among OEMs, traffic management, and other sources make some respondents hopeful for improved traffic systems and vehicle functions.

There is a strong call from the respondents for harmonisation of standards across sectors and cooperation between public and private entities to ensure efficient and reliable communication systems. Providing dynamic, real-time data for incident management and traffic regulations is highlighted as beneficial for CCAM functionality. Furthermore, some respondents believe safety-related traffic information must be accessible through national access points, with cybersecurity and resilience being paramount. A centralised infrastructure approach is highlighted by some as an alternative, but there is a lack of consensus on a definitive technology for CCAM communication going into the future, with multiple technologies being considered and discussed by the respondents. Satellite networks are also considered as a safety net for minimum connectivity where terrestrial networks are unavailable or unreliable.

Connectivity aspects of CCAM vehicles

Connectivity protocols such as C-ITS/DSRC and C-V2X are seen as beneficial for the development of CCAM vehicles. However, compatibility between protocols, unknown requirements, and standardisation may present issues that need to be solved for industry-wide benefits to be realised. Moreover, establishing traffic information services through standardised communication is considered especially important for CCAM vehicles. For instance, receiving supporting information from the infrastructure, from roadside sensors and cameras, may assist CCAM vehicles in locations where full-scene monitoring is difficult or unfeasible.

There is a general agreement that coordination activities and standardisation work is critical and need to be prioritised by all stakeholders for system-wide benefits.

There is a consensus on the need for coordination to ensure interoperability and trust in data. Trust in data from other vehicle manufacturers is seen as a significant issue with some respondents raised concerns that a vehicle might only trust its own sensors due to liability concerns. Coordination efforts are already happening with the involvement of various authorities and existing standardisation bodies and organisations such as 3GPP and ETSI.

In terms of requirements, current cellular networks dimensioned for mobile devices could be expected to handle substantial amounts of CCAM vehicles in a few years. Additionally, data-demanding services such as video-based remote management could pose further demand on these networks.

There is a general agreement that today's mobile networks should be able to handle the data demands from an early scale up of CCAM vehicles*.*

Increased reliance on real-time connectivity also raises serious security and privacy aspects that need to be considered by all parties involved.

There is an overall agreement that security and privacy aspects are important but that current and ongoing legislation work is tackling these issues to a sufficient degree.

There is a consensus among the respondents on the importance of security in vehicle connectivity with an emphasis on the need for secure communication between vehicles and back-end systems. The role of trust in data exchanges was also highlighted as a critical factor that needs particularly attention, pointing again at the need for standardisation work going forward. Privacy aspects were also discussed by the respondents relating to the implications of broadcasting personal information such as position and speed. Generally, existing regulations like UNR 155 and 156 and solutions such as pseudonymisation and contractual agreements address these concerns to a certain extent. Some of the respondents even argued that privacy issues might in fact be less significant in an automated transport system.

Ownership, costs, and placement of connectivity infrastructure

It remains an open question who will be responsible for connectivity infrastructure related to investment costs and placement challenges and how and to what extent the OEMs and CCAM vehicle owners will use this digital infrastructure through their existing data stream.

Overall agreement is found among the respondents regarding that the telecom operators are likely the best suited stakeholder to continue to provide connectivity and that low-earth orbit satellite constellations could provide coverage in remote areas and provide redundancy. Costs should be paid for by the consumers and subscribers and cannot be expected to be heavily funded by public financing.

The telecom networks are generally considered as the backbone of connectivity. However, the responsibility for the investment, operation, and maintenance of connectivity infrastructure is a multifaceted issue that involves a range of stakeholders and there is a strong consensus among the respondents on the need for a collaborative approach. It is also widely acknowledged that end-users will ultimately bear the costs of connectivity infrastructure. Therefore, there is a need to balance investment with the benefits to users, ensuring that costs do not hinder connectivity access.

Cross-sector understanding and collaboration are deemed essential, with different sectors having varying business models, life cycles, and measures of success. Opinions vary among the respondents on the role of the authorities, with some perceiving a reluctance from government agencies to invest in communication infrastructure, preferring private industry investment. However, government involvement is crucial, either through direct investment or by setting regulations that encourage or mandate deployment by private entities. There are also calls for regulation that ensure service availability at manageable costs by fostering competition while ensuring service provision even in less populated areas. Some respondents believe for instance that there is a potential for more stringent licensing requirements to ensure coverage along major roads and the use of innovative solutions like network slicing to guarantee quality of service for critical connectivity. Long-term agreements with mobile network operators are also suggested to ensure consistent service provision, with the need to balance the infrastructure to support current and future connectivity demands while ensuring that technological development and innovation is not hindered. The concept of shared responsibility and costs is repeatedly mentioned by the respondents, with different stakeholders, including mobile network operators, vehicle owners, and public transport fleets, contributing to the connectivity infrastructure. Overall, the private sector is seen as the primary provider of network coverage, with authorities unlikely to be the owners of this infrastructure. There are also divergent views on the necessity of infrastructure for communication, with some advocating for dedicated short-range communication systems and others arguing for the sufficiency of existing cellular networks.

The potential for low-earth orbit satellite solutions and private networks for specific geographical areas are also discussed by the respondents. Here, new and sustainable business models are needed, potentially involving revenue-sharing models and consumer payments for services.

3.4.4 Positioning and Navigation Technologies

Positioning and navigation technologies are crucial and necessary components to enable safe and accurate navigation for CCAM vehicles. The rapid development of new and better technology in this field is seen as a key contributor to making CCAM vehicles feasible. In many cases and specific geographical global locations, the positioning provided by GNSS is not accurate enough, for instance when vehicles travel through tunnels, mountain passes or dense urban canyons. Advanced global positioning services and local navigation technologies in combination is proposed as potential solutions for improving these issues for CCAM vehicles.

Potential solutions to improve positioning accuracy

One proposed solution to overcome and improve these issues is through Real-Time Kinematic (RTK) correction. This technology uses a network of base stations with known locations to correct low-precision GNSS signals. The technique is based on mature and well-known technology and can provide centimetre-level precision under optimal conditions. However, the quality of the GNSS signal, even with correction, can also vary based on a range of factors, such as atmospheric conditions, receiver quality and satellite visibility. Additionally, CCAM vehicles can be equipped with a large set of onboard sensors that can provide local navigation support. The most notable are cameras, LiDAR, RADAR, and ultrasonic sensors. These sensors are used for monitoring various information from the environment. This information can subsequently be used to map-match to an HD Map or a known position, such as a landmark.

- Cameras, combined with AI/ML, can identify objects and measure distances but can struggle in harsh weather conditions and darkness
- LiDAR is useful for measuring distances but is, in many cases, limited by range and the inability to “see through” objects or weather conditions; it is also currently quite costly

- RADAR can assist with these problems through sensor fusion techniques, but this is, as of yet, not a fully solved problem

All sensors have their strengths and weaknesses, suggesting sensor fusion could play a vital role going forward. Finally, a range of V2X techniques, like vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I) and vehicle-to-network (V2N), can also be used as assistance in positioning, for instance, roadside units and other vehicles.

General agreement is found that, at this stage of development, it is hard to see the vehicles rely on a single sensor. The OEMs will also likely equip their vehicles with multiple sensors for redundancy and rather scale down or remove sensors if they become redundant over time.

There is a consensus among the respondents of the necessity of integration of multiple sensors and technologies with the use of GNSS and RTK correction, cameras, LiDAR, RADAR, and ultrasonic sensors. All are mentioned as combinations of sensor integration to ensure reliable and safe positioning of CCAM vehicles. This integration is seen as crucial for solving challenging environments. While initial sensor costs may not be a significant concern for the OEMs early in the development of CCAM vehicles, it is expected that these technologies will have large cost reductions as they mature and scale up from the integration of mass-production of CCAM vehicles. Some respondents from the OEM side also highlight that as CCAM vehicles becomes more prevalent, the focus will shift from high-cost sensors towards operational efficiency. This transition will ensure that CCAM vehicles can handle all traffic situations with the available sensors before considering the removal of any deemed unnecessary in the long term.

The relative position of CCAM vehicles to their immediate surroundings should be emphasised over absolute positioning due to the limitations of GNSS and RTK. Relative positioning will be enabled by effective data fusion from various sensors and the processing power to interpret this data. V2X communication is recognised for its potential to enhance CCAM vehicle positioning and provide complementary data, such as auditory cues. Overall, the respondents generally believe that the integration of services for traffic regulation and navigation systems should involve both public and private sectors through collaborative approaches. The public authorities are expected to maintain and provide official data and infrastructure, while private industry is responsible for technological advancements and the development of end products. Ensuring the high quality and reliability of data is also regarded as essential. There is also a need for systems that can validate the trustworthiness of the data provided. Some respondents also highlight the technical challenges that still exist in fusing data from different sources and ensuring the timeliness of communication. These issues must be addressed for the actors to rely on the data for these services accurately.

In order to secure the necessary funding and continued maintenance of robust and reliable position and navigation services there is a strong emphasis on creating sustainable business models, whether through taxpayer funding or service subscriptions. Additionally, some respondents raised concerns about the potential for long-term contracts with service providers to become technological barriers, suggesting a need for flexibility and adaptability in contractual agreements to accommodate technological advancements.

When it comes to implications related to GDPR and privacy for position services, most respondents believe that privacy issues have been addressed with protocols and standards. There is however a concern that data minimisation, a principle in GDPR, might limit the data available for algorithms, potentially hindering technology development. Overall, privacy protection should be the starting point when developing a service but most respondents do not see privacy issues as a showstopper as the most likely outcome is that the data stays within the context of the vehicle combined with the use of pseudo anonymisation systems. Some respondents mention that exceptions could be made for contractual measures, such as insurance services.

3.4.5 HD Maps

HD Maps are digital representations of roads and their surroundings and contain rich semantic data such as the physical dimensions of the roads, lanes, signs, and traffic rules. Compared to traditional maps, HD Maps require higher precision and preferentially real-time updating of changes to road properties. HD Maps are, therefore, not a one-time investment – they need continuous updates to stay useful and relevant. Such updating will require a stable and sufficiently high bandwidth internet connection. Limited on-board storage and the effects of large amounts of data transmission through mobile networks are still considered challenges. It is also expected that CCAM vehicles themselves will be significant data providers in the future.

Fairly strong agreement that some form of digital maps will be present in CCAM vehicles *of the future. However, there is significant degree of differing opinion on the extent of level of detail and who should provide which data.*

HD Maps are widely recognised as a critical component for automated driving, providing detailed environmental data necessary for navigation and decision-making. The integration of sensor data with HD Maps is considered crucial, with various sensors being necessary for a comprehensive understanding of the environment. The industry perspectives vary, with some OEMs considering HD Maps essential for navigation and others questioning their absolute necessity, with some industry players relying even more heavily on vehicle sensors and alternative solutions like electronic horizon or ADAS horizon are being explored for more efficient data transmission.

The trustworthiness and reliability of HD Maps is considered critical, with calls for regulatory authorities to verify their accuracy to ensure safety and determine liability. Some respondents also indicate that the industry is moving towards less precise but more scalable HD Maps to address challenges in scalability and maintenance, suggesting a pragmatic approach to their integration into CCAM vehicles. Collaboration among OEMs, map providers, and public authorities is essential for the development and maintenance of HD Maps. There is a debate on whether HD Maps should be a public service or developed by private entities, with some suggesting a layered approach where public authorities provide basic infrastructure data and private companies handle the detailed mapping. Standardisation efforts are also highlighted by the respondents as crucial to ensure consistency and interoperability across different systems and regions.

Providers of data input, ownerships and data handling

It has been suggested that road and mapping authorities should provide some critical data types to HD Maps, i.e., accurately positioned landmarks, such as signs and road markings. These sources have to fulfil the requirements needed for CCAM vehicles. Today this is not always the case, where HD Maps are primarily created by OEMs and third parties providing them to OEMs. These solutions are mostly proprietary. There are also different viewpoints and perspectives on ownership structures and data handling of HD Maps. On one side, HD Maps are expected to be handled from the vehicle side and are, therefore, the responsibility of the OEMs and their providers. On the other side, there is growing attention concerning whether HD Maps are or will be critical infrastructure, should be public, free, and open source. Some countries, South Korea being a prominent one in this regard, are currently undertaking a significant national effort to produce national HD Maps.

Overall, there seem to be agreement that the public authorities should provide the "basic rules" in a digital form, e.g., speed limits and road works with the highest trust level in which the private sector can provide their technology and higher resolution layered on top of this base level. Additionally, authorities can provide some critical data types to the HD Maps such as accurately positioned landmarks, e.g., signs and road markings.

The respondents widely agreed that for HD Maps to be scalable, authorities should make critical data types available to the OEMs with authorities holding accurate and essential data that could significantly aid CCAM vehicles. However, the "freshness" of this data is often compromised by delays in updating public digital databases. Authorities are viewed as responsible for providing reliable input data for the regulation layers on these maps, such as road standards, markings, and signs. As a principle, authorities should provide digital information for elements they are the source of. For more dynamic data, such as real-time traffic changes, the responsibility may shift towards private entities due to their ability to gather data from numerous vehicles on the road.

The respondents generally agree that maintaining up-to-date HD Maps is costly, and there is a debate on whether taxpayer money should be invested in this. The process requires substantial resources, both in terms of technology to collect and update the data and in managing the intellectual property rights (IPR) involved. Respondents believe that data should serve multiple purposes beyond HD Maps, for instance related to safety and commerce.

There is also a need for mechanisms to integrate data from various sources, including public authorities, to enhance the accuracy and timeliness of HD Maps. The authorities are increasingly utilising digital technologies such as point-cloud scans for road infrastructure. This integration is essential for maintaining up-to-date digital representations of real-time road situations, which can extend to planned road works and incidents. Standardising how changes, like speed limits, are communicated and ensuring that corrections to maps are shared across the industry are therefore highlighted as critical standardisation steps going forward.

There is also a potential for beneficial collaboration between private and public sectors. The quality of data and the processes for updating information need standardisation and possibly regulation to ensure reliability. This includes establishing clear guidelines for data quality and feedback mechanisms for reporting issues like potholes and pinpoint areas needing maintenance. While sharing data to support HD Maps is deemed to have benefits, concerns about data ownership, trustworthiness, and liability are significant among the respondents. The quality and accuracy of the data are also questioned, with the need for a reliable relationship between data providers and users to ensure continuous improvement of data assets.

The debate on whether HD Maps production ultimately should be a commercial or public endeavour is ongoing. Currently, the commercial sector is leading the efforts. However, some countries like South Korea and Japan adopt different approaches. It is suggested that if taxpayer money funds the data collection, it should be freely available to all, including HD Maps providers, to encourage broader use and integration with other data sources. There is a clear need for agreements and collaboration within the industry, particularly among OEMs and the development of universally compatible HD Maps that can be used by all OEMs is seen as a desirable outcome.

3.5 MODI Workshop: National Strategies for Automated Transport

Workshop Overview

On April 3rd, 2024, representatives from seven European countries (Norway, Sweden, Denmark, Netherlands, Germany, Belgium (Flanders), and the UK), industry stakeholders, and researchers met in Oslo to share insights on national strategies and infrastructure needs for CCAM vehicles. The workshop aimed to validate and expand upon findings from the literature review and interviews, discussing these insights through the perspective of national strategies and exploring areas for collaborative alignment on digital and physical infrastructure to support CCAM vehicle deployment across Europe. This section presents a brief overview, the full summary of the workshop is available in Annex II.

National Strategies and Key Takeaways

In the workshop, each country presented its approach to automated transport:

Norway: Emphasizes a comprehensive framework to guide automated transport development, focusing on testing environments, regulatory support, and collaboration among stakeholders. The strategy aims to position Norway as a leader in safe, reliable CCAM vehicle operations.

Sweden: Adopts a balanced strategy, integrating intelligent vehicle-based systems with adaptable infrastructure to minimise regulatory burden. Sweden’s approach prioritises high-quality data sharing, especially around critical information like speed limits and road conditions, to support safe CCAM vehicle operation.

Denmark: Focuses on collaboration within Europe and investments in infrastructure, emphasizing shared knowledge and solutions that can be scaled across borders. Denmark’s strategy seeks to boost mobility and environmental benefits while managing costs effectively.

Netherlands: Establishes a national task force to ensure Automated Driving Systems (ADS) are safely integrated within the country’s complex road network. With a strong emphasis on public safety and public engagement, the Dutch strategy supports ADS adoption through adjustments in legal frameworks and infrastructure.

Germany: Prioritizes regulatory support and international leadership to maintain its position as a front-runner in automated vehicle technology. Germany invests heavily in research partnerships and has enacted a strong legislative framework to support CCAM deployment and cross-border operability.

Flanders: Concentrates on shared mobility solutions with ongoing pilot projects to test and refine CCAM use cases. Flanders emphasises the importance of 5G infrastructure to enhance connectivity and real-time data transmission, supporting CCAM functionality across different regions.

United Kingdom: Aims to commercialise self-driving technology with targeted infrastructure funding and clear regulatory frameworks. The UK's strategy includes extensive testing and seeks to create a competitive market for CCAM technology, ultimately integrating self-driving capabilities into mainstream transport.

Industry Perspectives

Industry stakeholders provided brief pitches, stressing the need for digital infrastructure, especially in HD mapping, real-time data, and secure data-sharing. Public-private collaboration was underscored as crucial to creating reliable infrastructure that meets CCAM needs.

Key Findings and Challenges

The workshop highlighted that the public sector's role in automated transport is shifting from traditional traffic management toward data provision, policy frameworks, and infrastructure investment to support CCAM operations. Harmonising standards across Europe was identified as essential for enabling seamless cross-border functionality. Participants also emphasised the need to rethink liability, suggesting that some responsibility could shift away from vehicle manufacturers to better reflect the shared nature of automated transport systems.

Participants noted that governments should draw on best practices from private sector innovations and successful international deployments, emphasising a transition toward reducing private vehicle use in favour of automated transport solutions. Ensuring data quality and establishing clear management responsibilities—especially in maintaining accurate digital traffic data—was seen as vital. Additionally, some participants suggested that CCAM vehicles be designed with vehicle-centric intelligence to reduce reliance on external infrastructure and improve operational flexibility.

Looking forward, participants agreed on the need for clear roadmaps and frameworks for testing and regulatory approval, providing industry players with guidance on plans and standards. Collaboration with industry on real-world deployment was also encouraged, particularly for data sharing on safety metrics and operational challenges. Additionally, participants highlighted the importance of adapting and modernising regulatory approaches to account for the unique characteristics of CCAM vehicles, facilitating their safe integration with existing traffic systems.

The workshop underscored the need to prioritise development and implementation of a digital infrastructure and foster public-private partnerships to support the introduction of CCAM vehicles and features on public roads.

4 Detailed Requirements for the MODI Use Cases

4.1 Introduction

The MODI project encompasses five distinct Use Cases (UCs), each designed to address specific challenges and opportunities related to the implementation of L4 CCAM features in the logistics sector. The Use Cases span various scenarios, encompassing both confined areas like ports and terminals, as well as public roads. The goal of MODI's Use Cases is to demonstrate the capabilities and potential of L4 CCAM vehicles in logistics, while also identifying necessary adaptations and requirements for both physical and digital infrastructure.

The MODI Use Cases are divided into several sub-Use Cases (sub-UC), where each sub-UC addresses a specific real-life scenario that L4 CCAM vehicles in logistics will encounter. This chapter provides an overview of how these sub-UCs contribute to the development of PDI on public roads. Chapter 4.2 presents an overview, while Chapter 4.3 details the general PDI requirements to the specific needs of each Sub-Use Case. This analysis examines each sub-UC individually, dedicating one page to each to outline its requirements and planned adjustments to PDI on public roads. Overall, this chapter offers a comprehensive view of the infrastructure customisations necessary to support the varied operational environments along the MODI corridor.

The UC CCAM Test Corridor, however, stands out as a distinct Use Case. Its primary objective is to demonstrate the readiness of the MODI corridor to accommodate L4 CCAM vehicles in logistics. This assessment is carried out through targeted data collection campaigns, which gather and analyse carefully selected data points to evaluate the MODI corridor's capacity to support L4 CCAM vehicles. Given the unique nature of this Use Case, the UC CCAM Test Corridor is not described in the same manner as other sub-UCs in Chapter 4.3, focusing instead on the data collection efforts as steps in preparing the corridor for future deployment of L4 CCAM vehicles.

4.2 PDI Requirements in MODIs Use Cases

Tabell 4-1 presents an overview of the PDI elements and special road sections relevant to the specific MODI sub-UCs. This overview illustrates the varying degrees of dependency on public PDI across the UCs; while some are heavily reliant on public infrastructure, others operate more independently.

Tabell 4-1: PDI and special road sections in the MODI Sub-Use Cases

Requirements	UC NO: Border crossing	UC NO: Customs	UC NO: Motorway	UC NO: Port	UC SE: Gate access	UC SE: Automated charging	UC SE: Automated loading and unloading	UC SE: Driving on public roads	UC GE: City traffic and VRU protection	UC GE: Port-road traffic optimisation	UC GE: Motorway & ODD transition	UC NL: On-terminal automated driving	UC NL: Drayage	UC CCAM Test Corridor
1. Physical Road Infrastructure	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes	No	Yes	Yes
2. Connectivity	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
3. Positioning[1]	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
4. HD-maps	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes	No	Yes	Yes
Special road sections														
Tunnels	No	No	No	No	No	No	No	Yes	Yes	Yes	Yes	No	No	Yes
Bridges	Yes	No	Yes	No	No	No	No	Yes	Yes	Yes	Yes	No	No	Yes
Toll plazas	Yes	No	No	No	No	No	No	Yes	Yes	Yes	Yes	No	No	Yes
Charging stations	No	No	No	No	No	Yes	No	No	No	No	No	No	No	Yes
Ferry stops	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes
Customs	No	Yes	No	No	No	No	No	No	No	No	No	No	No	Yes
Border crossings	Yes	No	Yes	No	No	No	No	No	No	No	No	No	No	Yes
Complex intersections	No	No	No	Yes	No	No	No	Yes	Yes	Yes	Yes	No	No	Yes

[1] *All sub-Use Cases that rely on GNSS positioning will utilize the GALILEO satellite constellation when possible.*

4.3 PDI considerations in each sub-use case

Sub-Use Case: Motorway (UC NO)

UC NO: Motorway

This sub-UC will demonstrate and give insigths related to PDI for CCAM vehicle operation on the motorway. The route is illustrated in Figure 4-1. OEMs aim to strengthen the safety case on motorways, while public authorities will explore PDI requirements and challenges. Insights into standardizing HD maps, point clouds, communication, surrounding physical infrastructure, and positioning technology, providing valuable data for authorities. Technology providers will also gain understanding of PDI's role in supporting CCAM vehicles and the market potential it creates for motorway driving.

Figure 4-I: The route of UC NO: Motorway crossing the Swedish/Norwegian border.

PDI challenges

Supporting safe and efficient automated driving on motorways.

Key requirements overview

MODI_PDI_D42_r.2.1: Ensuring continuous and reliable connectivity for data exchange with the remote operator during motorway driving**. MODI_PDI_D42_r.2.2:** Network coverage will be documented and analyzed. **MODI_PDI_D42_r.2.3:** Ensuring sufficient data transmission capability for real-time communication. **MODI_PDI_D42_r.3.1:** In the demo, the vehicle will rely on accurate RTK positioning for navigation**.** **MODI_PDI_D42_r.4.ALL:** UC NO is exploring the creation of HD-maps, the data will be used for preparation and simulation purposes.

Planned changes to public physical infrastructure

No changes, the physical infrastructure will be used as is.

Planned changes to public digital infrastructure

Public road data and point clouds will be used for simulation and preparation purposes. Annex VIII: Public data infrastructure in Norway contains an overview of the available data sources. This data is further enriched with a detailed scan of the area in question.

Other considerations and challenges

Driving on the motorway in the sub-UC requires extensive safety measure. These measures include reduced speed, operation during low-traffic hours, and truck-mounted attenuators behind the Einride vehicle.

Sub-Use Case: Border crossing (UC NO)

UC NO: Border crossing

This sub-UC examines the challenges and technical requirements for automated driving across national borders, specifically between Sweden and Norway. The Einride vehicle will cross the Svinesund bridge as illustrated in Figure 4-2. The demonstration requires acquiring permits for automated driving in both countries and highlights the need for harmonized regulations and permitting processes for cross-border operations. It also emphasizes the need for robust connectivity and positioning solutions to ensure continuous operation across borders.

Figure 4-II: The iconic Svinesund bridge illustrating the Swedish/Norwegian border crossing.

PDI challenges

Seamless operation and data exchange for cross-border automated driving.

Key requirements overview

MODI_PDI_D42_r.2.1: Ensuring continuous and reliable connectivity for data exchange across borders, potentially through roaming agreements or dedicated communication infrastructure. **MODI_PDI_D42_r.3.2:** Harmonizing positioning data and reference systems used by different service providers across borders for seamless navigation.

Planned changes to public physical infrastructure

No changes, the physical infrastructure will be used as is.

Planned changes to public digital infrastructure

Connectivity: UC NO will implement seamless mobile network connectivity for the Einride vehicle across the Swedish-Norwegian border.

Other considerations and challenges

The Einride vehicle will utilize GNSS RTK, with the border crossing covered by both the Swedish and Norwegian national RTK services. Einride will use the Swedish SWEPOS service. When using correction data from CPOS, SWEPOS or other NRTK providers, you inherently utilize Galileo satellites, as their signals are part of the GNSS data incorporated into the correction calculations for enhanced positioning accuracy.

UC NO: Customs

This sub-UC focuses on demonstrating the use of the Norwegian customs' digital express clearance system (Digitoll) without a driver present in the vehicle. The sub-UC involves driving at the Norwegian customs, with the route illustrated in Figure 4-3. It explores the feasibility of automated declaration processes and investigates the need for secure communication channels between customs officials and remote operators. The demonstration highlights the need for adjustments to the existing digital customs system to accommodate CCAM vehicles and remote operation, ensuring efficient processing and mitigating potential legal and security challenges. It could also inform the development of standardized digital communication protocols and data exchange requirements for seamless integration with public PDI elements related to border control and customs operations.

Figure 4-III: The route at the Norwegian Customs.

PDI challenges

Secure and efficient integration of CCAM vehicles with digital customs systems.

Key requirements overview

MODI_PDI_D42_r.2.1: Communication of traffic light status from infrastructure to vehicle.

Planned changes to public physical infrastructure

No changes, the physical infrastructure will be used as is.

Planned changes to public digital infrastructure

The Use Case will implement a provisional workaround to send the status of the traffic light at the customs entrance to the vehicle. The green light will be communicated to Einride's operator through standalone hardware.

Other considerations and challenges

The use of the Norwegian service Digitoll will be demonstrated for use by an L4 CCAM vehicle. The service itself will work in the exact same way as it is currently used by manually operated vehicles.

Sub-Use Case: Port (UC NO)

UC NO: Port

This sub-UC explores the use of CCAM solutions in port operations, focusing on assessing the business case and societal impacts of new automated logistic solutions. The sub-use case will explore three different demonstrations: Awareness driving via V2X at the drive in/out of ASKO Vestby central storage; Manoeuvre coordination based on V2X roadworks warning on E6; VRU detection and V2V Awareness Driving near the gate of Port of Moss. All demonstrations will take place in close proximity to the Port of Moss, with the ASKO sea drone port in Moss portrayed in Figure 4-4.

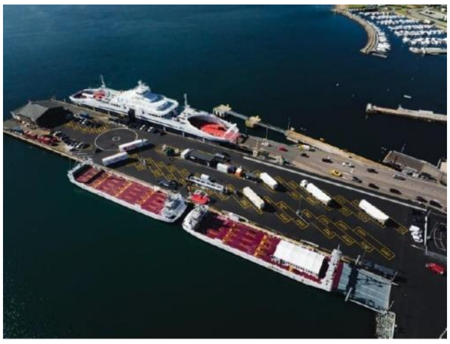

Figure 4-IV: ASKO sea drone port at the Port of Moss.

PDI challenges

Awareness Driving and Collective Perception via V2X, merging lanes caused by a roadworks warning, infrastructure detecting VRU's in a complex traffic situation.

Key requirements overview

MODI_PDI_D42_r.1.1 Road Marking Visibility: Clear and visible lane markings are crucial for automated trucks to operate safely and efficiently on public roads, particularly when navigating intersections and complex traffic situations. **MODI_PDI_D42_r.1.2** Signage Placement: Consistent and easily readable signage is vital for both human and automated drivers to understand traffic regulations and make safe decisions on public roads. **MODI_PDI_D42_r.4.1** Situation Data: Real-time information on traffic incidents, road closures, and other events affecting traffic flow is critical for automated trucks to navigate public roads safely and efficiently, particularly in a dynamic environment like a port where traffic patterns can change frequently. **MODI_PDI_D42_r.4.3** Traffic Regulation Data: Accurate and up-to-date digital data representing traffic regulations, including speed limits, overtaking restrictions, and turning movements, is essential for automated trucks to operate legally and safely on public roads.

Planned changes to public physical infrastructure

Temporarily removing or covering a sign with misleading information for demonstration purposes, and temporarily establish a physical road works area for demo purpose.

Planned changes to public digital infrastructure

The Volvo vehicle will receive a roadworks warning (DENM (ETSI)) and additional messages critical to safe maneuvering concerning lane closures and speed reductions. The messages will be distributed using the Norwegian Interchange Node from the NordicWay project.

Other considerations and challenges

For the UC CCAM MODI Test Corridor from Alnabru to Svinesund, the NPRA is working on a solution to convert VMS data into the DATEX II (METR) format and distribute it through existing traffic management systems. The demo on E6 in UC NO: Port will benefit from this development.

Sub-Use Case: Driving on public roads (UC SE)

UC SE: Driving on public roads

This sub-UC tests and evaluates C-ITS services that can support the transition toward higher levels CCAM solutions for Volvo trucks and investigates L4 driving capabilities for Einride trucks on public roads. Figue 4-5 illustrates how UC GE views business cases in logistics as drivers for increasing the level of automation. For Volvo, the focus is on digital PDI on public roads, cooperative lane merging, and hazard warnings from infrastructure. Real-time ETA updates using traffic data will also be tested. The results could lead to recommendations for broader C-ITS deployment and improvements in V2V and V2I communication protocols.

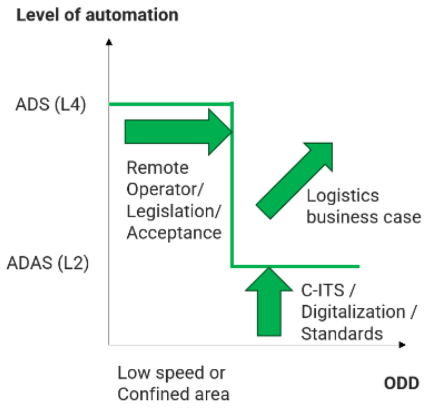

Figure 4-V: Graph illustrating the progression of CCAM operation from L2 to L4 in logistics.

PDI challenges

Ensuring safe and efficient L4 truck operation in mixed traffic environments.

Key requirements overview

MODI_PDI_D42_r.2.1: Guaranteeing widespread and reliable C-ITS infrastructure coverage to support V2X communication and improve situational awareness.
MODI_PDI_D42_r.4.3: Providing real-time traffic data, including road works, accidents, and weather conditions, for dynamic route planning. **MODI_PDI_D42_r.4.4:** Maintaining accurate digital maps of road infrastructure, including lane markings and potential obstacles, to support safe manoeuvring.

Planned changes to public physical infrastructure

No changes, the physical infrastructure will be used as is.

Planned changes to public digital infrastructure

Highway merging with/without roadworks: Automated merging based on roadwork information. Hazard warning informing of a stationary vehicle in one lane: Infrastructure sends alerts. Real-time ETA updates: Adjust ETAs using real-time traffic data.

Other considerations and challenges

The sub-use case will also explore cooperative lane merging; V2V communication to decide merge order.

Sub-Use Case: Automated loading and unloading (UC SE)

UC SE: Automated loading and unloading

This sub-UC demonstrates automated loading and unloading at a loading dock. The sub-UC explores several alternative technical solutions, like the one using an automated skateboard for loading pallets as shown in Figure 4-6. While this part of the MODI project focuses on private site operations, learnings regarding automated loading and unloading processes and their integration into logistics chains could inform the development of standardized digital communication protocols and data exchange requirements for seamless interaction with PDI elements on public roads.

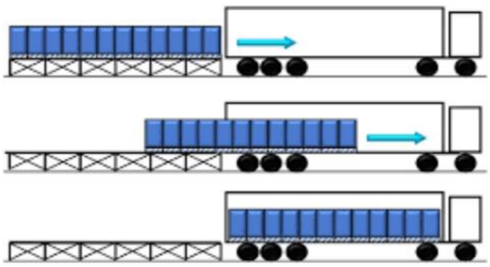

Figure 4-VI: Sequential loading process of pallets onto a truck trailer.

PDI challenges

Limited direct impact on public PDI, but standardized data exchange protocols could influence future I2V interaction.

Key requirements overview

N/A

Planned changes to public physical infrastructure

N/A

Planned changes to public digital infrastructure

N/A

Other considerations and challenges

Sub-Use Case: Automated charging (UC SE)

UC SE: Automated charging

This sub-UC focuses on automated electric charging for trucks, investigating physical infrastructure requirements, connector compatibility, and grid integration. Figure 4-7 shows automated charging using a robotic arm, which is one of the technical solutions evaluated in this Sub-Use Case. While not directly focused on public PDI, learnings could inform future development of public charging infrastructure for heavy-goods vehicles.

Figure 4-VII: Automated robotic arm charging an electric vehicle.

PDI challenges

Limited direct impact on public PDI.

Key requirements overview

Findings might provide input to further detailing of **MODI_PDI_D42_r4.6:** Energy infrastructure data

Planned changes to public physical infrastructure

No changes, the physical infrastructure will be used as is.

Planned changes to public digital infrastructure

No changes, the physical infrastructure will be used as is.

Other considerations and challenges

In logistics, companies will likely aim to *minimize* reliance on public or third-party chargers, preferring to charge at their own terminals while vehicles are stationary. See Section 3.4 Semi Structured Interviews. Mutual use of chargers between companies will require standardized systems to ensure compatibility, allowing vehicles to charge at any terminal.

Sub-Use Case: Gate access (UC SE)

UC SE: Gate access

This sub-UC explores automating gate access services, specifically for Einride and Volvo trucks entering and exiting confined areas, as illustrated by the gate in Figure 4-8. While it primarily focuses on private site access control solutions, it investigates the potential for common solutions across various sites. This could lead to recommendations for standardized digital communication protocols for secure data exchange between vehicle, gate systems, and back-end systems, potentially paving the way for integrating public PDI elements for wider implementation of automated gate access in the future.

Figure 4-VIII: Illustration of a gated entry with traffic lights securing a confined area.

PDI challenges

Limited direct impact on public PDI; however, standardisation of communication protocols could influence future integration.

Key requirements overview

N/A

Planned changes to public physical infrastructure

No changes, the physical infrastructure will be used as is.

Planned changes to public digital infrastructure

No changes, the physical infrastructure will be used as is.

Other considerations and challenges

This sub-use case has investigated various gate access solutions, such as key pad calling and automatic number plate recognition, and has selected C-ITS messages as the preferred method. The focus is on utilizing standardized C-ITS messages, typically used on public roads, within a confined area for access control.

UC GE: Motorway & ODD transition

This sub-UC examines on- and off-ramp maneuvers on federal motorways, focusing on the transition between automated and manual driving triggered by ODD changes. Figure 4-9 shows a photo from Hamburg city, which is the location for this sub-UC. The sub-UC utilizes existing cooperative infrastructure and C-ITS services in Hamburg to support driver tasks, such as dynamic speed adjustments and merging manoeuvres. Learnings will inform the definition of ODD exit trigger points for L4 to manual driving transition and could necessitate adjustments to traffic management schemes on motorway ramps for smooth integration of CCAM vehicles

Figure 4-IX: Photo of Hamburg from UC GEs Reference Drive in November 2023, conducted to evaluate the current conditions as a foundation for further analysis.

PDI challenges

Ensuring seamless and safe transitions between automated and manual driving modes.

Key requirements overview

MODI_PDI_D42_r.2.1: Providing seamless and reliable C-ITS infrastructure coverage along highways to support cooperative automated driving and safe ODD transitions.
MODI_PDI_D42_r.4.3: Providing real-time traffic information, including incidents and congestion, to enable dynamic route planning and efficient ODD transitions.
MODI_PDI_D42_r.4.4: Ensuring accurate and up-to-date digital maps of highways, including lane configurations and speed limits, for reliable automated driving.

Planned changes to public physical infrastructure

No changes

Planned changes to public digital infrastructure

No changes

Other considerations and challenges

OEMs will test and collect data on the driving manoeuvres on the on- and off-ramps of federal motorways. Depending on the precise location and driving task, OEMs can validate their systems.

Sub-Use Case: Port-road traffic optimisation (UC GE)

UC GE: Port-road traffic optimisation

This sub-UC will test and demonstrate the use of GLOSA and urban data lake information to optimize traffic flow and efficiency of the port-road system in Hamburg. Existing C-ITS infrastructure, specifically roadside units and traffic signal systems, will be leveraged. The traffic lights in Hamburg already equipped with GLOSA is shown in Figure 4-10. Findings will reveal the effectiveness of GLOSA in real-life traffic situations and potentially lead to improved coordination strategies with traffic management bodies. It could also highlight the need for more readily available real-time and historical traffic flow data for integration into planning and scheduling systems.

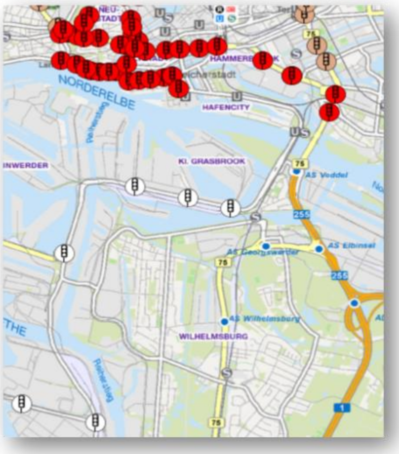

Figure 4-X: GLOSA equipped traffic lights in Hamburg city.

PDI challenges

Optimizing traffic flow between ports and roads.

Key requirements overview

MODI_PDI_D42_r.4.3: Leveraging existing real-time traffic data from C-ITS infrastructure and integrating additional sources for accurate traffic flow prediction and optimisation.

Planned changes to public physical infrastructure

No changes

Planned changes to public digital infrastructure

No changes.

Other considerations and challenges

The public authorities, research institutes and infrastructure operators will receive valuable data on the reliability and effect of C-ITS infrastructure. Thus, better decisions and planning on future equipment are possible. The logistic companies will learn how port-road traffic optimisation like a GLOSA service can improve planning, scheduling, and the overall logistic process.

Sub-Use Case: City traffic and VRU protection (UC GE)

UC GE: City traffic and VRU protection

This sub-UC focuses on the safe navigation of trucks within a complex urban environment, particularly turning among vulnerable road users, as illustrated in Figure 4-11. It will leverage and test the effectiveness of existing C-ITS infrastructure, such as roadside units and GLOSA (Green Light Optimal Speed Advisory) services. Findings will inform the development of generally accepted safety requirements for CCAM vehicles interacting with VRUs, potentially leading to necessary adaptations of C-ITS infrastructure for VRU protection and enhancements to communication protocols for secure data exchange between vehicles and infrastructure.

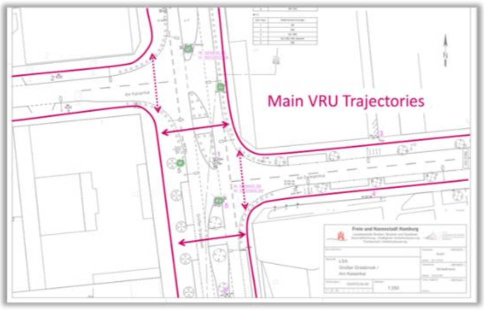

Figure 4-XI: Map highlighting VRU trajectories at an intersection in Hamburg inner city.

PDI challenges

Enhancing safety in urban environments, especially regarding VRU interactions.

Key requirements overview

MODI_PDI_D42_r.2.1: Ensuring comprehensive C-ITS infrastructure coverage in urban areas to enable reliable V2I communication. **MODI_PDI_D42_r.4.3:** Integrating real-time data on pedestrian and cyclist movements from sensor networks to enhance VRU detection and improve safety.

Planned changes to public physical infrastructure

No changes.

Planned changes to public digital infrastructure

One intersection in Hamburg HafenCity will be equipped with sensors and RSU for the VRU service

Other considerations and challenges

The OEMs will explore the validity and reliability of C-ITS infrastructure in real-life traffic. Test to what extend trucks can rely on infrastructure information for safety critical services such as emergency braking. How the C-ITS infrastructure supports trucks and what the limits of these systems are.

Sub-Use Case: Drayage (UC NL)

UC NL: Drayage

This sub-use case explores the business case for automated drayage operations on public roads, focusing on the readiness of existing public PDI, such as traffic lights, road layouts, and regulations, to support CCAM vehicles. The route explored is shown in Figure 4-12. The demonstration will take place in a highly complex environment involving traffic lights, bicycle lanes, roundabouts, and multiple lanes. The vehicle will be equipped with sensors and technology comparable to those on a L4 driving, but it will be controlled by a driver in the seat, with sensor data collected for analysis. It will assess potential limitations and identify necessary adjustments for successful implementation, including enhanced connectivity and optimized traffic management. The key question it aims to answer is: What is required to enable CCAM vehicles on L4 to operate effectively in such an environment

Figure 4-XIII: The route for the UC NL Drayage

PDI challenges

Reveal the limitations of existing PDI on public roads near the APM terminal.

Key requirements overview

MODI_PDI_D42_r.1.1: Road markings must be highly visible to ensure the vehicle can maintain lane discipline. **MODI_PDI_D42_r.4.4:** Physical infrastructure representation data to ensure safe navigation of complex road features.

Planned changes to public physical infrastructure

In this demonstration, the truck's technology and existing infrastructure along the route will be used, with no additional systems installed. The objective is to assess the need for further systems.

Planned changes to public digital infrastructure

Due to the complexity of the traffic patterns, the vehicle will require detailed map information, especially for navigating lane changes and roundabouts. This map will be specifically developed for the demonstration. Details on the development of this map is presented in other MODI deliverables.

Other considerations and challenges

The vehicle will rely on vehicle sensors to detect cyclists in the bicycle lane.

UC NL: On-terminal automated driving

This sub-use case focuses on utilizing standard interfaces for automated driving within the APM terminal in Rotterdam, as shown in Figure 4-13. While it does not directly demand changes to public PDI, it assesses the required capabilities for communication and positioning within a complex environment. Learnings from this sub-UC, particularly regarding interactions with manually driven vehicles, could inform future requirements for public PDI when automated trucking expands beyond confined areas.

Figure 4-XIV Freight vehicle loading at the APM terminals.

PDI challenges

Limited direct impact on public PDI, but findings could inform future adaptations.

Key requirements overview

N/A

Planned changes to public physical infrastructure

N/A

Planned changes to public digital infrastructure

N/A

Other considerations and challenges

This sub-UC will assess the driving capabilities of trucks at terminals, giving valuable input to the discussion on balance between what the vehicle can handle and what requires infrastructure support. It highlights the need for standardized traffic rules across terminals, given the varying procedures and signs at different ports. Key areas for learning include infrastructure support for precise container pickup, such as sensors in docking bases, and monitoring systems for terminal-wide traffic and incidents. Communication units and additional signaling, such as gate status, will likely be installed, but no changes will be made to the existing operational terminal. The sub-use case will implement a control tower concept that can give instructions to the CCAM vehicles.

PDI elements in UC CCAM Test Corridor

The UC CCAM Test Corridor aims to demonstrate the readiness for CCAM implementation along

Figure 4-XV shows the corridor from Oslo to Rotterdam. The corridor evaluation carried out in this Use Case focuses on identifying specific challenges and barriers faced by vehicle providers, logistics operators, and road authorities. Through an extensive analysis of different data sources, critical components of the PDI necessary to support CCAM vehicles are identified and validated with comprehensive data collection across the entire corridor.

Figure 4-XV: UC CCAM test corridor from Oslo to Rotterdam

The data collection campaign uses sensor-equipped vehicles operating with automation systems in passive mode—collecting data without actively controlling the vehicle. This approach enables a thorough assessment of PDI requirements, aiming to harmonise standards across countries and offer practical guidance for stakeholders.

Data collections are carried out by multiple MODI partners, each with a different main point of interest and scope of collection. Completed data collection efforts and their focus are presented in Table 4-1 with further campaigns by Einride and Volvo planned for 2025.

Table 4-1: Data collection efforts in MODIs UC CCAM Test Corridor

MODI Partner(s)	Main Focus	Data gathered	Scope of data collection	Status
BASt	Vehicle interactions and driving behaviour analysis	Lidar, radar, positional data, video footage	German part of corridor	Data collection completed, Analysis ongoing
DAF/ Gruber	Assessing lane marking detection under challenging conditions like poor markings, complex lane structures, and bad weather	CAM data, lane marking and sign detection; video footage	Entire corridor from Rotterdam to Oslo	Data collection completed, Analysis ongoing
Q-free	GNSS and Connectivity analysis, lane marking detection, general observations of route	Connectivity, GNSS positioning, and lane marking data, video footage	Entire corridor	Data collection completed, Analysis completed
Mapping using road databases	Potential challenges such as lane markings, signage, bridges and tunnels, and dynamic signs	Information national databases and dedicated visual inspections	Entire corridor	Data collection completed, Analysis ongoing

The variety of data sources and analysis aims to ensure that the MODI corridor is adequately assessed in its entirety. The findings from the data collection campaign will be presented in the upcoming deliverable, D5.5 Assessment of CCAM Implementation along the MODI Corridor, due by the end of 2025. This deliverable will be publicly accessible, providing valuable insights for advancing CCAM readiness across Europe.

5 Optimal Designs of Physical Infrastructure

5.1 Introduction

This chapter builds upon each of the five involved National Road Authorities assessing the readiness of the roads in their respective countries with respect to deployment of L4 CCAM vehicles. The general requirements for physical road infrastructure, shown in Table 5-1 and the identified special road sections, is taken as a basis in their assessments, with section 5.2 below presenting the results.

Table 5-1: General Requirements to Physical Road Infrastructure

ID	Description	Comments/Examples
MODI_PDI_D42_r.1.1	**Road Marking Visibility**: Road markings are sufficiently visible for detection by vehicle sensors.	This is a basic requirement, as lane markings are crucial for lane-keeping and other driving tasks.
MODI_PDI_D42_r.1.2	**Signage Placement**: Road signs and signals are consistently placed, visible and readable.	Consistent placement and visibility are important for both human and automated vehicles.
MODI_PDI_D42_r.1.3	**Road Surface Quality**: Road surfaces are maintained to a certain standard.	This is important for both sensor accuracy and traffic safety.
MODI_PDI_D42_r.1.4	**Safe Harbour Availability**: There must be room for CCAM freight vehicles to perform MRMs safely and with as little interference with other traffic as possible.	The required extent and frequency of safe harbours must be found in collaboration between authorities and the industry.

5.2 Corridor assessment

This analysis of the readiness of the infrastructure draws on input gathered from authorities in all five countries involved in the MODI project. Representatives participated through a web-based mapping tool, identifying challenges in seven key infrastructure categories. These challenges were self-assessed by the authorities. The complete evaluations can be found in Annex VI, while provides a summary of the major findings.

At a later stage in the project, MODI will provide an analysis of readiness based on empirical data collection, as described in Section 4.3. This analysis will challenge or confirm the statements from road authorities, and when viewed in conjunction, these analyses provide a solid foundation for the further development and investments in PDI along the MODI corridor and other transport corridors in Europe.

The Last Mile Problem is a well-known challenge in Logistics. In the context of PDI on public roads, the last mile involves different infrastructure than major motorways. The financial scope of motorway infrastructure projects is significantly larger than the relatively minor investments required for last-mile roads near terminals. Our assessment does not give specific attention to the last mile near the Alnabru and APM terminals. These sections include roundabouts, cyclist lanes, sharp corners, and severely worn road markings—some of which have completely disappeared. In the Netherlands, this road section is given particular attention in UC NL Drayage. The findings from this sub-UC will also be relevant to the last mile near Alnabru terminal.

Table 5-2: Corridor Assessment of Physical Infrastructure

	Norway	Sweden	Denmark	Germany	Netherlands
Road marking	Good condition overall, but some sections are worn. Acceleration lanes are not marked to the end, as is common in other European countries.	Generally in good condition, normal wear and tear to be expected.	Good condition overall. Interpreting barrier markings at intersections can be challenging.	Generally good, possible sections with worn out markings	Peak-hour lanes (A50; Arnhem-Apeldoorn), with narrow, non-standard markings, complicate lane discipline
Static signage	Signs are in good condition overall.	No specific challenges noted.	Signs with HGV restrictions may confuse CAVs.	Along the route, many standard signs include additional textual information, such as time- or weather-specific prerequisites.	Additional Dutch text on signs (A15, A50)e.g., heavy vehicle overtaking restrictions and signs intended for exits or service roads, could be confusing
Dynamic signage	Frequent VMSs along the E6, but no digital representation of the information is publicly available. LED speed limit signs may cause sampling issues for camera detection systems. Currently, two physical variable signs have malfunctioned.	VMSs around Gothenburg must be accurately interpreted by CAVs.	VMSs near the Øresund Tunnel regulate speed, lane usage and emergency warnings.	Sections with dynamic signage (VMS) present. No digital content available.	Frequent dynamic signage along the A15 and A50, with gantries spaced 500-800 meters apart, provides real-time updates.
Road geometry	No sharp curves or other special challenges on the motorway between Ulvensplitten and Svinesund.	Challenging around Gothenburg due to lane changes and tight geometry.	No challenges identified.	Overall, the road geometry corresponds to the road class.	Tight curves at interchanges (e.g. Valburg) lack specific speed limits
Entrances, interchanges, and exits	There are no interchanges on the motorway. No challenges regarding entrances and exits noted.	A specific challenge is the exit ramp to the left in Gothenburg, which are not so common elsewhere. Short entrance lanes, such as those near Helsingborg, might cause problems.	On entry, vehicles on the motorway are obligated to adjust their speed as needed to ensure safe merging with entering traffic.	Very few transitions on the route. Transitions paired with lack of hard shoulders and tight curves in exit/entry ramps might be challenging.	Complex interchanges near Rotterdam, Valburg, Arnhem and Hengelo require frequent lane changes by heavy vehicles. Challenging for lane management and navigation
Tunnels, bridges, toll stations, and ferries	Seven tunnels and several bridges, including the Svinesund Bridge on the E6. No additional challenges were noted for these road sections.	One tunnel runs under the Gothenburg River, with several lanes. Lane changes might be necessary for correct navigation. High bridges near the sea pose wind challenges.	Dynamic barriers near the Øresund Tunnel require real-time decision-making.	Ferry terminal at Puttgarden. Bridges and one tunnel along the route.	Tunnels in Rotterdam (Caland, Botlek, Noord) have special traffic lights and barriers. Wildlife crossings over the A50 and A1 add variability.
Other infrastructure elements	The right lane is used for multiple purposes in urban areas close to Oslo; Signs indicate when the right lane changes from a bus lane to a entry/exit lane.	HGV lanes exist on steep sections. Weather near Hallandsåsen often causes problems for HGVs.	No additional elements noted	No additional elements noted	No additional elements noted

5.3 Optimal Physical Infrastructure and Required Investments

This section focuses on the requirements outlined in Table 5-1 to frame required investments in physical infrastructure along the MODI corridor to support L4 automated vehicle deployment. The assessment in Table 5-2 concentrated on categories adopted from MODI's UC CCAM Test Corridor: Road marking, static signage, dynamic signage, road geometry, entrances, interchanges, and exits, tunnels, bridges, toll stations, and ferries, and other infrastructure elements. However, the discussion on optimal physical infrastructure relies on high-level criteria from literature and interviews in Chapter 3, steering clear of specific and potentially unnecessary recommendations, such as extensive tunnel modifications, unless justified by clear and broadly accepted operational needs.

The need for clear and consistent road markings are highlighted by **MODI_PDI_D42_r.1.1: Road Marking Visibility**. Lane markings support lane-keeping and precise navigation. The Road Authorities report that the road markings on the MODI corridor generally maintain good condition but note that variability between countries may affect their readability.

The signage along the MODI corridor is generally regarded as adequate, with road signs appropriately placed and clearly visible, thus fulfilling **MODI_PDI_D42_r.1.2: Signage Placement**. However, concerns have been raised about the presence of non-English text on signs in some countries. It is not yet clear whether this represents a significant issue for automated vehicles, as their systems may be able to interpret such signs accurately.

Variable Message Signs (VMS) are frequently used across the MODI corridor to provide real-time traffic updates, especially in response to sudden changes such as road closures, accidents, or adverse weather conditions (e.g., high winds on bridges). These signs are crucial for ensuring that both human and automated drivers can respond appropriately to dynamic road conditions.

Some countries along the corridor offer a digital representation of VMS data that can be integrated into vehicle systems. However, in Germany, the digital information is not legally binding, meaning that in cases of discrepancy, the physical sign's information takes precedence. Other countries rely solely on physical signage without a digital equivalent, leaving the responsibility of reading the information entirely on the driver or the automatic driving system.

Camera-based detection of information on VMSs is a challenge due to interference between the LED sign's lights and the camera's sampling frequency [55]. This issue can potentially be addressed through technical improvements to the camera system, the sign, or mitigated by providing machine-readable digital information, as explored in the sub-use case UC NO: Port, where the NPRA is working on converting VMS data into the DATEX II (METR) format for integration with existing traffic management systems. Ensuring accurate data sharing with automated systems will be a key focus moving forward, this report provides further discussion on this in Chapter 6.4

The road surface quality along the MODI corridor is generally good, as it is part of the TEN-T network, which ensures high maintenance standards. This indicates that **MODI_PDI_D42_r.1.3: Road Surface Quality** is met on the MODI corridor. However, winter weather conditions, particularly snow, ice, and frost, pose a challenge throughout the corridor, with more severe conditions occurring in the northern sections. The steep incline at *Hallandsåsen* has been specifically highlighted by the

Swedish Transport Agency as a notable challenge for Heavy Goods Vehicles (HGVs). Our findings do not suggest that winter maintenance procedures for CCAM vehicles need to differ significantly from those for conventional vehicles. Nonetheless, issues such as reduced visibility of lane markings and snow-covered signs persist and will require further attention. While these challenges are acknowledged, they fall outside the primary scope of this project and demands additional focused research in the future.

Requirement **MODI_PDI_D42_r.1.4: Safe Harbour Availability,** is referring to designated areas where automated vehicles can safely perform Minimum Risk Manoeuvres (MRMs) in the event of an emergency, requires further definition. While all involved stakeholders in the MODI project recognise the importance of providing these areas (see Chapter 3.2.3, Chapter 3.3.2), there is currently no unified approach to their placement or frequency along the corridor. Safe harbours could take the form of emergency stops, rest areas, or parking spaces, depending on the country and specific road conditions. Collaboration between industry and road authorities will be needed to ensure that safe harbours are adequately spaced and appropriately located to support the safe operation of automated vehicles.

6 Optimal Design of Digital Infrastructure

6.1 Introduction

This chapter describes the optimal digital infrastructure for a successful deployment of SAE L4 automated freight vehicles on the MODI Corridor and other transport corridors based on the stakeholder input and considerations in Chapter 3. The infrastructure needed to meet the requirements introduced in Chapter 2.2 are discussed for the three main categories of digital infrastructure: Connectivity Services, Positioning, and HD Maps.

6.2 Connectivity Services

6.2.1 Introduction and Requirements

Connectivity is an essential component of the digital infrastructure supporting L4 CCAM vehicles along the MODI corridor. CCAM vehicles rely on strong, stable cellular networks to enable communication that supports safe and efficient navigation, especially in responding to evolving traffic situations and complex road environments. This section reviews the key connectivity requirements from Chapter 2.2 with Table 6-1 summarising these requirements for easy reference.

Table 6-1: General Requirements to Digital Infrastructure: Connectivity

ID	Description	Comments/Examples
MODI_PDI_D42_r.2.1	**Basic Connectivity**: Challenging areas have connectivity solutions to enable, at minimum, emergency communication for L4 CCAM vehicles.	This ensures that L4 CCAM vehicles can communicate, even in areas with limited cellular connectivity
MODI_PDI_D42_r.2.2	**Cellular Network Coverage**: Cellular network coverage is documented.	Cellular networks must have the necessary coverage along the road networks to support automated driving.
MODI_PDI_D42_r.2.3	**Data Transmission Capability**: Network capacity supports data transmission to and from L4 CCAM vehicles.	The network must be able to handle the volume of data needed for L4 CCAM vehicle operations.
MODI_PDI_D42_r.2.4	**Cybersecurity**: Communication-related systems for L4 CCAM vehicles have basic cybersecurity safeguards in place.	This is important for protecting L4 CCAM vehicles from cyberattacks and ensuring the integrity of communication data.

6.2.2 Optimal Infrastructure for Connectivity

Literature and stakeholder input indicate that reliable cellular networks are essential for the operation of CCAM vehicles. Preliminary MODI findings show strong cellular coverage along the corridor overall; however, border crossings pose a significant challenge. Test run data reveal that 80-90% of signal loss occurs within 5 km of these crossings and nearly 100% within 10 km. In total, less than 2% of the distance driven during the test run had poor or missing connectivity, with border crossings accounting for nearly all these interruptions.

To address this issue, Use Case Norway is developing a temporary solution for the demonstration day to mitigate cellular connection loss at border crossings. Details on the technical solution are not yet publicly available. Upcoming MODI deliverables will include a thorough analysis of the above-mentioned collected data to assess whether requirements **MODI_PDI_D42_r.2.1**, **MODI_PDI_D42_r.2.2**, and **MODI_PDI_D42_r.2.3** are met along the corridor.

Additionally, several MODI Sub-Use Cases will showcase C-ITS infrastructure supporting communication in complex road sections. This infrastructure will aid vehicles in performing specific manoeuvres and issuing warnings on traffic regulations and incidents, such as VRU detection (V2V, I2V), cooperative merging (V2V), traffic light status communication (I2V), and hazard warnings from infrastructure (I2V). See Chapter 4 for further details.

Stakeholder insights and the literature in Chapter 3 also highlight the critical importance of protecting data integrity and guarding against cyber threats, supporting **MODI_PDI_D42_r.2.4**. Current standards, like UNR 155 and 156, provide a foundation, yet stakeholders emphasise the need for dynamic, adaptable cybersecurity measures as automated freight transport scales up.

Looking ahead, operators may aim to reduce reliance on cellular networks, allowing vehicles to operate autonomously in cases of temporary disruptions or connection loss, see Section 3.4.3. C-ITS infrastructure will most likely play a role in special road sections by ensuring connectivity and delivering targeted, situation-specific data.

6.3 Positioning

6.3.1 Introduction and Requirements

Positioning accuracy is essential for deploying CCAM freight transport along the MODI corridor. CCAM vehicles rely on precise positioning data to navigate safely, detect their surroundings, and respond effectively to road conditions. Designing infrastructure that delivers high-quality positioning data with robust redundancy is critical to ensuring continuous and reliable CCAM operations. Table 6-2 revisits the key positioning requirements from Chapter 2.2 and sets the stage for this chapter's discussion on the optimal PDI design for Positioning.

Table 6-2: General Requirements to Digital Infrastructure: Positioning

ID	Description	Comments/Examples
MODI_PDI_D42_r.3.1	**Positioning Services**: Publicly available and reliable positioning services, e.g. GNSS, are accessible.	This is important for providing L4 CCAM vehicles with accurate location information. Where GNSS signals are unavailable, other positioning services can be provided.
MODI_PDI_D42_r.3.2	**Reference Frame Definition**: Positioning data are provided within a defined geodetic reference frame.	This ensures consistency of positioning data across different systems and regions.

6.3.2 Optimal Infrastructure for Positioning

Despite the advancements in sensor fusion, satellite-based positioning remains essential for L4 automated systems. For reliable performance, L4 freight vehicles need consistent access to satellite signals, particularly on public roads where the access to reliable physical reference points may vary. Preliminary analysis data collected in UC CCAM has shown strong GNSS performance on most of the MODI corridor, with expected challenges in tunnels and urban areas where signal interruptions are common. In these locations, supplementary data, such as landmark positioning, can enhance accuracy by providing alternative reference points for navigation. This is addressed directly by **MODI_PDI_D42_r.4.5: Physical Infrastructure Representation Data.** Collaborative efforts between authorities and industry will be needed to define content, accuracy standards, and technologies for effective data exchange.

In addition to data collection campaigns, modelling helps predict whether **MODI_PDI_D42_r.3.1** requirements are met across the MODI corridor and potentially other European transport corridors. Annex IV provides an analysis of GNSS performance using Dilution of Precision (DOP) indicators, identifying MODI corridor sections where GNSS performance may be impacted by environmental obstructions, such as buildings, vegetation, or terrain. These findings align closely with the empirical data collected, suggesting overall strong GNSS coverage along the corridor.

Another crucial element of precise positioning is the geodetic reference frame that underpins geographic data. Annex V studies the challenges of integrating different national reference frames on the MODI corridor, with discrepancies of up to 2 cm across borders. In some cases, unaccounted-for reference frame differences could lead to discrepancies as large as 70 cm. To meet MODI's requirement **MODI_PDI_D42_r.3.3**, adopting a unified reference frame like WGS84 is recommended. There are also ongoing initiatives to create a common European reference frame to eliminate such issues across Europe, see Annex V for details.

The European Union's Galileo system, especially with the rollout of the Galileo High Accuracy Service (HAS), offers a significant improvement for positioning precision in automated vehicles. Unlike GNSS RTK, which relies on costly infrastructure and regional base stations, Galileo HAS provide free, centimetre-level accuracy directly from satellites, enabling broad coverage across Europe without additional infrastructure. This capability reduces dependency on terrestrial systems, offering scalable, cost-effective, and reliable real-time positioning that is essential for CCAM vehicle operations along the MODI corridor.

6.4 High-Definition Maps

6.4.1 Introduction and Requirements

This chapter examines the role of HD maps in the digital infrastructure of automated transport, focusing on the need for standardisation and the contributions of public authorities. The data requirements necessary for developing this part of the digital infrastructure are outlined in Table 6.3, which summarizes the types of information essential for CCAM vehicle operations.

Table 6-3: General Requirements to Digital Infrastructure: HD-maps

ID	Description	Comments/Examples
MODI_PDI_D42_r.4.1	**Situation Data**: Real-time information on traffic incidents, road closures, and other events affecting traffic flow are available.	This helps L4 CCAM vehicles to navigate safely and efficiently in dynamic traffic conditions.
MODI_PDI_D42_r.4.2	**VMS Data**: Data describing the position and messages from variable message signs (VMS) are available.	This provides L4 CCAM vehicles with information about upcoming traffic conditions and regulations.
MODI_PDI_D42_r.4.3	**Traffic Regulation Data**: Data representing traffic regulations, including speed limits, overtaking restrictions, and turning movements, are available.	This provides L4 CCAM vehicles with information on legal and safe driving practices.
MODI_PDI_D42_r.4.4	**Physical Infrastructure Representation Data**: Detailed and accurate geometric data representing road infrastructure elements, such	This type of data is essential for safe and efficient navigation, as it allows L4 CCAM vehicles to identify lanes, avoid obstacles,

ID	Description	Comments/Examples
	as road markings, signage, structures, and other relevant features, are available, with precise position data provided for key features.	and follow traffic regulations. It also includes information on the location of important road features, such as toll plazas, charging stations, and rest areas.
MODI_PDI_D42_r.4.5	**Road Traffic Data**: Real-time and historical traffic flow data are readily available.	This helps L4 CCAM vehicles to avoid traffic congestion and plan routes efficiently.
MODI_PDI_D42_r.4.6	**Energy Infrastructure Data**: Data on the location and availability of charging stations and other energy infrastructure are available.	This type of data is essential for planning routes for electric L4 CCAM vehicles and ensuring access to charging stations. It is also highly relevant for the MODI corridor, as the use of electric L4 CCAM vehicles is expected to increase.

6.4.2 Optimal Infrastructure for High-Definition Maps

Early in the MODI project, it became clear that a strong data infrastructure for HD maps would be essential for supporting vehicle operations. This topic drew significant interest from various stakeholders and led to a project-wide initiative. Representatives from multiple MODI Work Packages collaborated in a workshop to discuss critical data requirements, the need for standardisation, and the roles of different stakeholders. See Annex III for details from the workshop on HD maps. Public authorities, holders of in-vehicle generated data and service providers were identified as the primary data providers, supplying both static (e.g., road infrastructure, traffic regulations) and dynamic (e.g., real-time traffic, VMS updates) information. Effective collaboration between public authorities, map providers, and vehicle manufacturers, along with investment in digital infrastructure, emerged as key factors in enabling HD map functionality.

To address the need for authorities to provide standardised and reliable data, key data types from public databases have been prioritised based on their potential to enhance infrastructure support for large-scale deployment of L4 CCAM vehicles. The focus was on identifying the most critical data types across various national databases—such as road geometry, speed limits, and height restrictions—to better align public resources with the requirements of automated driving technology.

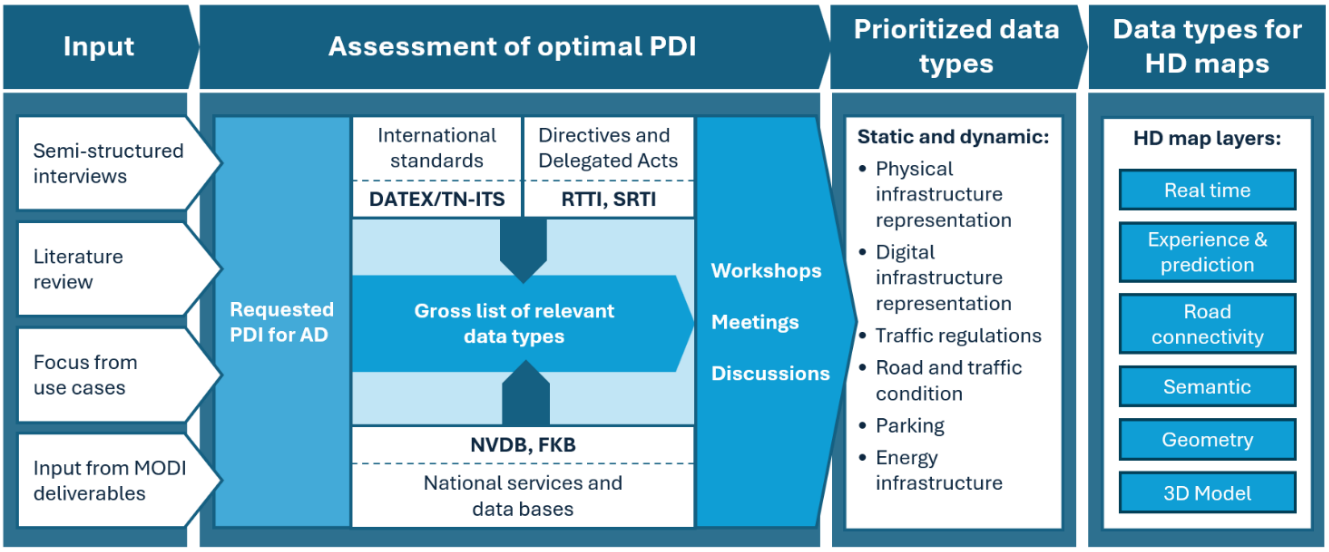

Figure 6-I: Assessment of data types to support optimal PDI (adopted from Annex VII: Data Types for HD Maps)

Figure 6-I provides a visual overview of the workflow for prioritising data types to support HD maps in L4 automated vehicles. It outlines the primary inputs from public databases, international standards, and European directives, forming a comprehensive list of data types. This workflow includes the categorisation, prioritisation, and selection of essential data types based on their relevance to L4 vehicle operations. Finally, each prioritised data type is integrated into one or more HD map layers adapted from Elghazaly, Frank et al. (2023) [1].

In the process, more than 700 data types were evaluated and prioritised according to the following prioritisation categories:

1. Data types that are prerequisites for driving on SAE L4, according to international and national regulations.
2. Data types that provide relevant and important information to support an SAE L4 CCAM vehicle.
3. Data types that may offer useful information to support an SAE L4 CCAM vehicle.
4. Data types that may become relevant in the future.

Data types have been identified using Norwegian public datasets as an example of available data. Many of the datasets used for data type identification lack comprehensive national or international coverage and are not fully standardized, resulting in incomplete or inconsistent data fields. Our focus has been to provide a broad overview of the data types that may be available from public databases or through international standards, rather than limiting our scope to data types currently accessible. Consequently, some of the identified data types may not yet meet the necessary quality standards or may be insufficiently managed within existing national databases.

Table 6-4 shows examples from the full dataset [56] organised by category, priority level, and the data layer based on HD map layers adapted from Elghazaly, Frank et al. (2023) [1]. This approach provides a guidance for further enhancement of data quality, real-time accuracy, and infrastructure readiness, ensuring that essential data needs are met first.

Table 6-4: Examples of data types for HD Maps

Category	Data type	Pri.	Layer
Physical Infrastructure Representation	Road network geometry and topology	1	Road connectivity
	Sign plate	1	Geometry
	Road marking	1	Geometry
Digital Infrastructure Representation	Address / Point of interest	1	Semantic
Traffic regulations	Speed limit	1	Semantic
	Height restrictions	1	Semantic
	Direction of travel	1	Semantic
	Restricted driving manoeuvre	1	Semantic
	No overtaking	1	Semantic
Road and traffic conditions	Weather-related road conditions	1	Real-time
Physical Infrastructure Representation	Pedestrian crossing	2	Semantic
	Tunnel	2	Geometry
	Bridge	2	Geometry
	Light poles	2	Geometry
	Guard rail	2	Geometry
	Curb	2	Geometry
	Hard shoulder width	2	Geometry

Category	Data type	Pri.	Layer
Road and traffic conditions	Roadworks	2	Real-time
	Accident	2	Real-time
	Obstruction	2	Real-time
Physical Infrastructure Representation	Acoustic barrier	3	Geometry
Road and traffic conditions	Travel time data	3	Real-time
	Infrastructure damage obstruction	3	Real-time
	Winter maintenance class	3	Semantic
Parking	Parking site / Occupancy	3	Real-time
	Rest area	3	Semantic
Energy infrastructure	Electric charging point status	3	Real-time
Physical Infrastructure Representation	Playground equipment	4	Geometry
	Public transport hub	4	Semantic
Road and traffic conditions	Avalanche point	4	Semantic

The results of this analysis provide clear guidance for advancing digital infrastructure to support L4 CCAM vehicles. Considering the high costs of maintaining accurate databases, it is wise to concentrate investments on data types with the highest potential impact for L4 CCAM deployment—those offering the most value for the cost. Next steps will involve determining the necessary data quality, update frequency, and maintenance standards for these prioritised data types. According to the research in this deliverable, this approach will directly support efforts to enhance automation levels on public roads. Together with other strategic and operational priorities, it contributes to building a sustainable, safe, and efficient transportation system.

6.4.3 Collaboration with ULTIMO and Standardisation Efforts

Although targeting different applications—freight vehicles and public transportation—the MODI and ULTIMO projects both recognise the crucial role of HD maps in enabling CCAM operations. To address this, they have collaborated to explore approaches for establishing common standards for HD maps. Their shared goal is to ensure that HD maps can support various operational environments, contributing to a unified framework for commercial deployment.

In Annex VII, there is a detailed overview of ongoing standardisation efforts. ISO initiatives, such as the ISO 17572 series for location referencing, and CEN standards like DATEX II for road and traffic information, form the backbone of HD map development. Additionally, consortiums like the Open Autodrive Forum (OADF) and SENSORIS are actively contributing to the evolution of standards for map data and sensor information exchange. These initiatives aim to ensure interoperability and reliability in HD map use across regions and vehicle types.

7 Conclusions

7.1 General Conclusions

This deliverable presents a comprehensive analysis of the physical and digital infrastructure requirements necessary to enable safe and efficient deployment of L4 CCAM vehicles in freight transport along the MODI corridor. The conclusions are built on a robust foundation of research; an extensive literature review, semi-structured interviews, workshops, in-depth analysis of requirements for physical and digital infrastructure, and insights drawn directly from MODI project Use Cases. Together, these sources provide a nuanced understanding of how the MODI project recommends that the automotive industry and public authorities prepare the infrastructure to support automated driving.

The findings highlight that while general infrastructure upgrades may not be necessary for initial deployments of L4 CCAM vehicles, targeted improvements are crucial. Specifically, digital infrastructure—such as connectivity, precise positioning, and HD maps—emerges as fundamental to CCAM vehicle operations. Interviews and Use Cases underscore the industry's reliance on consistent and accurate digital services, particularly in complex environments like intersections and border crossings. Additionally, stakeholders consistently identified data standardisation and cross-border interoperability as critical for cohesive CCAM vehicle deployment across Europe.

While the automotive industry often seeks to minimise dependency on public infrastructure by utilising onboard systems and commercial services, public authorities emphasise the importance of infrastructure adaptation to ensure public safety and integration with traditional road users. Both perspectives underscore the value of collaborative efforts to define standards and guidelines for infrastructure development, from establishing common HD map specifications to setting connectivity protocols that support CCAM vehicle operations seamlessly across different regions.

Ultimately, this deliverable advocates for a balanced strategy that pairs targeted physical upgrades with a strong emphasis on advancing digital infrastructure. The collaborative standardisation of PDI will allow both public authorities and the automotive industry to coordinate investments effectively, ensuring infrastructure that is responsive to the evolving needs of automated freight transport.

7.2 Recommendations

Table 7-1 outlines key requirements across physical and digital infrastructure domains that enable L4 vehicles to operate safely and efficiently. Each requirement highlights the need for alignment on specifications, data accuracy, and implementation standards to support consistent functionality across Europe. Developing these elements through **cooperative efforts** will be vital to ensuring that infrastructure investments are adaptable, scalable, and aligned with evolving CCAM vehicle technology.

Table 7-1: Topics for development of the PDI in collaboration between authorities and industry stakeholders.

ID	Infrastructure Group	Topic	Comment
T4.2-R1	Physical	Safe harbours	CCAM vehicles will need room to perform MRMs safely and with as little interference with other traffic as possible.
T4.2-R2	Physical	Maintenance standards	The required level of maintenance for signs, markings and pavement must be developed in collaboration between authorities and the automotive industry.
T4.2-R3	Digital – Roadside equipment	Coverage of RSUs	CCAM vehicles may in certain situations, like complex intersections and other critical points, need support from RSUs or collective perception V2V implementations with standardised interfaced to gain the necessary perception overview.
T4.2-R4	Digital – Connectivity Services	Coverage of cellular network	CCAM vehicles depend upon connectivity. Cellular networks must have the necessary coverage along the road networks to support automated driving.
T4.2-R5	Digital – Positioning Services	Coverage and quality of positioning services	Positioning is urgent for CCAM vehicles. Positioning services must have the necessary coverage and quality (scalability, accuracy, protection, etc.) along the road networks to support automated driving. The coverage is especially crucial in complex areas like intersections and cities.
T4.2-R6	Digital – Positioning Services and HD Maps	Accurate positions of landmarks	Accurate landmark positions are crucial for improved sensor-based positioning. Road and mapping authorities may provide such data to HD Map producers.
T4.2-R7	Digital – HD Maps	HD Maps and Required Content	HD maps are essential for safe navigation of CCAM vehicles, requiring accurate, up-to-date digital representations of traffic regulations, lane-level road networks, and precise landmark positioning. Road authorities should provide machine-readable data on traffic rules and road details, including dynamic changes (e.g., construction zones) to support legal and safe navigation in complex areas. D4.2 includes a prioritised list of data types, pinpointing those most essential for accelerating the deployment of L4 CCAM features across Europe.

ID	Infrastructure Group	Topic	Comment
T4.2-R8	Digital – HD Maps	Standardised HD Maps	Standardizing HD map content, accuracy, and data formats is essential for large-scale CCAM vehicle deployment across Europe. Current vendor-specific formats limit interoperability, so industry and public authorities must establish common specifications to ensure seamless CCAM vehicle access and functionality across borders.

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Annex I: Literature review

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Executive Summary

This document investigates and compares literature from recent research concerning the required physical and digital road infrastructure (PDI) for connected and automated vehicles (CAVs). The primary purpose is to identify the main findings relevant to MODI T4.2 in previous and ongoing research and innovation concerning physical and digital infrastructure requirements for automated driving. By studying this research question, the document lays a fundament for answering the research questions for MODI T4.2.1, focusing on what requirements will be put on the physical and digital road infrastructure on public roads at different levels for supporting freight transport with SAE level 4 vehicles.

The findings indicate that connected, cooperative and automated mobility (CCAM) for logistics has received comparatively less attention than passenger transport. Most of the studied literature concerns connected and automated vehicles (CAVs) in general, while only a few studies have investigated requirements for larger vehicles for logistics, as studied in MODI. Therefore, specific requirements for freight transport with SAE level 4 vehicles have not been found in the studied literature. Still, the requirements and recommendations concerning the introduction of CAVs in general are considered relevant for MODI as well.

Authorities need to plan for the future of automated drivers but invest cautiously and avoid vehicle-specific technologies. More safe harbours may be required to prevent conflicts between CAVs and other road users, which may be particularly important for large vehicles such as MODI. Upgraded maintenance of signs and markings is crucial for the perception of onboard units. The digital infrastructure will be crucial for authorities to support and control CAVs. Critical elements include roadside equipment for enhanced situational perception; continuous coverage of communication networks; the availability and accuracy of services, point clouds and landmarks for positioning support; and provision of HD maps with machine-interpretable traffic rules and regulations, road network and dynamic data. Standardisation of the PDI and requirements is needed before introducing CAVs in large numbers to ensure information exchange and continuity, and authorities are recommended to take a leading role.

I.1 Methodology

I.1.1 Research question for the literature review

This report describes the results of a literature review conducted to gain knowledge about the state of the art. The results are fundamental for building on existing knowledge when working on the MODI T4.2 subtasks, especially for defining ST 4.2.1 and 4.2.2 requirements.

The research question for the literature review was formulated as follows:

What are the main findings relevant for MODI T4.2 in previous and ongoing research and innovation concerning physical and digital infrastructure requirements for automated driving?

I.1.2 Review methodology

The literature review was conducted in two parallel tracks, as illustrated in Figure I-.

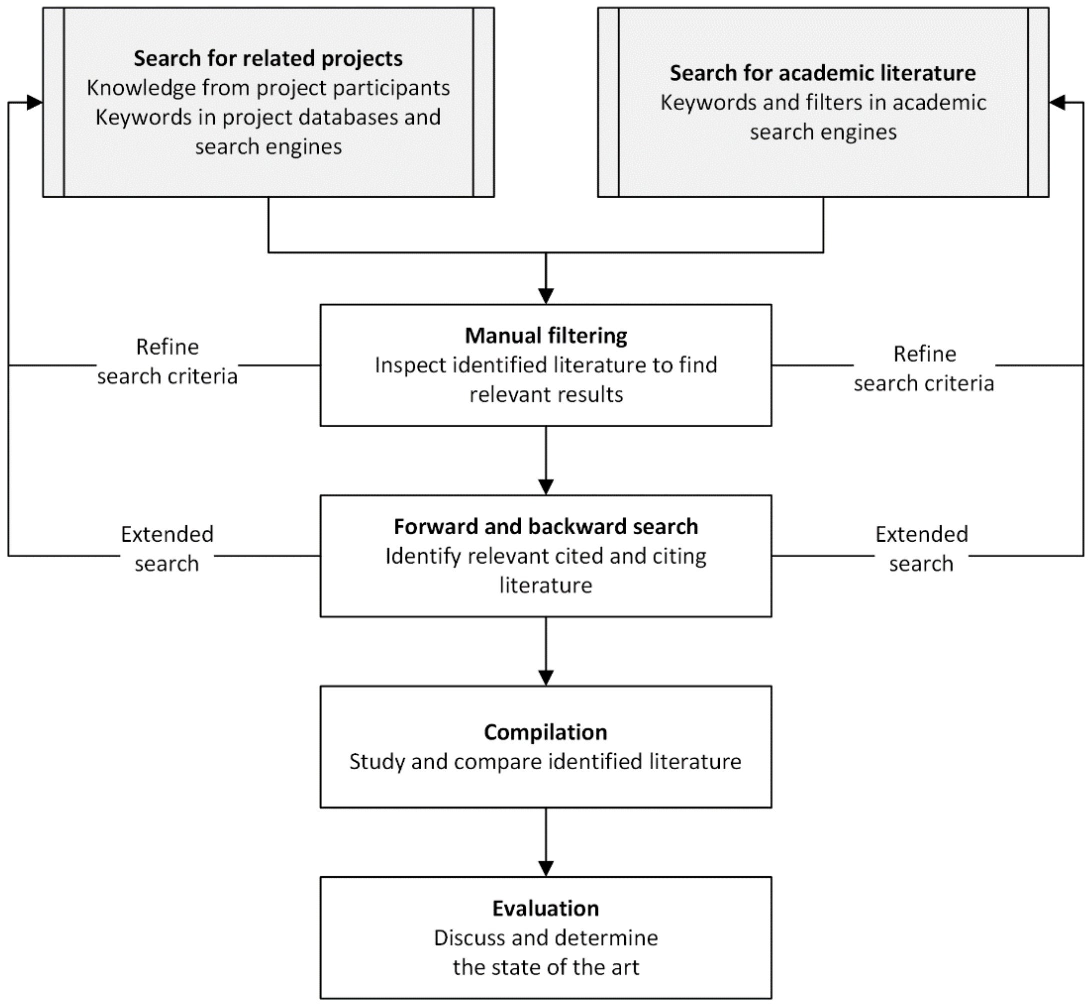

Figure I-1 *The review methodology.*

One track searched for relevant literature through keyword searches in project databases, such as the EU Knowledge Base on Connected and Automated Driving [1], to align with EU projects and anchor MODI requirements in previous work for deployment.

A second track followed a multi-faceted approach to identifying literature in academic databases. This literature is narrower in the topic for each paper, but the main direction gives valuable insights into future possibilities and requirements. An initial pool of keywords was chosen, which was used to identify seminal publications and research groups working on the topic(s). The initial keywords and publications were then categorised using Table I-1. Finally, the publication-matching website Connected Papers [2] was used to identify similar publications.

Table I-1. Keywords for the search on academic literature.

	Positioning	Connectivity	Machine Readability
Digital	GNSS/INS, GPS, Multi-sensor fusion, SLAM, RTK positioning, Odometry	V2X, V2V, V2I, DSRC, 5G, C-V2X technologies, Network cooperation, Secure communication	Traffic light recognition, HD Maps, Lane detection, Object detection
Physical	Highway engineering, Traffic analysis, Infrastructure development, Urban planning, Toll systems	Roadside units, Smart traffic light, Intelligent traffic systems, Traffic signal control, Smart roads	Road maintenance, Human-vehicle interaction, Pedestrian detection, Collision avoidance

I.1.3 Results

After conducting a thorough search, applying filters, and compiling the results, an extensive list of documents was identified for final review, as listed in Table I-2.

Table I-2. List of compiled documents.

Reference type	Number of documents
Project deliverables and other reports	45
Academic literature	139
Total	**184**

The search for projects and reports identified several finished and ongoing projects and activities, as listed in Table I-3. These projects and reports have various geographic and thematic scopes but represent research related to PDI at national, regional, and international levels from Europe, Oceania, and North America. The list could have been longer, with more national activities from different countries, especially those involved in MODI. This would require input from project members from those countries.

Table I-3. Projects and activities identified for review.

NAME	GEOGRAPHIC SCOPE	TIMELINE/STATUS
ACUMEN [3]	EUROPE	JUNE 2023 TO JUNE 2026
ATLAS L4 [4]	GERMANY	JANUARY 2022 TO SEPTEMBER 2024
AUGMENTED CCAM [5]	Europe	September 2022 to December 2025
AUSTROADS FSP6088 [6]	Australia and New Zealand	Finished 2019
AUTMOTO [7]	Finland	Finished 2021
AUTOPIA [8]	Norway	Finished 2022
AVENUE [9]	Europe	Finished 2022
AWARD [10]	Europe	January 2021 to December 2023
C-ROADS [11]	Europe	February 2016 to December 2023 (Dec. 2024 in some countries)
CSA REPORTS	Canada and the US	Finished 2021
DIREC [12]	Europe	September 2021- August 2023
ENSEMBLE [13]	Europe	Finished 2022
EU-EIP [14]	Europe	Finished 2021
HI-DRIVE [15]	Europe	July 2021 to July 2025
HYPOS [16]	Norway	March 2022 to February 2026
IN2CCAM [17]	Europe	2022-2025
INFRAMIX [18]	Europe	Finished 2020
ITF WORKING GROUP [19]	Global	Finished 2023
JAMMERTEST	Norway	Yearly, since 2021
L3PILOT [20]	Europe	Finished 2021
LAMBDAROAD	Norway	Finished 2021
MANTRA [21]	Europe	Finished 2020
MCSINC [22]	Norway	
NORDICWAY [23]	Europe – The Nordic Countries	2017-2023
NPRA REPORTS	Norway	
PODIUM [24]	Europe	October 2022 to September 2025
SHOW [25]	Europe	January 2020 to January 2024
TEAPOT	Norway	2020 to 2023
TM4CAD [26]	Europe	September 2021 to March 2023
TRANSAID [27]	Europe	Finished 2020
ULTIMO [28]	Europe	October 2022 to October 2026
UK GEOSPATIAL REPORTS	United Kingdom	

Several MODI deliverables also describe relevant findings and requirements that have been used as input in this document:

- D1.1 User and stakeholder requirements [29]
- D1.2 Safety and security requirements [30]
- D1.3 Report on border processes [31]
- D3.1 Report on connectivity requirements [32]
- D3.2 Report on automation requirements [33]

I.2 Findings

I.2.1 Findings from finished projects

Austroads FSP6088

The project 'Infrastructure Changes to Support Automated Vehicles on Rural and Metropolitan Highways and Freeways' (FSP6088) was run by Austroads in Australia and New Zealand and was finished in 2019. The project studied the physical and digital infrastructure on Australian and New Zealand freeways and highways and its readiness for automated driving. The project was divided into five modules, where the last and final Module 5 [34] summarised findings and recommendations. Module 1 identified the quality requirements for automated vehicles. Module 2 performed an audit of 25.000 km of road with more than 8.000 signs based on recommendations from Module 1 [35]. Module 3 compared asset standards towards the needs of automated vehicles. Module 4 studied opportunities for using data from automated vehicles to support asset management.

Among the essential findings were that quality and visibility, defined by extent, colours, contrast and retro-reflectivity of line markings and traffic signs, are essential for automated vehicles. Electronic signs are challenging for automated vehicles to read and interpret. Markings and signs need regular maintenance to be kept in a reasonable condition. A specific suggested change in the physical infrastructure is to add clear edge line markings to more roads. Technical guidelines for traffic management and road design need to be updated to focus on the extended needs of automated vehicles. However, when writing the Module 5 report, there was still too much uncertainty regarding the detailed needs.

Automated vehicles must rely on many sensors and other sources, including V2X local connectivity, Vehicle-to-cloud connectivity, GNSS (augmented and not augmented), and HD Maps. For HD Maps, the report from Module 5 [34] states, "Road authorities will not own or operate maps for ADAS, but may have a key input into attributes/changes in the map." The HD Map will likely be integrated with sensor data for highly automated vehicles to build a complete perception of the environment. Also, dynamic information about road works and other changes needs to be provided to the vehicles by road operators.

Likewise, for cloud connectivity, it is stated that "Road authorities will not own or operate cellular networks, but should play a role in ensuring coverage of key networks to support ADAS/automated driving." Also, to ensure coverage of augmented GNSS services, "Road authorities can influence cellular coverage of roadways for ADAS/automated driving."

It is recommended that stakeholders from road authorities, automotive manufacturers, road constructors and maintainers, and digital infrastructure suppliers come together in a Concept of Operation for automated driving. A rating for the roads' readiness for automated driving should be developed, although it is challenging to set and measure benchmark levels for acceptance.

AUTOMOTO

The Finish project AUTOMOTO (AUTOmated driving on MOTOrways) [36, 37] was finished in 2021. The project studied infrastructure support and classification for automated driving at SAE levels 3 and 4 on motorways in Finland. It carried out a detailed inventory study of how the physical and digital infrastructure on a 160-km motorway section could support the two SAE levels. The studies of how the physical and digital infrastructure can support automated driving at SAE levels 3 and 4 are highly relevant for MODI T4.2.

The inventory study indicated that the current physical and digital infrastructure provided good support for the two SAE levels. The studies of the current physical infrastructure focused on the road dimensions (road and shoulder width) concerning possibilities for minimum risk manoeuvres (MRM), road markings, pavement (road surface) conditions, and traffic management. One question regarding MRMs was whether there should be room on both motorways' inside and outside shoulders. They also observed that digital solutions were needed in addition to ordinarily visible road markings and signs for challenging weather conditions.

The studies of digital infrastructure focus on communication networks, positioning services, and traffic information services. Automated vehicles require reliable, high-capacity communication networks. Although the Finish mobile network has good coverage, it has not been designed to meet the requirements of connected and cooperative driving. The studies of different correction services for GNSS positions found good availability of services and little difference in accuracy between service providers. Still, they highlighted the importance of coordinate reference systems and metadata. Finally, studies of traffic information services found many service providers that could provide critical information, which is particularly important in Nordic conditions. However, they found no open services that provided messages according to C-ITS communication standards with the needed data quality.

After evaluating previous work on road classification systems, the project decided to build further on the ISAD classification from the INFRAMIX project. The classification was extended by adding more criteria in four categories, according to BSI PAS 1883:2020 [38]: physical infrastructure, digital infrastructure, environmental conditions, and dynamic elements such as traffic amount. Also, the most critical attributes for defining ODD on motorways were identified within the four categories. Finally, specific requirements for ISAD-based classification of the service level for automated driving on motorways and main roads in Finland were described.

A final and essential observation from the AUTOMOTO project was that the attributes that define the ISAD levels might be more important than the classification system: *"It may very well prove in the future that the targeted level of support is not any single ISAD-level, but a combination of support elements on different ISAD-levels, depending on the local circumstances and needs. With regard to facilitating automated driving, an important future target is to develop, deploy, operate, and maintain a secure, up-to-date, standardised data set containing the values of each ODD attribute utilised in the ISAD classification." [36]*

AUTOPIA

The Norwegian project AUTOPIA (Autonomous Universal Transport Of People In Viken) was finished in 2022. The project tested small, shared, and connected automated vehicles as a part of the public transport system in a small area outside Oslo. The effects and possibilities of automated transport were studied in close collaboration with the market and other public stakeholders. In collaboration with the project, the Norwegian Public Roads Administration (NPRA) ran a pilot project focused on collecting experiences and knowledge on the development of automated transport. The pilot project gave insight into the role of public road authorities in terms of authority and regulations for public transport and goods deliveries, now and in the future. Also, the consequences of automated transport when mixed with regular traffic were studied. Two reports from the NPRA pilot project were published as part of the AUTOPIA project (in Norwegian): Report 5.2 [39] identifies sources for publicly available data relevant to automated transport, while Report 5.3 [40] describes the digital infrastructure for sharing data with automated vehicles, grouped into communication technologies, positioning technologies and roadside equipment.

Although small vehicles for public transport are outside the scope of MODI, findings and recommendations for public authorities presented in the two AUTOPIA reports are relevant for identifying information possibly provided by authorities and the digital infrastructure for sharing information.

Sources identified in Report 5.2 [39] include the Norwegian National Access Point (NAP) – Transportportal.no, the Norwegian Road Database (NVDB), C-ITS services, public base map data and point clouds, travelling times, public transport schedules and weather information. Furthermore, international standards and specifications, such as NDS, INSPIRE, SENSORIS, ADASIS, DATEX II and TN-ITS, were studied.

The studies showed that Norway has a large amount of publicly available data relevant to automated transport. Still, they indicated that the data needs to be better prepared for use in automated vehicles. Coverage and content need to be extended, and metadata must be described, especially descriptions of the data quality. Also, the data quality may be improved through feedback from automated vehicles. One example where improvements are needed is the Norwegian Road Database, where only centre lines are described geometrically, with related restrictions. In contrast, automated vehicles need detailed information at the lane level.

In Report 5.3 [40], the digital infrastructure is grouped into communication technologies, positioning technologies and roadside equipment. Relevant standards and specific initiatives in the EU and the United States are also discussed. Some of the studied communication technologies were the Autopass system for electronic tolling and calculation of travelling times, 5G C-ITS Services, the DAB radio network, the TETRA emergency network and the eCall emergency registration system. Several technologies for accurate positioning that could improve positions from GNSS are discussed, such as augmented GNSS, differential GNSS and positioning within point clouds. The roadside equipment includes AID cameras and radars in tunnels, signalling systems and automated physical blockings, climate sensors, traffic registration systems, VMSs, and control towers.

Based on the studies and discussions with relevant stakeholders, the report concludes with a brief discussion of expectations and recommendations for the future, including a suggested set of infrastructure support within distinct functional road classes and ISAD categories. For the latter, the infrastructure requirements are grouped into communication technologies (4G, 5G, RSUs), publicly available data (static and dynamic), positioning technologies (PPP-RTK, RTK, R-ITS, RTLS), the physical road (road marking, separate lanes for automated traffic), and roadside equipment (AID, VMS, Signal systems, RSUs).

AVENUE

The European project AVENUE (Autonomous Vehicles to Evolve to a New Urban Experience – https://h2020-avenue.eu/) was finished in 2022. The project's scope was the demonstration of fleets of automated minibuses for urban transportation. Although minibuses for urban public transport are outside the scope of MODI, findings and recommendations for public authorities presented in AVENUE Deliverable D9.1 [41] are relevant regarding (1) creating and providing data and (2) the traffic and communication infrastructure.

AVENUE Deliverable D9.1 [41] suggests a list of data that should be considered high-value data for CAVs: geographical data; orthographic data; satellite data; weather data; data on crash or near-crash situations; and data on mobility, traffic patterns and participants. The data should be free and open. Standardised, non-commercial, platform-neutral schemes and taxonomies must be developed, and data must be harmonised and provided according to such schemes. The European Mobility Data Spaces may be an arena for such policies.

It is also stated that standards and harmonisation are required for the physical and safety-related infrastructure –for example, a minimum set of standards for road traffic signs and markings. Furthermore, technical solutions should require as little intervention in the infrastructure as possible, although the road infrastructure must be a manageable factor for deploying automated vehicles.

Finally, it is suggested that European-wide digital twins of the road traffic infrastructure be established. Such digital twins must be fit for cross-border traffic and include traffic regulations and other relevant conditions.

A highly relevant conclusion from AVENUE Deliverable D9.1 [41] is the lack of standards and interoperability between high-definition maps of different vehicle manufacturers and the complexity of updating these maps.

AWARD

The European project AWARD (All Weather Autonomous Real logistics operations and Demonstrations – https://award-h2020.eu/) ran from January 2021 to December 2023. The project focused on automated transportation with heavy-duty vehicles that can operate under harsh weather conditions.

AWARD is one of a few projects focusing on automated heavy vehicles and logistics. Use Case 2 in AWARD is particularly relevant for MODI task 4.2: "Hub-to-hub autonomous logistics," demonstrating an automated ruck driving on public roads between two hubs in Austria. Besides, use case 4 demonstrated an automated trailer at the Rotterdam port.

Deliverable D3.5 [42] describes the architecture of the ADS used in the project, while deliverable D3.6 [43] describes results from an evaluation of the ADS. The vehicles were equipped with lidars, radars, cameras, GNSS, and IMU. The sensors could compare fused results in real-time to a previously recorded map to locate the vehicles in space and detect obstacles. A stored site map is mandatory for almost all functions and was generated by driving the site manually while focusing on the potential paths that a vehicle would have to take during a mission. Landmarks for localisation were considered an urgent part of the stored site map.

The evaluation in deliverable D3.6 showed that the ADS had a reliable performance regarding localisation and perception in nominal weather conditions. However, it was expected to be challenging to conduct the same scenarios in harsh weather conditions.

Several other relevant deliverables from the AWARD project are not yet available to the public.

DiREC

The European project DiREC (Digital Road for Evolving Connected & Automated Driving) – https://direcproject.com/ ran from September 2021 to August 2023. The project acknowledged a need for better dialogue among National Road Administrations (NRAs), OEMs and service providers to articulate infrastructure requirements and define a roadmap and responsibilities for achieving safe and smart roads through CAD.

The final report [44] summarises findings from the project. DiREC performed a literature review and interviews with stakeholders, similar to what has been done in MODI. Many of the same observations are noted in the DiREC report as in this report:

- Limited changes to the physical infrastructure.
- Improved quality of road signs and markings.
- Prioritise gaps in the physical infrastructure that may be closed by digital infrastructure.
- NRAs must participate in designing and providing services for road and traffic information.
- Various standards and lack of standards for data exchange.
- Legislation and standards must define responsibilities for each actor within the CAD ecosystem.
- The legal aspects of data sharing and cybersecurity are particularly critical.

An essential observation was that CAD will disrupt the design and operation of road network infrastructure. NRAs will need to take a different role in the future, in which automated vehicles will become commonplace. This may include a bi-directional exchange of highly detailed data vital for the safe operation of the vehicles. The project established the CAV-Readiness Framework (CRF) to support NRAs in engaging better with OEMs and service providers, identifying more explicit responsibilities and liabilities, and including tools to calculate the costs and benefits of providing different levels of support to CAVs. DiREC recommends that NRAs take actions in the short and long term to implement and further develop the capabilities of the CRF.

ENSEMBLE

The European project ENSEMBLE (ENabling SafE Multi-Brand pLatooning for Europe – https://platooningensemble.eu/) was finished in 2022. It aimed to implement and demonstrate interoperable and safe platooning with diverse truck brands. The ENSEMBLE project was limited to platooning only. However, automated platooning is comparable to SAE Level 4, as the system takes full responsibility while in automated mode. Besides, ENSEMBLE was among the few projects that have studied the automation of heavy vehicles specifically.

ENSEMBLE Delivery D4.1 [45] describes and discusses results from studies on the impact of platooning on pavements, bridges, and tunnels. Platooning can lead to increased fatigue damage on the pavement, especially at high temperatures. An increased wandering of the trucks can reduce the issue. Other possible solutions are increased distance in the platoon, reduced load, or avoiding high temperatures. The experiments indicated platooning at low temperatures did not affect the pavement structure.

Bridges can be critical points for platooning, with heavier loads from multiple trucks combined. A dissolving or higher gap in the platoon may be needed on some bridges. Finally, platooning in tunnels may lead to higher traffic flow and more efficient use of the tunnel, but it can also become a bottleneck that decreases safety overall. As communication with the platoon inside the tunnel is essential, there may be a need for investments in sensors and communication technology.

ENSEMBLE D6.9 [46] contains recommendations and a roadmap for implementing platooning. One potential advantage of platooning is that it allows road authorities to regulate the parameters by which trucks operate on their roads, such as maximum speed, the number of trucks in one platoon, specific lateral positions, or giving trucks priority access to reserved lanes or toll gates. Road authorities and operators must invest in sensor and communication technology to make these advancements possible.

Hi-Drive

The European project Hi-Drive (https://www.hi-drive.eu/) ran from July 2021 to July 2025. The project aimed to extend the ODD of connected and automated vehicles to avoid frequent demands of a human driver taking control of the vehicle. With a more continuous ODD, automation can operate more continuously. Hi-Drive will develop and test new technical solutions (enablers) that may enable AVs to drive in previously unmanaged situations and make AD performance more robust and reliable. The technical solutions are grouped into four main groups: Vehicle Communications, High-Precision Positioning Technologies, Cybersecurity, and Machine Learning Techniques. Figure I-, from [47], illustrates the ODD discontinuity challenges and how they may be solved with different technological enablers.

Extending the ODD of automated vehicles is crucial for succeeding with the MODI demonstrations. The enabling technologies described and tested in Hi-Drive may also be potential solutions for the MODI Use Cases. Besides, the Hi-Drive Use-cases include relevant scenarios such as urban streets, motorways, the transition from motorways to urban areas, and border crossing [48]. Also, the Hi-Drive test-vehicle fleet includes one heavy vehicle [49].

As the project is in the early stages, the most relevant findings are not yet available through deliverables. However, Hi-Drive Deliverable D4.1 [47] defines the research questions for the project and shows that one research area is particularly relevant for MODI: "What is the effect of enablers on the ability of AD?". This area includes these medium-level research questions:

- To which environmental conditions do the enablers extend the ODD?
- To which road infrastructure elements do the enablers extend the ODD?
- To what extent do enablers enhance AD robustness in challenging environmental conditions?

- To what extent do enablers enhance AD robustness in challenging road infrastructure conditions?

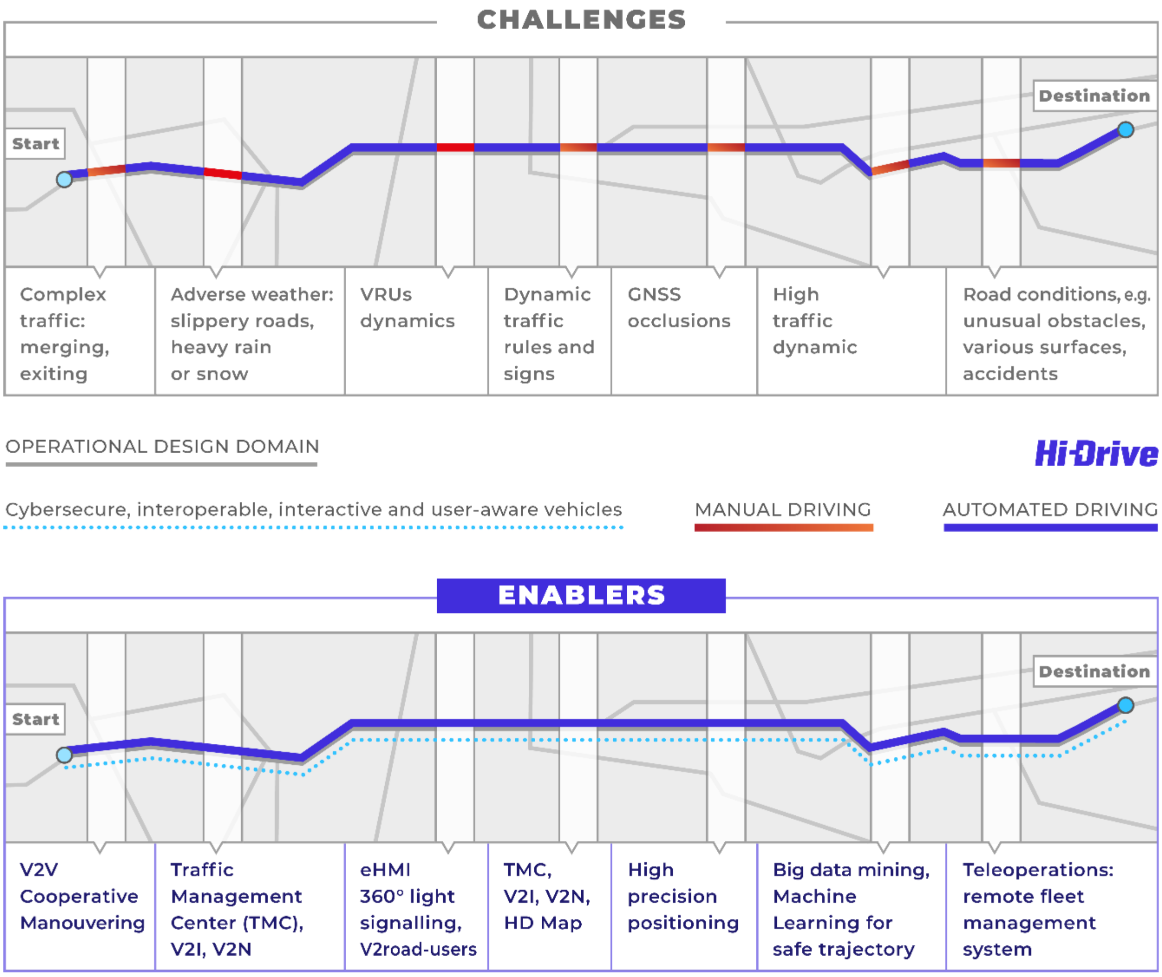

Figure I-2: Illustration of the scope of Hi-Drive. From [47].

Hi-Drive Deliverable D8.4 [50] identifies relevant standards for Hi-Drive. Standardisation and use of standards are also areas of interest for several tasks in MODI, for example, tasks 1.4 and 4.2. Both Hi-Drive and MODI acknowledge that Connected and Automated Driving is an essential challenge in standardisation. The technologies are new and emerging, and there are already many existing standards.

One of the challenges pointed out is the ability of stakeholders to share, compare, and re-use ODD attributes and definitions in a standardised structure and format. An ODD taxonomy for Hi-Drive was developed based on BSI PAS 1883 and other ODD-related technical reports [48]. The taxonomy is shown in Figure I-. Furthermore, a summary of challenging ODD conditions for the four Hi-Drive use case groups is listed in Table 3.8 of Hi-Drive Deliverable D3.1 [48]. Finally, a template for describing the ODD specification of the tested vehicles was developed and documented in Abstract 2 of Hi-Drive Deliverable D3.1 [48].

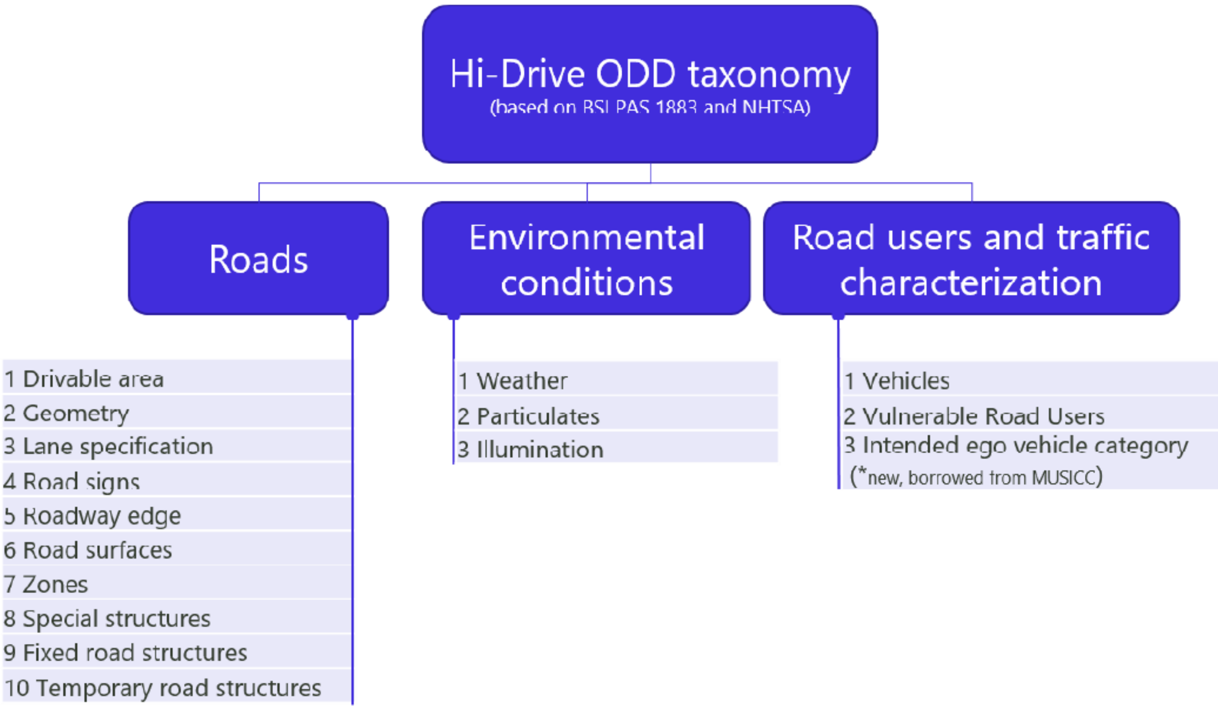

Figure I-3: The Hi-Drive ODD Taxonomy. From [48].

INFRAMIX

The European project INFRAMIX (Road INFRAstructure ready for MIXed vehicle traffic flows – https://www.inframix.eu/) was finished in 2020. The project's main scope was to prepare for a transition period where conventional and automated vehicles will coexist. Within this scope, the project studied the design, upgrade, and testing of the physical and digital road infrastructure for selected highway sections in Austria, Germany, and Spain. Besides the physical and digital infrastructure, the project referred to a 'hybrid' infrastructure as a project outcome after defining the necessary upgrades and adaptations of the current road infrastructure and designing and testing novel physical and digital elements. The hybrid infrastructure shall be able to handle the transition period and become the basis for future automated transport systems [51].

Three specific traffic scenarios were identified for the studies: Dynamic Lane assignment for automated vehicles, navigation through roadworks zones, and bottlenecks (on-ramps, off-ramps, lane drops, tunnels, sags). Use cases and requirements related to the scenarios were studied [52], and technologies and solutions for approaching the three scenarios were described. The studies in INFRAMIX included technologies for improving and preparing the physical and digital infrastructure. The suggested technologies included sensors, new visual and electronic signs, and RSUs [53, 54].

An essential outcome of the INFRAMIX project was the classification schema with five classes (A-E) of Infrastructure Support for Automated Driving (ISAD). The ISAD classification may lay a foundation for a standardised classification, which has later been studied and further discussed in other projects. The classification is not directly related to the SAE levels of automation. Still, it is the basis for identifying roads where vehicles may drive at levels of automation according to their defined ODD and expect help from the infrastructure to keep the ODD stable. Figure I- from [55] illustrates the ISAD classes and requirements for the digital infrastructure at a high level.

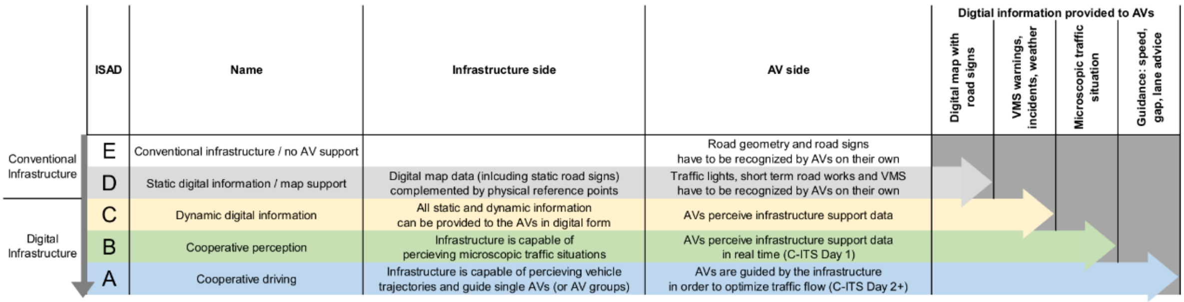

Figure I-4: The ISAD classification. From [55].

L3Pilot

The European project L3Pilot (https://l3pilot.eu/) was finished in 2021. The project's objective was to test and study the viability of automated driving as a safe and efficient means of transportation and explore new service concepts to provide inclusive mobility. Large-scale pilots of automated driving with developed SAE Level 3 and Level 4 functions in 70 passenger cars were performed. 750 test persons drove more than 400,000 km on motorways and more than 24,000 km in urban areas.

The focus of the L3Pilot project was on technical and traffic evaluation of the vehicles, user acceptance, impact assessment and socio-economic impact. The physical and technical infrastructure was not evaluated in the project. Nevertheless, the project has been referenced in various other projects as a crucial testing ground for automated vehicles.

The L3Pilot deliverable D1,7 [56] summarises the project results. Although the project focused little on the PDI, some relevant findings concerning data collection from vehicle sensors were described. First, it was observed that the collected raw data is interpreted differently for each OEM and sometimes even between platforms within one brand. This is a challenge for sharing and combining collected information from vehicles in the digital infrastructure.

Besides, the project results showed that the system performance and reliability of in-vehicle safety applications significantly declined or even failed under dire environmental conditions. This observation highlights the need for support from the digital infrastructure.

LambdaRoad

The Norwegian national research project LambdaRoad ran from 2019 to 2021 and focused on modern ITS technology's dependence on telecommunication infrastructure. It was identified in the predecessor project NordicWay that vehicle manufacturers and infotainment systems producers rely on mobile connections for their data needs. ITS G5 can also supply ITS G5-enabled vehicles with data, given that the receiving and transmitting vehicles or infrastructure can reach each other. The LambdaRoad project developed a computational model to calculate the coverage of mobile networks (approx. 900 MHz) and ITS G5 (approx. 5.9 GHz). As part of the project, measurements of mobile connectivity along the national roads E8 and E8 from the Finish border near Kilpisjärvi and down to the border with Sweden at Svinesund were measured, 1748 km. In addition, several measurements were made between Trondheim and Hitra and on the island of Hitra. This stretch is a microcosm of what one would expect along the Norwegian road network. A smaller segment was chosen due to national security – the location data of many mobile base stations are classified as national security data in Norway. This challenges road authorities when trying to understand connectivity on and along the road network. The data collected was used to create a coverage model that was independent of the coverage calculated by the telecommunication operators. The model also has an adjustable level of detail; hence, highly detailed terrain models could be used as input.

The project proved that it was possible to build a coverage model that is more detailed than existing models and that it could be optimised to calculate coverage along routes in a road network. However, the challenge is getting hold of data on base stations because these are classified as essential information from a national security perspective. A key takeaway from road authorities is that data they need to understand coverage along the road network is unavailable without agreements between authorities, and staff needs relevant security classification. On a positive note, the project has led to more and deeper cooperation between the Norwegian road and communication authorities.

Measurements also show that there are stretches of the main road network without communication, which can make sending and receiving data from vehicles challenging.

MANTRA

The European project MANTRA (Making full use of Automation for National Transport and Road Authorities - https://www.mantra-research.eu/) was finished in 2020. Deliverable D4.2 [57] focuses on the expected consequences of automation functions on the infrastructure. The deliverable presents recommendations for road authorities on what impact automated driving is expected to have on the physical and digital infrastructure and what changes will be necessary.

MANTRA Deliverable D4.2 [57] states that providing ODD information that will extend the coverage of where vehicles may operate in automated mode is a pressing issue that needs to be solved. This information is almost solely under the responsibility of road operators. It is also pointed out that the ODD will differ for each vehicle system, depending on sensors and software.

Neither a highly developed digital nor a physical infrastructure is sufficient alone for safe road transport, whether humans or machines operate the vehicles. Still, the impacts of automated transport on the infrastructure are undeniable. The digital infrastructure will require the most significant changes, and many changes will come from digitalisation processes. The physical road infrastructure is more or less in place already, and the support it provides to human-operated vehicles is expected to suffice for highly automated vehicles as well.

Among the expected consequences that will need to be handled for the physical infrastructure are the wear and tear of the pavement due to heavy loads and equal driving paths for freight vehicles in platoons. Furthermore, the design parameters of ramps and junctions will probably need to change, as dimensions and visibility are considered problematic. Road markings and road signs are pointed out as critical for machine readability, with a need for higher standards in terms of visibility and reflectivity, as well as an international standardisation of the design and digital representation. Signs and markings must be represented both in the physical and digital infrastructure. Finally, there will be a need for landmarks with accurately known positions to support vehicle positioning.

For the digital infrastructure, it is pointed out that road operators will need to provide data for HD Maps to map and service providers directly or via national access points. These data must include digital rules and regulations, real-time traffic management information, and geofencing information. Primarily, it is considered crucial that traffic rules and regulations become machine-readable in standardised structures to ensure correct interpretation by highly automated vehicles.

The deliverable concludes with tables listing ODD attributes of the physical and digital infrastructure for introducing highly automated vehicles.

SHOW

The European project SHOW (Shared Automation Operating Models for Worldwide Adoption – https://show-project.eu/) ran from January 2020 to January 2024. SHOW aimed to support deploying shared, connected, and electrified automation in urban transport to advance sustainable urban mobility. During the project, real-life urban demonstrations took place in 20 cities across Europe with the integration of fleets of automated vehicles in public transport, demand-responsive transport (DRT), Mobility a Service (MaaS), and Logistics as a Service (LaaS) schemes.

Deliverable D8.1 [58] discusses findings concerning the physical road infrastructure and how it should be assessed and improved for automated driving – based on a literature review and stakeholder interviews. A very consistent finding is that all development of automated vehicles focuses on the existing infrastructure and does not depend on improvements on these issues. Still, the analysis found that a number of measures and adaptions are necessary to prepare the infrastructure for automated vehicles. Essential issues in the physical infrastructure include sight distances and the visibility and detectability of lane markings and signs. One main result of the deliverable is checklists for the physical infrastructure to assess the readiness for automated transport.

The deliverable also discusses the requirements and ecosystem for digital dynamic maps (HD maps), which are defined to consist of static map layers with static information (road, lane, landmarks, POIs) and traffic rules; a quality layer describing the quality parameters of the road (surface material and quality, lane marking quality, etc.); and a dynamic real-time layer. Road authorities are pointed out as one potential source for the static layer. The maps are considered crucial for route planning and navigation; perception beyond sensor range; and localisation and positioning.

Teapot

The Norwegian TEAPOT project (Technology for advanced positioning within the transport system) ran from 2020 to 2023. It aimed to secure positioning for the future transport system under Nordic conditions, handling challenges such as climate, topography, weather, and space weather. The project can be summarised with three main goals:

1. Clarify the transport sector's needs for positioning technology, with particular attention to Nordic conditions.

2. Develop an approach to how different technologies and methods for positioning can be combined using sensor fusion.
3. Describe how to organise cross-sectoral collaboration between the road authority and the positioning community and how to regulate without hampering the Norwegian private sector.

WP1 in TEAPOT studies demands for positioning in the transport sector. The purpose of the positioning services in this project is to locate vehicles at speed through local and global positioning using different technologies. This work package maps out the requirements and needs for positioning services identified through literature studies and interviews with actors participating in the project.

The report [59] summarises the main findings from TEAPOT WP1 and WP2. The report thoroughly describes positioning technologies and how they are used by different stakeholders in the transport sector. The most relevant finding for MODI is the discussion on positioning requirements for different purposes and applications. Such requirements lay the basis for the required positioning services in the digital road infrastructure.

The findings show that the required positioning accuracy for automated vehicles depends on the purpose and application of the position. Different tasks require different accuracy. Also, scholars and professionals disagree on the required accuracy. A report from the European GNSS Agency suggests a required horizontal accuracy to be mostly at a level between 1 and 10 meters, while some tasks will require better accuracy. A report from the European Commission suggested a required positional accuracy of 10 cm for the discovery of vulnerable road users, while others have claimed that an accuracy better than 5 cm will be needed for some operations.

The accurate positioning of moving vehicles represents a new topic for positioning technologies. It will be crucial to standardise positioning services internationally so vehicles can cross borders and use national positioning services seamlessly. Road and mapping authorities have different focuses and competencies and must cooperate to ensure appropriate positioning services are available in the physical road infrastructure. The scalability of positioning services is an essential challenge as the number of users will be very high with large fleets of automated vehicles. Also, automated vehicles are foreseen to be potential victims of malicious equipment and attacks such as jamming and spoofing.

TM4CAD

The European project TM4CAD (https://tm4cad.project.cedr.eu/) ran from September 2021 to March 2023. The project focused on the provision of real-time information about ODD-relevant conditions and the role of the national road authorities and operators. Identifying ODD attributes where automated vehicles need support from the infrastructure is essential for developing an optimal PDI.

The project identified a range of ODD attributes and introduced a framework for Distributed ODD Awareness – DOA, where different sources collect and provide information about ODD attribute values [60, 61]. DOA acknowledges the need to monitor the values of each ODD attribute and the responsibilities for doing so. Automated driving systems must be aware of the current operating conditions and compare them with their ODD constraints to determine whether they may drive in automated mode, reduce speed, switch to an alternative route, or pull over to the shoulder and stop. Onboard sensors may only collect information in the immediate area around the vehicle. Besides, sensors cannot collect information such as load-bearing capacities and routing advice. Therefore, the DOA framework must include off-board sensing for information collection and infrastructure for information provision. The project analysed a range of ODD attributes and whether they can be based on vehicle sensors or need support from the infrastructure.

The information exchange for DOA requires investments in the infrastructure. The project highlighted the need for a close dialogue between road authorities, traffic managers, automated system developers and automated vehicle fleet operators. Furthermore, DOA needs to be two-way, where automated driving systems also provide information to the infrastructure for sharing with operators and other vehicles. Although the road authorities will be responsible for providing the relevant ODD information, they must also evaluate what kind of information they shall provide and what information can be provided by commercial services. Also, the criticality of the refresh rate for each attribute is essential. For this purpose, the project defined a categorisation of information change frequency from rarely changing attributes to attributes that may change every few seconds.

The project studied the information needs related to the listed ODD attributes from the perspectives of traffic managers, road operators, and automated driving systems. Following the study of information needs, the attributes were prioritised from the perspectives of the three stakeholders. The information needs and prioritisation of attributes are listed in tables in deliverable D3.1 [61]. Furthermore, a data quality framework for DOA was suggested, along with quality criteria and recommendations.

Harmonisation of the language for defining ODD attributes and the exchange format for sharing them is essential. Deliverable D3.1 [61] points out two explicit solutions: The ODD taxonomy in the standard ISO 34503 and the DATEX II format with extensions for data exchange.

The project also started studies on realistically implementable requirements that traffic managers and road operators can put on automated driving systems. As part of the studies, the project strived to develop a “codified highway code” for communicating rules digitally [62].

TRANSAID

The European project TRANSAID (Transition Areas for Infrastructure-Assisted Driving – https://www.transaid.eu/) was finished in 2020. The project’s scope was traffic management procedures and protocols to enable a smooth coexistence of automated, connected, and conventional vehicles, especially in so-called Transition Areas (TA). Transition Areas are where transitions between automation levels are likely to occur very often, such as near construction sites and complex intersections. One primary purpose of TransAID was to minimise the number of Transitions of Control (ToC) through traffic management and communication between the vehicles and the infrastructure.

Continuity of automation through complex areas means, in practice, removing ODD discontinuity in such areas. TransAID deliverable D8.3 [63] suggests actions for the physical and digital infrastructure, traffic management, and stakeholder collaboration. The recommended actions are based on a longer list of recommendations from the MANTRA project. The stakeholders considered are OEMs, road authorities, road operators, service providers and standardisation bodies.

Three topics from MANTRA are highlighted for the physical infrastructure: the planning and design of emergency bays, broad shoulders, and safe harbours in case of Minimum-Risk Maneuvers; the redesign of ramps and junctions; and the further development of the ISAD road categorisation.

The digital infrastructure is described as the critical component of the TransAID project and includes sensors, traffic lights and VMSs. More than 60% of participants in the TransAID final event considered that the digital infrastructure support at TAs was "Essential". TransAID points at 11 topics for improved digital infrastructure, where five are particularly relevant for MODI: Roadside stations for short-range V2I; Use of digital twins for the road transport system; Digitalise traffic rules and regulations; Standard communication protocols; and Sharing and storage of data.

One primary task is to enable communication around TAs for communication between vehicles and other equipment (V2X). Besides, all information, including traffic laws and regulations, must be digital, and more information must be shared between OEMs, road authorities, and road operators. Standards, including protocols, content structure, and format, are needed to share information.

I.2.2 Findings from ongoing projects

ACUMEN

The European ACUMEN project, Ai-aided deCision tool for seamless mUltiModal nEtwork and traffic management (https://acumen-project.eu/) runs for three years from June 2023. The project focuses on managing multimodal transport services by establishing a technological and methodological framework that integrates mobility modelling, data processing, prediction, and visualisation capabilities. Four pilot arenas are included: Athens, Helsinki, Amsterdam and Luxembourg. There are no deliverables available to the public yet.

ATLAS-L4

ATLAS-L4, Automated Transport between Logistics centres on highways, Level 4 (https://atlas-l4.com), is a research and development project that combines expertise from industry, scientific research and infrastructure operators to create an integrated approach to the operation of autonomous vehicles on public motorways and highways. The project is funded by the German Federal Ministry for Digital and Transport and runs from January 2022 to September 2024.

The project's aims and scope are very similar to some tasks in the MODI project, mostly concerning vehicle development, driving on public roads and highways, and demonstrations. Therefore, the project will likely be relevant to MODI. However, there are no deliverables available to the public yet. The first demonstrations are planned for the end of 2024.

AUGMENTED CCAM

The European project Augmented CCAM (https://augmentedccam.com/) runs from September 2022 to December 2025. The project aims to understand, harmonise and evaluate support solutions for Physical, Digital and Communication infrastructures to advance its readiness for large-scale deployment of CCAM solutions. Based on the studies, solutions for PDI support will be developed and tested. This will include, for example, the functional safety of the transport infrastructure, traffic safety and efficiency, driving behaviour, environmental footprint, service reliability, and trust and security.

The challenges studied and solutions developed for PDI support in AUGMENTED CCAM will likely be relevant for MODI. However, the project has not yet published any relevant deliverables.

Hypos

The Norwegian Hypos project (https://kartverket.no/en/forskning-og-utvikling-fou/hypos/hypos-project) runs from March 2022 to February 2026. The project studies how positioning technologies based on GNSS and 5G can complement each other in a hybrid positioning service. Positioning with satellites and GNSS performs very well in open areas like country roads, highways, and suburban areas where the line of sight to the satellites is good. Unfortunately, the technology has shortcomings for those who need high accuracy in urban areas with tall buildings. This is where a hybrid positioning service in interaction between GNSS and 5G gets relevant. The upsides for both technologies are utilised to create a better end-user service.

The project has four objectives:

1. Scale up precise positions from GNSS satellites to an infinite number of users.
2. Develop the 5G network to determine real-time positions.
3. Investigate how the technologies can complement each other
4. Create financing models for deploying GNSS corrections and hybrid positioning services.

One published report from the project [64] (only in Norwegian) describes the current state of the art in positioning technologies and identifies user needs for a hybrid positioning service. The user needs were identified through semi-structured interviews with stakeholders from three sectors: aerial transport with helicopters, emergency and rescue services, and automated agriculture. Stakeholders from automated road transport were not included in the analysis. Still, the report discusses the implications of hybrid positioning for automated road transport. Security challenges of GNSS-based positioning, such as jamming and spoofing, are highlighted. A hybrid positioning service can enhance the robustness and resilience of the system. The report also considers price a critical factor for adopting hybrid positioning services in automated road transport with many users.

IN2CCAM

The European project IN2CCAM (https://in2ccam.eu/) runs from 2022 to 2025 and aims to develop, implement and demonstrate innovative services for connected and automated vehicles, infrastructures and users. A set of physical, digital and operational solutions will be proposed and implemented in Living Labs in Finland, Greece, Italy, Spain and Portugal. The project has not yet released any relevant deliverables.

Jammertest

Jammertest was a sibling project to LambdaRoad, focusing on GNSS (Global Satellite Navigation Systems) and vulnerabilities. GNSS can establish one's location and is a tool for synchronising precise time. The satellite signal can be tampered with and jammed, where a competing signal blocks out the original signal. Spoofing is scarier; fake signals will make GNSS receivers give false information. And if automated systems depend on GNSS, this could have disastrous implications.

In Norway, we also have empirical evidence that jammers or personal protection devices are in use by road users. Also, the airspace in Norway's most northern region is plagued with GPS jamming from east of Norway's border with Russia.

Fallback mechanisms for short-term GNSS fallout exist, but the challenge is detecting when one should switch from GNSS to the fallback. Testing in laboratories is quite useful but does not replicate the real world. And jamming and spoofing in the real world is strictly forbidden. Four government agencies teamed up and created a testbed for GNSS jamming and spoofing to enable the industry to test their solutions.

Jammertest started with 25 participants from Norway in 2021; in 2022, this grew to 105 participants with international participation. Participants ranged from GNSS chip developers, industries integrating GNSS into their products, academia, and authorities. Jammertest 2022 showed that this way of working, where authorities provide a testbed for industry, academia, and authorities to test and learn about system responses when affected by jamming or spoofing, was much needed [65].

Jammertest has now gone from a pilot to an annual event. Jammertest 2023 had nearly 200 participants from over 60 companies and 17 countries. The tests in 2021 and 2022 gave companies quite a few surprises and hence showed a need to test equipment concerning GNSS disturbance. Automated vehicles and ITS G5 solutions are susceptible to GNSS interference, so these should be tested. Technologies used in the MODI project also should consider GNSS jamming and spoofing.

MCSINC

The Norwegian project MCSINC (Machine Sensible Infrastructure under Nordic Conditions https://www.sintef.no/prosjekter/2022/mcsinc-machine-sensible-infrastructure-under-nordic-conditions/) runs from 2022 to 2025 and aims to study the functionality of automated driving systems in harsh winter conditions. The project focuses on how these systems sense, reason, and act, including mapping the environment and localising the vehicle, perceiving dynamic objects, predicting their movements, planning routes, and navigating the CAV (including throttle, brake, steering, and shifting).

It is essential to gain more scientific knowledge on the limitations of these technologies brought about by Nordic conditions. This knowledge can help road authorities and decision-makers understand the limitations of CAVs under these conditions and adjust road designs and maintenance to increase the vehicle's and infrastructure's sensibility. The limitations of these systems may set requirements for road design and winter maintenance that the vehicle manufacturers cannot address alone.

Proprietary solutions characterise the vehicle industry, and insights into the limitations of CAV systems are not openly available information. Thus, there is a strong need for more open scientific studies that publish AI software and results on CAV technology, information unavailable from the vehicle industry today.

The project will process the data using an automated driving platform, an electric KIA with lidar, radar, and GNSS capabilities, and an NVIDIA DRIVE AGX Xavier vehicle system. It aims to use existing processes in the Norwegian Public Roads Administration, such as snow poles, for local navigation when line markings are unavailable. The project has no results yet, but MapTR (https://github.com/hustvl/MapTR) has been studied as a potential mapping technology.

NordicWay

Background

The NordicWay 2 and NordicWay 3 (https://www.nordicway.net/) pilot projects focus on C-ITS in the Nordic countries. These projects facilitate communication between vehicles, infrastructure, and network operators regarding hazards and other safety information from roads between different stakeholders. Public and private partners from Finland, Norway, Sweden, and Denmark collaborate in the projects, building on the achievements from the previous NordicWay project, which demonstrated and highlighted future services and challenges connected to vehicles with higher automation levels (SAE levels).

NordicWay 2 have built a data-sharing platform (Interchange) that serves connected vehicles with data relevant to more automated driving, with results described in the report from the Norwegian pilot [66]. NordicWay 3 – Urban Connection involves more cities than NordicWay 2.

The AUTMOTO project (ref chapter 0) in Finland was part of NordicWay 3. The project mapped and assessed the readiness of infrastructure for connected and automated driving on major freight routes in Finland [36]. The first research task of the project was to assess the feasibility of the selected motorway section (Highway E12 between Helsinki and Tampere) for the operation of SAE Level 3 and 4 automated vehicles (AVs). This assessment was implemented by identifying the likely critical attributes of physical and digital infrastructures through expert work and then by assessing or measuring the current state using various methodologies and field measurements.

Physical infrastructure

Regarding the physical features of the selected motorway section, implemented design requirements are likely to be sufficient for SAE level 3 and 4 vehicle automation. Providing sufficient space for Minimal Risk Manoeuvres (MRM) is essential (not least because of occasional poor weather conditions). On the right shoulder, a continuous width of 3 m or more is sufficient space for automated trucks and passenger vehicles. Currently, the hard shoulder on the left side is not wide enough to allow safe MRMs, and therefore, MRMs to the left shoulder are not recommended in the Finnish motorway environment with two lanes in both directions.

Rather than the design parameters of motorways, the critical attributes regarding physical support for automated driving concentrate on the condition of the infrastructure. In principle, pavement conditions should be at a reasonable level, and the maintenance of ruts or potholes should be of a high standard.

Regarding the feasibility of lane markings to support automated driving, field measurements prove that the lane-keeping system (MobilEye) currently on the market reliably recognises lane markings even during early spring conditions, when the markings are typically covered with salt and dirt. However, due to winter conditions and snowfall, there will be recurrent periods when lane markings are entirely covered with snow; therefore, AV operations cannot depend on this feature alone.

Analysis of the test section’s current infrastructure and traffic-related properties divided the 160 km motorway into 70 physically homogenous roadway sections per direction. This means that, on average, at least one road attribute changes every 2.3 km. This highlights the need for robust automated vehicle systems that aren't dependent on static road properties for standard motorways and can operate in variable traffic conditions.

Communication

Service speed rates and latencies of the current communications networks (4G and 5G) were measured along E12 from all three telecom operators (DNA, Telia, Elisa). The test results show that the speed rates vary from below 1 Mbit/s to above 500 Mbit/s. It should be noted that existing 3G networks were not included in the test, and 3G networks would likely provide some additional capacity in shadow areas now identified in the test section. Mobile data service is expected to improve in the short term as mobile network operators migrate their 3G service to 4G/5G technologies by the end of 2023. Hence, if the test is repeated at the end of 2023, it is likely that there will be more continuous capacity of at least 5 Mbit/s in both directions (uplink/downlink), which is considered sufficient capacity for the primary use cases of automated driving. It should be noted that upload performance will be equally crucial for more demanding use cases.

Regarding communication networks, it is crucial to differentiate the capacity that a single vehicle requires from the capacity of a mobile network cell. The capacity of one cell is divided between all the users connected to the cell; therefore, in cases where several users require high capacity, fast data transfers might not be available. In other words, heavy traffic along the roadway decreases the overall capacity available per vehicle. In practice, a 5Mbit/s upload speed is difficult for 4G networks, particularly if many users are within the same mobile cell service area.

Positioning

The service quality of the current positioning services is high for the entire motorway test section regarding the needs of automated vehicles. GNSS-based positioning accuracy is on a centimetre level for 83% of the section and at least a decimetre level for 96% of the section when the vehicle is using all satellite constellations (in this test, Galileo, GPS, and Glonass) as well as correction services. Positioning accuracy decreases when using any individual constellation; therefore, a combination of constellations is recommended. Optimised positioning accuracy requires good signal strength (Signal-to-Noise Ratio 40 dB or above). The test proved that there are only a few locations where the signal strength drops below this threshold value, which are explained by physical shadows or hindrances such as hill cuts, overpasses, or tunnels. In cases where the signal strength falls longer, positioning can be managed by other technologies. Different positioning correction services may use different coordinate frames, so the need for coordinate transformations must be addressed and facilitated.

PoDIUM

The European project PoDIUM (PDI connectivity and cooperation enablers building trust and sustainability for CCAM – https://podium-project.eu/) runs from October 2022 to September 2025. The project's scope addresses road automation and telecommunications challenges, especially those linked with connectivity, cooperation, data management, interoperability, reliability, trust and data truthfulness, which are required for higher levels of vehicle automation and advanced CCAM services. The project aims to accelerate the acceleration of essential technologies in the physical and digital infrastructure to reach higher levels of automation. The project's outcome will be a reference architecture that can be applied to various road environments and types of infrastructure equipment.

The identified challenges in PoDIUM, the suggested enablers, and the reference architecture will likely be relevant for MODI. However, the project has not yet published any relevant deliverables.

ULTIMO

The European project ULTIMO (https://ultimo-he.eu/) runs from October 2022 to October 2026. The project focuses on on-demand and door-to-door public services in cities. The aim is to target the operation without safety-driver on board, in fully automated mode and with the support of innovative user-centric passenger services.

Two of the objectives of the ULTIMO projects are relevant for MODI: validating integrated shared CCAM systems and services for people and goods across Europe and setting the basis for a standard and reusable model for High-Definition (HD) maps. ULTIMO Task 3.4 – Towards standard open HD Map - is particularly relevant for MODI. The task aims to specify a standard and open model for HD Maps. The work will be done by comparing existing standards and proprietary models and establishing minimum requirements. However, the project has not yet published any relevant deliverables.

I.2.3 Other relevant activities and reports

C-Roads

The C-Roads Platform (https://www.c-roads.eu) is a joint initiative of European Member States and road operators for testing and implementing C-ITS services in light of cross-border harmonisation and interoperability. The C-Roads platform was established in 2016, and the current project phase is funded until the end of 2023.

Being a part of Intelligent Transport Systems, cooperative ITS (C-ITS or cooperative systems) encompass a group of technologies and applications that allow effective data exchange through wireless communication technologies between components and actors of the transport system, very often between vehicles (vehicle-to-vehicle or V2V) or between vehicles and infrastructure (vehicle-to-infrastructure or V2I). Harmonised C-ITS specifications are indispensable to enable an efficient and undisturbed exchange of information within these services as well as a cross-border implementation. The approach starts from a functional perspective, then requirements applicable to all implementations and then towards technology specifications of currently validated implementations (ITS-G5 for short-range communication, IP-based for long-range cellular). To meet these challenges, the C-ROADS platform has installed five dedicated Working Groups. The first working group is concerned with organisational tasks, the second is technical aspects, and the third is evaluation and assessment. The fourth Working Group is about Urban C-ITS Harmonisation, and Working Group 5 is about Digital Transport Infrastructure (DTI).

The activities and documentation from C-Roads Working Group 2 are seen as most relevant for the scope of MODI T4.2 for topics regarding C-ITS. At the same time, the findings from Working Group 3 could be used in the evaluation tasks in Work Package 2 in the MODI project. However, it is essential to note that the C-Roads project does not explicitly handle the challenges of freight transport.

The C-Roads Working Group 2 covers a wide range of aspects related to several stages of a C-ITS project, including service and use case definitions, system specifications, ITS-G5 and IP-based C-ITS profiles, and (cross-border) test plans and validation concepts.

Figure I- shows the storyboard of a C-ITS implementation project in more detail and which C-Roads Working Group 2 documents are related to each stage. All documents in blue can be accessed over the C-Roads Platform, whereas the grey parts of the storyboard indicate that no specific C-Roads documentation is available yet for this specific part.

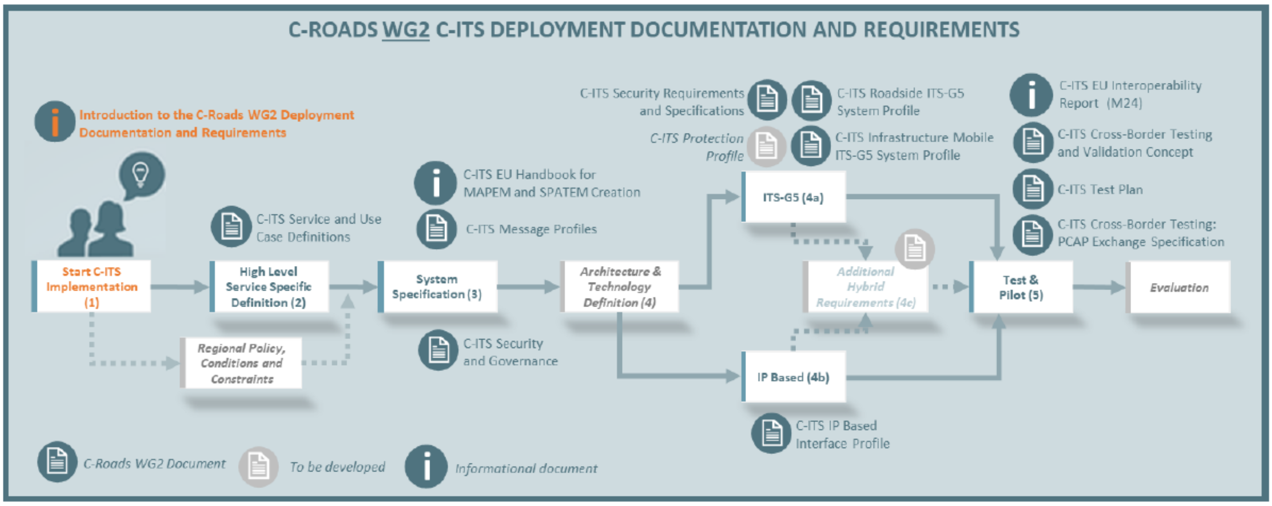

Figure I-5: Story Board and C-Roads documentation

CSA Reports on CAVs in Canada

The Canadian Standard Association (CSA) published a report in 2020 [68] concerning standards and technologies needed for the introduction of automated vehicles in Canada and followed up with a second report in 2021 [68] concerning the physical and digital infrastructure and its gaps in readiness for automated driving. Some parts of the studies included roads in the US as well. The first report [67] includes a thorough analysis of the current state of standardisation and technologies, internationally and regionally, in Europe and Canada/US.

Gaps are identified in eight categories:

- Harmonisation and Interoperability: Automated vehicles will need consistency and continuity of the physical and digital infrastructure across countries and regions. Standardisation of the physical and digital infrastructure is required now.
- Uncertainty with Enabling Communication Technologies: Harmonisation is needed concerning the spectrum allocation for communication services. Also, coverage in rural and remote areas was identified as a gap.
- Compliance Verification: There must be standards for verifying compliance concerning safety, security, and interoperability requirements.
- Physical Infrastructure: Focusing on the need for consistency and continuity.
- Operational Design Domain: The need to classify the roads' AV readiness with standardised and measurable definitions of ODD attributes.

- High-Definition Mapping and Localisation: The vulnerability of GNSS and the availability and lack of standardisation for HD Maps.
- Cybersecurity and Protection of Privacy: The needs for a security framework.
- Technology Maturity: The limitations of technology concerning challenging environments.

The second report [68] aims to establish a North American framework for the PDI. The report describes physical and digital infrastructure gaps and concerns cybersecurity as an additional topic. CAVs need good physical infrastructure and rely on sensing and interpreting road signs and markings. The quality and condition of these elements affect AVs' ability to navigate the environment, just like humans struggle to drive in certain conditions. The lack of standards to ensure continuity of the physical infrastructure is pointed out, as well as the need for higher maintenance standards for markings and signs. Besides, crosswalks are identified as particular and challenging objects, where the markings may be mistaken and understood as other kinds of markings. Bridges must be evaluated in terms of their ability to handle platoons. Concerning other changes in the physical infrastructure, it is noted that care "should be taken not to tailor standards too closely to current sensing technologies to the extent possible, so as not to inadvertently constrain the development of new and improved sensing and communications technologies."

An interoperable digital infrastructure that adheres to standardised protocols is considered imperative for CAVs. HD Maps are essential for safe operations and must include dynamic updates on work zones, weather events, etc. Also, enhancing GPS positions is essential and needs standardisation of signals and messages. Intersections and tunnels are also identified as cases where extra roadside equipment and communication are needed to guide CAVs.

EU-EIP Activity 4.2

The European ITS Platform (EU-EIP – https://www.its-platform.eu/) was active from 2016 to 2021 as a collaborative place for Road Authorities, Road Operators, National Ministries, and partners from the private sector. The goal was to facilitate a harmonised implementation of present and future ITS deployments on the main road network throughout Europe. The platform focused on five activities with individual sub-activities. CEDR published a project report [69] with findings from all activities, while more specific reports from individual activities and sub-activities present more details.

The objective of sub-activity 4.2 was to prepare road authorities and operators to make decisions on facilitating automated driving and the automation of their core business operations. Sub-activity 4.2 was divided into five tasks, with the first focusing on identifying requirements for road markings, traffic signs, real-time and predictive traffic information, digital maps, and cooperative ITS infrastructure for automated driving. The report [70] from Task 1 in EU-EIP Activity 4.2 describes requirements towards road operators for the physical and digital infrastructure. Moreover, the CEDR project report describes requirements and recommendations for implementing C-ITS and Real-time traffic information (RTTI) services on national access points (NAP).

An essential conclusion from the EU-EIP Activity 4.2 report [70] is that consistency is vital for automated driving – within and between networks. Therefore, establishing and adhering to physical and digital infrastructure standards is essential to preparing for a future of automated mobility. Road operators need to take a leading role in the development of standards as well as in the development of infrastructures.

For the physical infrastructure, the EU-EIP report notes that urban roads with higher complexity are more demanding for automated vehicles than rural roads. Like in other reports, it is expected that automated vehicles will need to handle the existing physical infrastructure. However, infrastructure maintenance will be more critical for automated vehicles. Road operators may need to upgrade their procedures and quality control to a higher level to ensure the visibility of markings and landmarks and the quality of the paving. Also, the paved shoulder width will be essential for minimum-risk manoeuvres.

The report defines digital twins (HD Maps), connectivity, and accurate positioning as the three critical elements of digital infrastructure. Road network operators must invest in and lead in its development to ensure public expectations and objectives are met. High-quality digital infrastructure will be the core for the development and reliability of automated driving systems. An agreed-upon method for defining ODDs for traffic regulation and operation is needed. Also, digital traffic regulations and restrictions must be available in real time through a known interface.

The infrastructure for C-ITS services for V2V and V2I communication will be vital for improved safety and efficiency, although full coverage with RSUs for V2I communication is not economically viable. As part of the EU-EIP work, a reference handbook for a harmonised implementation of core ITS services was developed.

Road operators must share quality-ensured and updated static and real-time information for HD Maps for navigation and positioning. HD Maps and landmarks that are accurately positioned and visible in real life will be vital for accurately positioning vehicles. Real-time information must be provided through a single access point, independent of the vehicle manufacturer. Information integrity, correctness, and consistency are more important for automated systems than human drivers.

HERE Report: The future of driverless road freight

HERE Technologies have published a report on Highly Automated Driving (HAD): The future of driverless road freight [71], where they describe how automated freight operations on highways, especially hub-to-hub operations, are expected to develop at a faster pace than passenger cars and taxis operating in an urban environment. Highways are more controlled environments with restricted access and less complex situations. While human drivers can control the first, final, and more complex route stages, vehicles can operate highly automated on highways. As HERE is a commercial map provider, it is no surprise that they emphasise the role of map data for automated driving for complementary information undetectable by in-vehicle sensors. A feedback loop from in-vehicle sensors ensures continuously updated map data. Besides, the report suggests the need for an ecosystem where different parties cooperate to maintain map data across car and truck manufacturers. Some data will be proprietary for certain parties, while others should be shared among all stakeholders. This includes authorities, map providers and vehicle manufacturers.

ITF Working Group on Preparing Transport Infrastructure for Autonomous Mobility

The International Transport Forum (ITF – https://www.itf-oecd.org/), administratively integrated with the Organisation for Economic Co-operation and Development (OECD), has published the report “Preparing Infrastructure for Automated Vehicles [72]. The report is based on input from the ITF

Working Group, "Preparing Transport Infrastructure for Autonomous Mobility", with experts from a wide range of countries: Australia, Austria, Belgium, Canada, Finland, France, Germany, Japan, New Zealand, Norway, Poland, Singapore, Spain, Sweden, Switzerland, the United Kingdom, and the United States. Besides, the report reflects questionnaires circulated to government officials in the countries represented in the Working Group, interviews with industry representatives, and contributions by US Department of Transportation members.

The ITF discusses what kinds of support are most in demand for the physical infrastructure, data and digital infrastructure, and institutional frameworks. Furthermore, the report focuses on immediate obstacles to the deployment of automated transport and the extent to which governments can address them through specific actions. This approach fits very well for a demonstration project like MODI.

According to the ITF report, there is insufficient information on the criteria that define an ideal road for automated vehicles in terms of physical infrastructure. Also, investments in the physical infrastructure are expensive. From the industry side, the intention is that automated vehicles need to be capable of working on the existing network to expand beyond niche uses. Industry contributors do not view the current network as a hindrance but as a necessary reality. They do not anticipate the need for exclusive zones or specialised roads dedicated solely to automated vehicles. They believe that designating specific areas for AVs would deter their utilisation on the broader road network. Automated vehicles present a new challenge to the existing road infrastructure rather than fundamentally changing its nature. As a result, it is necessary to have a clearer understanding of the requirements before investing in physical upgrades to the road network. The future of transportation will likely rely on a close connection between physical and digital infrastructure. Instead of developing a physical infrastructure with unclear requirements, efforts should prioritise digital advancements.

The report describes the physical infrastructure in four functional layers:

- The physical road (road design, road surface materials, geometric configurations, and facility separation)
- Traffic control infrastructure (traffic signs, signals, pavement markings, message signs, work-zone traffic controls)
- Traffic operation infrastructure (traffic operation centres, signal timing, lane operations, changing speed limits, travel information)
- Maintenance and operations (manage and maintain the infrastructure)

Although technology is advancing, physical markings and signs will remain necessary. The concept of a "naked road" where connectivity eliminates the need for traffic signs does not reflect current developments. Maintaining clear visibility is especially crucial for automated vehicles, as they do not have the same capacity as humans to understand when a marking or sign is missing or unclear. Therefore, maintaining markings and signs is even more critical for automated vehicles, requiring higher maintenance standards. Such standards must consider challenges concerning local conditions, such as winter weather or extreme heat. In addition, there is a need for design and visibility standards. Electronic (variable) signs pose a challenge as they are less readable for automated vehicles. Finally, reliable surface quality is crucial for paving, as defects can be challenging to interpret.

The report points out several challenges that need to be addressed for the digital communication infrastructure:

- Communication networks must be prepared for high data traffic. For example, handling intervention by remote operators instead of human drivers, based on video and sensors, will require much bandwidth.
- C-ITS technology is crucial in densely populated areas, especially at intersections and regions with limited mobile coverage. Fortunately, established standards and organisational systems are already in place for the continued advancement of C-ITS.
- 5G Mobile networks will become increasingly vital for a safe road.

Positioning technologies are one of the most crucial information needs of automated vehicles. The vehicles must rely on more than one technology for positioning; they need to combine complementary approaches. Furthermore, positions need to be more accurate than those given by GNSS. Therefore, positioning services are needed from government or commercial entities. Addressing challenges concerning vulnerability and cybersecurity is considered crucial.

HD Maps are considered essential for most of the involved developers and organisations. Unfortunately, there are many proprietary solutions and a need for more accepted standards. Although standards may not be perfectly fit for all use cases, they should be established before vehicles begin operating on-road in large numbers. The HD Maps must be based on a combination of data from different providers and sources. In particular, authorities need to get far better at sharing and exporting information, as the current data flow is slow and inefficient. The maps must include digital traffic rules and regulations besides static and dynamic road data. Although preferable, it is not likely that HD Maps will cover the whole network due to costs for mapping and maintenance. Furthermore, the HD Maps must be updated and precise, even in real-time. For this, automated driving systems will play a crucial role.

The report highlights the importance of having real-time information and a system for intelligent and efficient digital traffic management. To achieve this, there should be a network of traffic management centres and services, as well as operators of automated vehicle fleets. Prioritising access to these services is crucial while ensuring trust, protection, and recovery measures are in place.

NPRA Reports

C-ITS: Literature review and recommendations for themes and objectives in the Norwegian Public Roads Administration's technology initiative

The Norwegian Road Administration is involved in numerous C-ITS initiatives, including national technology investments and participation in EU projects. SINTEF was commissioned to identify national and international research and development efforts to ensure effective decision-making and avoid duplicating existing research. The effectiveness of CAVs heavily relies on infrastructure for several reasons. One of the most significant concerns is the ability to accurately sense and interpret physical infrastructure components such as road signs or markings. The capability of automated vehicles to identify infrastructure components or contextualise the surrounding environment's meaning as part of the data fusion and evaluation process depends on the quality, visibility, colour, and degradation of infrastructure elements. Just as signs covered by vegetation or snowfall can make driving harder for humans, infrastructure-related challenges can also make the dynamic driving task challenging. The ISO standard ISO 14813-1 [73] defines the reference model for the ITS sector, focusing on service domains, service groups and services. While ISO 14813-1 is expected to remain the same in the next 10-15 years, the underlying technology may significantly evolve. Therefore, the focus should be on functionality (ITS services) rather than technology, with road authorities defining functional and qualitative requirements. At the same time, ITS industry providers deliver the technology to meet those requirements effectively.

The literature study focused on four themes, with the highest emphasis on the first three themes:

1. The most relevant ITS services.
2. European reports and documents.
3. Scientific articles.
4. Articles from the industry.

The most relevant ITS services were categorised into different areas in the Traffic information service area, including real-time transport status information, in-vehicle display, route guidance and information, EV charging facility guidance, multi-modal trip planning, and travel services information. These services were briefly described based on ISO 14813-1.

After reviewing the collected literature, the report was published in 2022 [74], providing simplified recommendations for thematic areas that should be prioritised and summarised in the “executive summary” of the report. The report is only available in Norwegian, with an English executive summary.

The report is relevant to the MODI project as it outlines the current state of research and development, as seen from the Norwegian Public Roads Administration’s perspective. It contains specific advice on prioritised ITS services, what roles and responsibilities need to be filled within a road network comprised of automated and non-automated vehicles, and where the NRA's priorities should go. Some of the key takeaways are:

- Road authorities should plan future road maintenance based on the collection of relevant data from automated vehicles at various levels and the use of automated maintenance vehicles.
- Development of 5G technology is currently carried out mainly by the telecommunications industry. The road authorities' need for 5G along the road network should be communicated to speed development.
- Accurate positioning is essential for automated driving. The road authorities should ensure that GNSS correction data along the road network is available to an ever-growing market.

Road infrastructure for positioning of automated vehicles

The report Road Infrastructure for Positioning of Automated Vehicles [76] was written in conjunction with the ITS pilot program in the Norwegian Public Roads Administration. It focuses on positioning for automated driving in general, with the road segment E6 Oslo—Svinesund as a specific use case and with a primary objective to comprehensively assess the current state of positioning for automated vehicles.

One significant challenge identified in the report is the existence of areas with missing or limited GNSS coverage. Therefore, the report discusses alternative positioning methods, such as map-based matching and positioning in cellular networks (5G), what the technologies can do, and where they might fall short. Five recommendations for road authorities on their path towards automated driving are presented:

1. Secure available and sufficient **GNSS correction data** for the whole road network.
2. Work in collaboration with industry and academia to ensure proper **national data as input to HD maps**, focusing on areas with lesser available GNSS data, where accurate landmarks should be provided.
3. Develop **alternative systems for highly accurate positioning** in areas without GNSS coverage, such as tunnels. This should complement the efforts mentioned in point 2.
4. Investigate the need for **changes in road maintenance** to ensure the visibility of landmarks, including road markings, and **keep maps of objects updated** for input to HD-maps.
5. Work in close **collaboration with OEMs (Original Equipment Manufacturers) and Tier 1 suppliers to understand their requirements** and ensure the implementation of the right actions in points 1 to 4 above.

UK Geospatial Reports

Analysis and recommendations for self-driving vehicle testing in the UK

Zenzic and Ordnance Survey in the United Kingdom published a report in 2019 with analysis and recommendations for testing self-driving vehicles in the UK – followed up with additional findings in 2020 [75]. The reports aimed to investigate interoperability requirements for geospatial data for testing and development and establish a framework for operational deployments of connected and self-driving vehicles. The reports are most relevant for discussions related to HD Maps.

The relevant findings in the reports included that data quality from government organisations is a crucial issue. Consult responses indicated that existing data are not prepared for use in automated vehicles. The quality of public data can often be poor, with discrepancies within a dataset. It is considered necessary to know whether regional variance in data quality exists.

Also, common standards are needed concerning the content and expected quality of public data. The time is now to investigate what types of geospatial data are needed and further standardise and share this information in preparation for operational deployments. Digital Traffic Regulation Orders (TRO) were identified as crucial information from authorities where standards and digitalisation are needed.

Geospatial information is considered fundamental for automated vehicles. The requirements are complex and diverse. Therefore, mapping authorities like the Ordnance Survey are vital in developing automated vehicles. A neutrally hosted service as a single source for authoritative data would aid interoperability and increase confidence in the data. However, it is also suggested that commercially focused business models can play a significant role in unlocking and sharing data with the highest quality.

UK Geospatial Commission - Location data to enable connected and automated mobility

The UK Geospatial Commission published a report in 2023 highlighting the role of location data and location technologies for deploying CCAMs on UK roads [76]. The report presented the outcome of an evidence review of existing literature and interviews and discussions with an expert network representing the public sector, industry, research, and academia. Like the reports from Zenzic and Ordnance Survey [75], the report is particularly relevant for discussions related to HD Maps.

The findings show that authoritative and accurate location data will be essential for the safe deployment of automated vehicles. Vehicles will need to operate on a combination of sensors and HD Maps. The combination is critical as maps provide vehicles with information and foresight that sensors cannot deliver, while sensors can supply the map with real-time observations. Furthermore, sharing information is fundamental.

Concerning positioning technologies, the report notes that the EU Agency for the Space Programme has estimated that automated vehicles will need a horizontal accuracy of better than 20 centimetres, a vertical accuracy of better than 2 meters, timing accuracy of less than one microsecond, and availability of better than 99.9 per cent.

The report points to three opportunities for the further development of location data for automated vehicles:

- Improve the understanding of the road environment by addressing critical location data gaps.
  - The HD Maps must be based on authoritative, trustworthy, and precise data.
  - Data provided by Ordnance Survey needs to be improved in resolution, consistency, and accuracy.
- Improve how location data and location technologies can work together by defining accuracy standards.
  - There is currently no consensus on the level of accuracy needed from HD Maps.
  - Stakeholders from the industry, regulators, and government must work together to accelerate the development and implementation of standards that define content, accuracy, and exchange technologies.
- Improve data-sharing practices to make connected vehicle data more accessible and reusable.
  - Data must be shared between stakeholders in a larger ecosystem, including OEMs, authorities, regulators, insurers, etc.
  - Sharing of data from vehicles is a great opportunity but requires aggregation and anonymisation.

I.2.4 Findings from academic literature

Findings from specific publications

Farah et al. [77] presented a state-of-the-art on the integration of automated and connected vehicles in the existing road network, considering both the physical and digital infrastructure. They defined the physical infrastructure to include the geometric road design and the structural pavement design. The digital infrastructure includes sensors, connectivity and cloud, digital maps and road databases, and exact positioning.

The PhD thesis by Ane Dalsnes Storsæter [78] studied the design and maintenance of roads to facilitate automated driving. The thesis stated that current road infrastructure has been created primarily for human drivers. In preparation for automated driving, it is necessary to include automated drivers as road users and take them into account in road design and maintenance standards. The automated driver has different characteristics from human drivers, including an increased electromagnetic sensitivity range, a greater field of view, and fundamentally different cognitive processes. For the future design of roads, different eye heights for sensors compared to human drivers need to be considered, as well as the height of road features and the expected reaction time of vehicles. Furthermore, colours, patterns and textures can make road features and markings more visible. Relevant findings for road markings included that different sensor types see the road infrastructure differently; contrast between road marking and pavement is more critical for camera sensors than retro-reflectivity, and that the type and thickness of road markings may affect a successful detection for lane keeping.

A recent study from the University of Leeds [79] investigated requirements for highly automated vehicles at SAE Level 4 through a survey with 168 experts and stakeholders from academia, industry authorities and consultants from 29 countries. There was consensus from the stakeholders on the importance of infrastructure for automated driving and that infrastructure owners and operators should be responsible for assessing roads for automated driving. New challenges, particularly for the digital infrastructure, must be overcome before CAVs can start operating on the roads. Among 30 factors that affect the safe operations of automated driving, positioning was ranked the highest, followed by roadworks, facilities for vulnerable road users, intersection types and HD maps. Collaboration between stakeholders and standardisation of basic requirements were pointed out as necessary to ensure the safe operation of CAVs. However, the study also noted that authorities may face challenges in finding the funds for such investments. Therefore, CAVs must also demonstrate that they can operate safely without infrastructure support in some conditions.

General Academic literature review

Integration of Automated Vehicles in Existing Road Infrastructure

Emerging research underscores the multifaceted challenges and opportunities of integrating Connected and Automated Vehicles (CAVs) into existing road infrastructure. A common theme explores the co-evolution of digital and physical components in this transition.

Understanding the needs of current technologies and forecasting future trends is crucial for efficient network planning and design [80]. As CAVs become more prevalent, research in this domain will continue to play a pivotal role in shaping our transportation infrastructure.

A study by Yeganeh, Hendrickson, and Biehler [81] concluded that connectivity and Vehicle-to-Infrastructure (V2I) technologies would influence the transition to digital infrastructure. They also found that stakeholders such as departments of transportation (DOTs) would have to be cautious about new infrastructure investments in the short and the long term.

The impact of vehicles on physical infrastructure, such as road wear and tear, is non-uniform (Chen et al., 2016). It is argued that introducing CAVs could lead to higher road capacity, thus increasing the load on infrastructure. CAVs also have more precise steering than human drivers, which could lead to more wear and tear on specific points or lanes on roads (unless CAVs are instructed to behave less precisely). Predictions from the Netherlands using scenario analysis [82] placed full vehicle automation availability between 2025 and 2045, with conditional automation sooner, from 2018 to 2028. Investment, regulatory evolution, and growing consumer interest could fast-track this transition. The market could see a 1-11% penetration rate by 2030 (mainly conditional automation) and 7-61% by 2050 (primarily full automation).

The following implications about road network design about the transition to AVs were provided by Ye and Wang [83], given their simulation tool:

1. When AVs have low market penetration, congestion pricing is a productive mechanism for traffic management. As AV penetration intensifies, the efficacy of network design strategies correspondingly heightens, necessitating strategic adaptation from urban planners.
2. In escalating origin-destination (OD) demand, optimising network design and promoting AV usage are pivotal solutions for mitigating traffic congestion.
3. During the transition period featuring a mix of AVs and conventional vehicles (CVs), a combined approach employing network design planning (NDP) and congestion pricing distinctly surpasses either strategy in isolation, particularly when both AVs and CVs have significant market shares. This suggests the optimal strategy during this period is a hybridised approach, intertwining NDP with congestion pricing.

Madadi et al. [84] suggest that autonomous driving (AD) will be most effective on a subset of the existing road network, known as an AD subnetwork. The study refines this vision by framing it as a bi-level Network Design Problem (NDP), for which an optimal solution algorithm has been developed.

The process begins by identifying feasible links in the road network that, after certain adjustments based on sustainable safety principles, would be safe for AD. These links mainly include motorways, expressways, and major urban roads, which have limited or no intersections - intersections being where most AV accidents occur. These roads are the safest for AVs due to their inherent design and flow function, and some also due to their distribution function.

Adjustment costs are considered to bring these roads up to a standard suitable for AD. Requirements for this standard include limited access, high-quality infrastructure (like pavement, lane marking, traffic signs, and lights), segregated traffic to maintain homogeneity of mass and speed within each lane, and either grade-separated or clear at-grade intersections. Many roads deemed feasible for AD already meet most of these requirements, notably motorways, which may require minimal adjustments. Consequently, adjustment costs vary based on the type of road and its initial quality, with higher hierarchical roads (like motorways) requiring the most minor adjustments and incurring the most minor costs.

Given these findings, urban planners and transport authorities should consider implementing AD subnetworks within their existing road networks. This should start with prioritising high-impact areas, investing in adjustments necessary for AD, and then gradually extending these AD-friendly parts of the network in line with AV market penetration. According to the authors, this strategy maintains an optimal balance between investments and benefits over time.

AV-specific lanes are expected to improve efficiency and safety [85], while full AV fleet implementation could revolutionise highway design [86].

The potential changes to highway geometry, load distribution, and lane width with AV integration have been extensively investigated by Yeganeh, Vandoren, and Pirdavani [87]. The study utilised a finite element approach to understand how various load distribution modes impact pavement performance. The maximum rutting position varies based on the loading scheme. Automated vehicles with uniform or zero-wander distribution in a dedicated lane could accelerate pavement rutting damage significantly. For instance, a uniform-wander distribution for CAVs would cause rutting depths 14.49 times larger than HDVs in a 3.5-m lane and 27.75 times larger in a zero-wander distribution. Narrower lanes for CAVs using a uniform wander distribution can substantially affect pavement rutting performance. Compared to a 3.5-m lane, lane widths of 3 and 3.25 m would increase rutting depth by 20.48% and 7.31%, respectively. In a zero-wander distribution, rutting depth is independent of lane width. A uniform-wander distribution for CAVs could reduce total rutting depth by 42.35%, 38.13%, and 30.54% for lane widths of 3.5, 3.25, and 3 m, respectively, compared to the zero-wander distribution.

Wang et al. [88] argued that sensor systems will increasingly take over the responsibilities of human senses, whether full automation happens or not. Many aspects of geometric road design can thus be ignored or reduced in importance since such aspects were in place to accommodate human sensory systems. This is especially true for dedicated lanes. The study doesn't account for the limitations of perception sensors under adverse weather conditions, assuming ideal road environments for all scenarios. However, Lu [84] argues that dedicated lanes are unfeasible until the majority of vehicles are SAE level 4.

Furthermore, nuanced studies into driving environment characteristics, such as lane width and weather conditions, and their impact on automated vehicle performance highlight the need for adaptable infrastructure [89, 90]. They found that weather conditions and lane width significantly affect the performance of Lane Departure Warning (LDW) and Lane Keeping Systems (LKS)-enabled vehicles. Their findings highlight the need for infrastructure to be flexible and adaptable to these variables, emphasising road authorities' role in successfully integrating CAVs.

This, along with ongoing research into mixed traffic flow management and safety evaluations in mixed traffic scenarios, emphasises the role of cooperative adaptive cruise control and V2V communication in enhancing safety and traffic stability [91, 92].

The Emergence of Digital Infrastructure

With the integration of cooperative technologies such as high-precision positioning, V2X communication, and advanced digital maps, a transition towards a combination of physical and digital infrastructure is becoming inevitable, supporting the operation of these vehicles in complex urban settings [93].

Parallel to this transition is the emergence of smart roads, enabled by predictive sensor technologies for proactive infrastructure management, which fundamentally change the traditional maintenance processes [94]. This evolving paradigm also highlights the correlation between urban smartness, enhanced digital connectivity, and shifting commuting patterns [95].

Despite these advances, the path to CAV-compliant infrastructures is an ongoing journey, with systematic literature reviews proposing phased upgrade plans [96]. They argue that successfully deploying CAVs requires vehicle-mounted devices and roadside digital infrastructure for various connectivity needs (V2X). This requires numerous in-roadway sensors (like loop and magnetic detectors) and over-roadway (cameras, radars, and ultrasonics) to monitor traffic and allocate resources for smoother traffic flow. Internet connectivity can be established through mobile networks (4G/5G) or Wi-Fi-based facilities. Future-proofing roads with fibre-optic cable at major junctions could simplify future digital infrastructure setup.

They also report that safe harbour areas, like hard shoulders or emergency refuge areas (ERAs), are vital for SAE levels 3-4, providing safe spots for emergencies or exiting automated operation areas. With some converted into running lanes, misuse has led to safety concerns. Future planning should reassess safe harbour frequency and design standards and potentially introduce regulations to prevent misuse and accommodate CAVs.

Lilhore et al.'s research [97] introduces an Adaptive Traffic Management system (ATM) using ML and IoT to mitigate existing transport issues. The ATM system, focusing on vehicles, infrastructure, and events, uses ML-based anomaly detection and constantly updates traffic signal schedules based on traffic volume and nearby movements. Compared to conventional strategies, the ATM system reduces travel time, congestion, and accidents, improving the overall journey experience and making it a strong contender for smart city transport planning.

The contributions of high-definition mapping technologies and scalable mapping solutions are also significant in this context, enabling precise localisation essential for autonomous driving [98, 99]. Alongside these advancements, the development and use of comprehensive datasets for training and testing traffic monitoring systems, like the Annotated Virtual Detection Lines, accentuates the intersection of technology and infrastructure in shaping the future of autonomous vehicles [100].

Creation of HD Maps

Advancements in road extraction from remote sensing imagery have manifested themselves through several novel approaches. For instance, HsgNet [101], which uses high-order spatial and global context semantic information, and CRESIv2 [98], which infers semantic features of road graphs, have both demonstrated superior performance. However, Batra et al. addressed the issue of fragmented road segments by a unique connectivity task, Orientation Learning [102].

Techniques such as the two-stage transfer learning strategy [103] and a point-based iterative graph exploration scheme [104] further enhanced the robustness of segmentation and improved alignment in road network extraction. On another front, Bandara, Valanarasu, and Patel [105] and Xu, Liu, Gan, Hu, et al. [106] made substantial contributions to autonomous navigation systems by innovatively separating roads from other geographical features and by automatic city-scale road-boundary detection, respectively.

The connectivity-preserving loss method enhanced the detection of road curbs, which is essential for High-Definition maps in autonomous driving [107].

The connectivity attention network (CoANet) by Mei et al. [108] leverages the learning of segmentation and pair-wise dependencies to overcome occlusion challenges and preserve road connectivity.

Meanwhile, road marking extraction and classification from mobile LiDAR point clouds have been enhanced by a capsule-based deep learning framework presented by Ma, Li, Li, Yu, et al. [109], offering a robust solution for autonomous vehicle development and high-definition mapping. This approach is complemented by a dynamic point-wise convolutional operation, achieving superior performance in extracting high-level 3D point cloud features in large-scale road environments [110].

The work by Ma et al. [111] introduced BoundaryNet, a deep-learning framework for accurate road boundary extraction and completion using mobile laser scanning point clouds and high-resolution satellite imagery. This innovation includes curb-based extraction, erroneous boundary denoising, and a conditional deep convolutional generative adversarial network for road boundary completion.

Additionally, the vertex-by-vertex road network graph detection approach proposed by Xu, Liu, Gan, Sun, et al. [112] represents a novel solution, employing a transformer and imitation learning to overcome the limitations of traditional segmentation-based and graph-based approaches.

Sun et al. [113] delve into the digital infrastructure domain, presenting a dynamic digital twin model for resource allocation in the Internet of Vehicles (IoV).

Martinelli et al. [114] propose a system for assessing road surface conditions. Lin and Zhang [112] introduce a LiDAR-inertial-visual fusion framework, suggesting broad physical and digital infrastructure applications.

Digital Roadside Infrastructure

Holistic monitoring of the road scene can still be a problem for CAVs, especially without LiDAR. One approach to alleviating this problem is using a V2I approach involving cameras installed in a shared traffic environment. Research on this problem is still ongoing, but Wang et al. [115] report improvements over state-of-the-art.

Collecting open, high-quality LiDAR data that can be used to create HD Maps is still an ongoing issue. Wu et al. [116] addressed the issue by creating an efficient semi-automated annotation tool that automatically annotates LiDAR sequences using tracking algorithms. They also introduced a human-in-the-loop schema for annotators to refine imperfect predictions from the tool iteratively. This not only increased annotation speed but also improved annotation quality.

V2X infrastructure traffic scene sensors such as LiDARs are increasingly considered essential infrastructure for CAVs. However, optimal placement of such LiDAR is a rarely studied problem, according to Cai et al. [117]. The researchers addressed this problem by proposing an efficient pipeline that identifies the best installation positions for infrastructure sensors in a realistic simulated environment. To do this, they developed a realistic LiDAR simulation library to simulate the unique characteristics of different popular LiDARs, producing high-fidelity LiDAR point clouds in the CARLA simulator. Using this simulation library, they could evaluate the perception accuracy of various sensor placements with different detection models. By analysing the correlation between point cloud distribution (density and uniformity) and perception accuracy, they found an optimised placement scheme that improved average precision by 15% compared to conventional placement schemes. The team validated that density and uniformity can serve as performance indicators.

On a related note, Vijay et al. [118] tackle the safety issue in autonomous vehicles by proposing a cost-effective methodology for strategically placing Vehicle-to-everything (V2X) infrastructure sensors. Leveraging advancements in ray-casting and linear optimisation, this tool is beneficial to city planners and AV operators, as validated by experimental evaluations.

Wurst et al. [119] introduce a method to detect novel traffic scenarios in scenario-based testing for autonomous vehicles, focusing on infrastructure images. The approach uses an autoencoder triplet network to create latent representations for these images, aiding outlier detection. The network's training leverages connectivity graphs of the infrastructure, and expert knowledge shapes the latent space to incorporate a pre-defined similarity. An ablation study underscores the importance of the triplet autoencoder. Based on vision transformers, the best-performing architecture outperforms other outlier detection approaches.

Despite being a relatively new field of study, infrastructure-based object perception is rapidly gaining significance in bolstering perception abilities for CAVs. A plethora of research efforts have served to set the groundwork and stimulate inspiration for future investigations, which are reviewed by Bai et al. [120] as follows:

1. Current Challenges
   (a) Sensor System: Most studies are based on single sensor systems. Few consider multi-sensor perception systems in terms of roadside sensor-based perception. Key challenges include determining the optimal fusion schemes of different sensor combinations and developing efficient fusion methods.
   (b) Core Perception Methods: There's a significant gap between general object perception and infrastructure-based object perception. Many existing roadside LiDAR-based detection approaches rely on DBSCAN for clustering, which exhibits a performance gap compared to state-of-the-art methods. One major challenge is enhancing roadside data acquisition and annotation to boost deep learning-based research in infrastructure-based perception systems.
   (c) Communications and Synchronisation: Processing and communication delays often cause synchronisation problems, posing a significant challenge for large-scale implementation.
2. Future Trends
   (a) Towards Multi-Sensor Fusion: Multi-sensor-based perception systems can potentially improve performance by leveraging complementary sensor data. Infrastructure-based perception systems are more flexible for multi-sensor equipment and can support high-computational edge servers.
   (b) Towards Cooperative Perception: Single-node perception cannot address physical occlusion limitations. Perceiving the environment from multiple nodes can help overcome the challenges posed by occlusion, a significant bottleneck in current perception systems.

(c) Towards Lightweight On-Board Units (OBUs): Equipping every vehicle with a high-performance computation system for perception can be costly. With the advancement of high-speed wireless communication technologies, it becomes more cost-effective to use lightweight OBUs for local situation awareness perception and rely on data from infrastructure-based high-performance nodes for broader range perception.

The current approach to environment perception in CAVs, which relies solely on onboard sensors, faces challenges in detecting occluded areas and mitigating sensor outages, particularly in complex traffic intersections. Integrating smart infrastructure nodes on roads can help overcome these problems by providing an elevated and static viewpoint to detect more objects and communicate this information to CAVs, enhancing their situational awareness. Mishra et al. [121] seek to alleviate this problem using low-cost, wide field-of-view fisheye cameras used in this context, which must be localised or registered within the same map used by the AV for navigation to ensure consistency in data interpretation. The proposed solution uses a two-step approach, beginning with feature matching between the rectified fisheye image and satellite imagery for an initial camera pose, then refining this localisation through maximising mutual information with a 3D LiDAR map. Given the cost surface's potential non-differentiability, an exhaustive grid search is employed instead of gradient descent methods to find the optimal camera pose. Although this process can be time-consuming, it's suitable for this application as the smart infrastructure node needs to be localised only once during installation, and this can be done offline. Furthermore, the speed of the method can be improved with GPU use.

Lee et al. [122] address the issue of vehicle localisation in autonomous vehicles using infrastructure-based sensors, specifically an infrastructure node (ix-node). This node, equipped with a camera and LiDAR, provides additional perspectives to enhance vehicle perception. An Extended Kalman Filter is employed for data association and time synchronisation between the vehicle and ix-node, which generates vehicle candidates for integration into a multi-fusion system. This approach was tested using a Ford autonomous vehicle on a test track, demonstrating superior performance than GPS and ix perception with less than one meter of mean position error, including compensation for GPS failure in a tunnel. Future work will aim to implement this framework with multiple ix nodes and explore sensor-level information integration.

Broader Implications for Society

The proliferation of CAVs poses transformative implications for urban planning and travel behaviour. Duarte and Ratti [123] highlight CAVs as potential catalysts for urban redesign, impacting car design, infrastructure demand, and urban sprawl. Similarly, Soteropoulos, Berger, and Ciari [124] underscore the effects on travel behaviour and land use, suggesting that CAVs could increase vehicle miles and contribute to dispersed urban growth. However, they posit that shared automated vehicles could counterbalance these impacts, reducing the number of vehicles and parking spaces.

The advent of CAVs also engenders social and ethical ramifications, with Morton et al. [125] focusing on professional drivers. The qualitative study provides insights into the pioneers of driverless technology, highlighting practical opportunities and challenges. Through interviews with drivers from the haulage industry, they found that the development of driverless tech often overlooks input from these drivers despite their role as primary users. They express apprehensions about the future functioning of these technologies and agree that significant societal changes are required for full implementation.

However, there is potential for user benefits with autonomous vehicles. The onus is on designers to identify these opportunities and learn from HGV drivers' experiences. Acceptance of driverless tech remains a hurdle due to the shortcomings of early versions, such as their inability to emulate human understanding and behaviour. This has led to general scepticism about trusting such technologies without human intervention.

The tensions that emerge in urban planning, particularly the conflict between visions of reduced car ownership and exacerbated car dependency, are examined by Legacy et al. [126]. They underscore the need for proactive public sector planning to address potential unintended impacts on the built environment and society.

The broad context of urban planning must consider the disruptions by CAVs on the built environment and land use, as Yigitcanlar, Wilson, and Kamruzzaman [127] outline. Given the lack of knowledge about CAVs' social implications and disruptive potential, urban planners' unpreparedness is stressed.

On a similar note, Gavanas [128] analysed the challenges for European cities, highlighting the impact on location choices and infrastructure design. They also underline the scarcity of data for planning, proposing CAVs as potential data sources for urban planners.

The advent of CAVs yields potential improvements in traffic flow and emission reduction, as highlighted by Qin, Wang, and Ran [129]. They indicate that cooperative adaptive cruise control vehicles could significantly influence environmental benefits. This idea aligns with the overview provided by Rashidi et al. [130], which discusses various adoption scenarios and implications for city and transport systems.

Meanwhile, Jeong, Lee, and Gim [131] and Othman [132] focus on potential transformations in the built environment due to CAVs, emphasising the role of regulatory actions and technology uncertainties.

On the safety side, Zou et al. [133] used virtual reality to investigate how roadway design and autonomous vehicle (AV) signals affect pedestrian crossing behaviours at unmarked midblock locations. Findings indicate both these factors significantly impact crossing times, but only roadway design affects walking time. Older individuals tend to wait longer to cross, but past behaviours and walking exposure have little impact on pedestrian behaviour with AVs.

Truck Platooning

Autonomous truck platooning and its impacts on infrastructure are central themes in the works of Couto Braguim, Lou, and Nassif [134] and Tohme and Yarnold [135]. While the former posits that truck platooning could mitigate fatigue damage on steel girder bridges, the latter identifies potentially inadequate bridges for platooning based on various configurations. Complementarily, truck platooning implications for bridge infrastructure were analysed, providing safe headway calculations by Yang et al. [136] and a prioritisation framework for bridge evaluation by Thulaseedharan and Yarnold [137]. Contrarily, Othman [138] argues that truck platooning could pose challenges for current infrastructure like bridges.

Innovative technologies, such as Digital Twin technology, could become critical for real-time monitoring and maintenance of critical infrastructures such as bridges [139].

Significant reduction in freight transport costs due to the adoption of driverless trucks is explored by Engholm, Kristoffersson, and Pernestål [140]. Yet, they are also cautious about societal costs associated with infrastructure investments and increased emissions. More specifically, the study investigated the impacts of large-scale driverless truck adoption in Sweden under two scenarios: all trucks being driverless (AllDL) and a hub-to-hub system (H2H). Findings revealed both scenarios caused a shift from rail and sea to road transport, increased truck traffic, and significantly reduced logistics costs. Lower driverless truck costs amplified these effects, whereas higher costs reduced them. A similar line of inquiry is pursued by Roh, Jeon, and Son [141], who analyse the influence of heavy vehicles on traffic flow and find that they may reduce vehicle-to-vehicle conflict.

Additional references

The literature review included several publications in addition to those referenced above. All publications are listed in the references section of this report [79 - 214].

I.2.5 Findings from MODI deliverables

D1.1 User and stakeholder requirements for autonomous transport in Logistics

MODI Deliverable D1.1 [29] identifies user and stakeholder requirements for highly automated freight vehicles in logistics based on semi-structured interviews. The users represented a range of logistics actors with the potential to purchase or lease autonomous trucks for transport and distribution. Stakeholders were identified from two groups: 1) technology developers (including OEMs), CCAM providers, and terrestrial connectivity providers, and 2) road authorities, owners, and operators. The analysis of interviews resulted in 48 user and stakeholder requirements, comprising 21 user requirements, 11 technology developer requirements and 16 road actor requirements. The two latter groups of requirements, representing the stakeholders, are considered the most relevant for task 4.2.

Among the findings were some common focus areas, where two may be particularly relevant for task 4.2:

- All actors call for standardisation of physical and digital infrastructure to increase the extent to which autonomous trucks are interoperable and can be used flexibly (in conflict with the need for gradual change to existing infrastructure
- All actors share a need to progress models of remote monitoring and functional, usable data interfaces, which are to be achieved by private and public actors working together to develop standards and regulations and to perform operations.

The deliverable identifies several completed and ongoing EU projects related to CCAM. Five were found to be most relevant for identifying MODI requirements: AWARD, SHOW, AUTOPILOT, L3Pilot, and ENSEMBLE. Two important observations were that CCAM for logistics had received comparatively less attention than passenger transport and that more needs to be done to explore the requirements created by the complex interactions of stakeholder groups in autonomous logistics.

Some requirements will be particularly critical for task 4.2:

- Technology developer aggregated requirements (TAR):
  - TAR8**: We need adaptations to the physical infrastructure** to enable and expand use areas for autonomous trucks.
  - TAR10: We (must[2]) have the data we need to develop regularly updated, accurate and standardised HD digital maps (**local dynamic maps**) for autonomous truck operations.
- Road authorities/operators aggregated requirements (RAR):
  - RAR8: We (must[3]) have an **open dialogue with harmonised manufacturers on data we** must (digital signage, regulations) and could **provide** for autonomous trucks to ensure efficiency, safety and traffic flows. We (must be able to[4]) **direct** the autonomous truck, control road accessibility, flexibly set maximum speed limits and orchestrate traffic flows.
  - RAR16: **We prefer simple, gradual changes** to the physical road infrastructure that are evaluated as beneficial for other road users in tests on private roads that can be rolled out as short-term pilots with simple ODD on public roads; **we need a roadmap for autonomous truck implementation** to inform us about what PDI changes might be expected when so that we can consider them alongside other road user and AV needs, make ROI calculations and evaluate alternative financing options.

A final recommendation from the deliverable states that *"Technology providers should work together to provide logistics actors and road* ***authorities*** *with roadmaps for the future development of autonomous truck operations logistics, outlining needs for PDI investment and development."*

D1.2 Safety and Security Requirements

MODI Deliverable D1.2 [30] analyses external traffic safety and cybersecurity requirements for the vehicles to be used and the activities to be demonstrated by MODI, examines the need to address public acceptance of the risks associated with automated trucks, and looks at the implications of current crime trends involving freight vehicles have for automated or driverless vehicles. It also uses safety and security scenarios to examine risks associated with the MODI use cases. The purpose is to lay the landscape for MODI's concrete safety and security requirements. The foundational requirements are that vehicles in MODI need to follow traffic rules; do not cause accidents; and account for mistakes of others as much as possible. This deliverable is classified as sensitive and is only accessible to MODI partners.

D1.3 Report on Border Processes

MODI Deliverable D1.3 [31] aims to identify requirements for a higher communication and positioning network that will be needed for the transfer of fully automated vehicles through a border crossing scenario. The deliverable states that very precise positioning and the correct reference

[2] T4.2 Interpretation of the requirement formulation
[3] T4.2 Interpretation of the requirement formulation
[4] T4.2 Interpretation of the requirement formulation

frames are key to automated vehicles passing a border of any kind. Especially a variation in systems between countries or between confined private and public areas can easily cause various issues.

The deliverable lays out several requirements that are relevant to this analysis:

MODI_BC_Req_03: When crossing a border, the automated vehicle shall be able to connect to national, regional and local communication and C-ITS services, e.g., real-time traffic information (most often National DATEX II service), weather information, C-ITS services, confined area services, etc.

MODI_BC_Req_04: When crossing a border, e.g., between two countries or between a publicly accessible area and a confined area with access control, the automated vehicle shall connect to a positioning service with the required accuracy for the area the vehicle enters.

MODI_BC_Req_05: When crossing a border, the automated vehicle shall ensure that the same reference frame is used when combining positions from positioning services, information services, digital maps and C-ITS services.

NOTE*:* This is one of the most crucial requirements related to border crossings.

MODI_BC_Req_06: When crossing a border, the automated vehicle shall connect to national, regional, and local services for the provision of static data updates and services for dynamic information.

D3.1 Report on connectivity requirements

MODI Deliverable D3.1 focuses on connectivity requirements for CCAM vehicles, outlining relevant technologies such as C-ITS, mobile networks, and vehicle energy supply. The deliverable emphasizes functional connectivity needs in various operational scenarios, particularly during transitions between public and private networks or across border areas. Key requirements include the ability to handle dynamic information like traffic signals and hazardous situations, as well as static data such as traffic regulations and parking locations. Infrastructure considerations include reliability, security, redundancy, and resilience. This deliverable is classified as sensitive and is only accessible to MODI partners.

D3.2 Report on automation requirements

MODI Deliverable D3.2 addresses safety and automation requirements for vehicles in MODI Use Cases, with a focus on operational integration, vehicle subsystems, and harmonization of map, positioning, and time data. It highlights the need for HD Maps with electronic traffic regulations, GNSS augmentation services, and precise positioning to enable automated driving. Specific requirements include self-monitoring of operational conditions, high-accuracy positioning for parking and docking, and the standardization of HD Map formats for navigation and decision-making. This deliverable is sensitive and available exclusively to MODI partners.

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Annex II: MODI workshop on National Strategies for Automated Transport

II.1 Introduction

Title: MODI workshop on National Strategies for Automated Transport,

Date: April 3rd, 2024

Venue: Jernbanetorget 1, Oslo

II.1.1 Agenda

- 10:30 – 10:40: Welcome and objectives
- 10:40 – 12:15: Presentation of national strategies/road maps for automated transport
  Norway, Sweden, Denmark, Netherlands, Germany, Flanders, UK
- 12:15 – 12:45: Lunch
- 12:45 – 13:00: Main findings from MODI T4.2: Develop optimal design of physical and digital infrastructures for public roads.
- 13:00 – 13:30: 2-minute elevator pitch from industry stakeholders
  TomTom, SWARCO, RUTER, The Port of Moss, Gruber Logistics, 5GAA, ZEEKR
- 13:30 – 15:20: Workshop
- 15:20 – 15:30: Closing remarks

II.1.2 Participants

- **Public Sector**: Norwegian Public Roads Administration, Buskerud County Council, Norwegian Mapping Authority, Federal Highway Research Institute (BASt), Swedish Transport Administration, Rijkswaterstaat (Netherlands), Vejdirektoratet (Denmark), Department for Transport UK Government, Flanders' Department of Mobility and Public Works (MOW)
- **Research and Interest Organisations**: Oslo Metropolitan University, ITS Norway, SINTEF, University of South-Eastern Norway, Nord University
- **Industry Stakeholders**: TomTom, 5GAA, SWARCO, Ruter AS, XPENG MOTORS (Norway), The Port of Moss, Gruber Logistics, Norwegian Space Agency, Dynamic Map Platform Europe GmbH

II.1.3 Workshop Description

In this workshop, representatives from seven countries presented their strategies and roadmaps for the integration of automated transportation systems. Six industry actors gave 2-minute pitches on their needs from the strategies, and the MODI project presented preliminary results from "T4.2 – Develop Optimal Design of Physical and Digital Infrastructure on Public Roads". The nations involved were Norway, Sweden, Denmark, Germany, Netherlands, Flanders (Belgium), and the United Kingdom.

The presentations and industry pitches are available here:

II.2 Summary of presentations from national authorities

Norway

Norway is taking decisive steps towards a future of automated road transport. The nation is actively developing a comprehensive national strategy that focuses on three key pillars: establishing a robust framework for testing and implementing automated vehicles, ensuring public services are adapted to accommodate these advancements, and fostering cross-sector cooperation between various stakeholders. The Norwegian Public Roads Administration (NPRA) is leading the development of regulations and action plans to guide the transition smoothly and efficiently.

Sweden

Sweden's approach to automated road transport emphasizes a balanced strategy that avoids both excessive regulation and deregulation. The Swedish Transport Administration (STA) believes that the primary intelligence for automated vehicles should reside within the vehicles themselves, with infrastructure support playing a supplementary role at crucial points in the road network. STA prioritizes providing high-quality data to support prioritized use cases such as driver assistance systems and communication related to speed limits, road closures, and accidents. They also highlight the importance of data exchange and collaboration between public and private stakeholders to ensure a seamless and secure transition to automated transport solutions.

Denmark

With established test legislation and ongoing trials in various locations, Denmark actively explores the potential of these technologies. The Danish Road Administration (VEJ) is conducting a thorough analysis of both physical and digital infrastructure requirements to support automated vehicles. Collaboration remains a key aspect of Denmark's strategy, as they actively participate in European partnerships and initiatives to share knowledge and develop solutions collectively. Their primary objective is to leverage these advancements to improve mobility, road safety, and the environment, while carefully avoiding pitfalls such as unnecessary investments and monopolies.

The Netherlands

The Netherlands is committed to fostering a collaborative environment for the safe and predictable integration of automated driving systems (ADS) within the Dutch road network. Recognizing the potential of ADS to transform mobility, a national task force is being established to bring together key stakeholders from government agencies, research institutions, and the industry. This collaborative approach aims to address the unique challenges and opportunities presented by ADS within the context of Dutch road design and traffic situations. By prioritizing safety, engaging the public, and adapting existing legal frameworks, the Netherlands aims to maximize the benefits of ADS for its transportation system.

Germany

Germany's strategy for automated driving prioritizes maintaining its position as a global leader in the development and implementation of this transformative technology. With a focus on research, development, and production, Germany aims to be at the forefront of Mobility 4.0. The country has already established a comprehensive legal framework, including the Act on Automated Driving and the Act on Autonomous Driving, demonstrating its proactive approach to regulating ADS. Germany is actively exploring potential applications for ADS, such as shuttle services, hub-to-hub transport, and automated valet parking, with the goal of achieving a leading position in the market penetration of automated and connected vehicles.

Flanders

Flanders is strategically focusing on shared automated mobility solutions to maximize societal benefits and mitigate potential drawbacks. They recognize the need for a collaborative approach, involving various stakeholders through knowledge centers, task forces, and pilot projects. A "learning by doing" philosophy is emphasized, with close monitoring of pilot project impacts to refine business models and regulations. Additionally, Flanders sees teleoperation as a crucial bridge technology, addressing limitations of current automation and driver shortages. The "5G-Blueprint" project explores using 5G connectivity for remote vehicle operation, leading to a future where teleoperated and automated driving systems coexist and complement each other.

United Kingdom

The United Kingdom has taken a structured approach to automated transport, prioritizing the establishment of a comprehensive regulatory framework. The Automated and Electric Vehicles Act, along with supporting initiatives, addresses key aspects of safety, liability, and insurance for self-driving vehicles. Significant government funding has been directed towards research and development of connected and automated mobility, fostering numerous collaborative projects and testing ecosystems. The UK actively promotes the commercialisation of self-driving technology, with substantial investments in large-scale deployments of passenger and freight services across the country. Furthermore, the UK explores the potential of self-driving technology to improve mass transportation, particularly in rural and underserved urban areas, through various pilot projects and initiatives.

II.3 Key Takeaways from Discussions

II.3.1 Introduction

The workshop brought together representatives from seven European countries, along with research institutions and industry stakeholders, to discuss national strategies and roadmaps for integrating automated transport. The discussions highlighted several key findings and challenges:

All stakeholders, including the public sector, private companies, and research institutions, must work together to achieve the full benefits of connected and automated vehicles (CAVs). This collaboration should encompass data sharing, infrastructure improvement, accident management, and the development of regulatory frameworks and cybersecurity measures. Public awareness and acceptance are also vital aspects that require attention.

Harmonized regulations and data formats are needed across Europe to facilitate cross-border operation of AVs and ensure their seamless integration into existing infrastructure. This includes addressing differences in passenger and freight CAVs, as well as varying national regulations and road infrastructure.

Both public and private sectors need to invest in large-scale deployment of AVs and the development of supporting digital infrastructure. Public-private partnerships can play a significant role in securing the necessary funding and expertise.

Building public trust in CAV technology requires a strong focus on safety and transparency. Open data sharing, clearly defined operational design domains (ODDs), and continuous innovation are essential for achieving this goal.

II.3.2 Stakeholder Responsibilities

We asked: *If we agree that in order to get full benefit from AVs, we need cooperation across sectors and actors – what are the different stakeholders' responsibilities?*

Key Stakeholders Identified:

- OEMs (Original Equipment Manufacturers)
- Vehicle manufacturers
- AV software developers
- Telecommunication companies
- Charging/fuel infrastructure providers
- Public authorities (various levels)
- Drivers
- Customs
- Road operators
- Buyers, sellers, and freight forwarders (commercial transport)

Main Points:

- **Public Sector is Redefining its Role**: Shifting from comprehensive traffic management towards data provision and policy frameworks.
- **Need for Harmonisation**: Collaboration across borders in Europe is crucial for aligning infrastructure and laws.
- **Liability Needs Rethinking**: There's a desire to shift a portion of the liability away from vehicle manufacturers.

- **OEMs Need to Collaborate on Data and Standards**: Sharing data while respecting privacy is key. Unifying standards will ease AV operation.
- **Consumer Trust is Critical**: Demonstrating the safety of AVs is essential to combat public skepticism.
- **Europe's Potential Advantage**: Some participants believe Europe is better positioned than the US for AV development.
- **Focus on Commercialisation**: Addressing regulatory hurdles and attracting investment are vital for large-scale AV deployment.
- **Public-Private-Research Partnership**: This type of collaboration is seen as critical for innovation and problem-solving.
- **Data Responsibility**: There's a need for clarity on who manages and is responsible for the accuracy of data across multiple stakeholders.

II.3.3 Role of Government

We asked: *How and what should the government do in relation to facilitating infrastructure for automated transport?*

Main Points:

- **Shift in Transportation**: Emphasis on reducing private vehicles in favour of automated transport solutions.
- **Learning from Private Sector and Global Leaders**: The government should adopt best practices from businesses and examine successful CAV deployment strategies in other countries.
- **Strategic Infrastructure Investment**: Pinpoint the most critical locations requiring infrastructure upgrades for CAVs.
- **Focus on Supporting Systems**: Prioritize infrastructure development for vital systems like telecommunications and charging networks.
- **Data Quality and Management**: Prioritize the quality of digital traffic data and clarify who is responsible for maintaining and updating maps.
- **Government-Supported Charging Network**: Prioritize investment in charging infrastructure along major transportation corridors.
- **Vehicle-Centric Intelligence**: AV intelligence should primarily reside within the vehicle itself, minimizing reliance on external infrastructure.

II.3.4 Next Steps

We asked: *Based on what you just heard about national strategies, what important actions are needed in the next 2 to 3 years? Discuss concrete problems/challenges that need to be solved.*

Main Points:

- **Develop Clear Frameworks and Roadmaps**: Create explicit frameworks for open road testing and type approval, providing industry players with a roadmap outlining future plans and regulatory directions.
- **Prioritize Data Standards and Responsibility**: Continue standardizing data formats and traffic regulations, clarifying roles related to data in the AV ecosystem.
- **Collaborate with Industry on Real-World Deployment**: Engage with industry players and service providers, encouraging data sharing on safety metrics and potential failures.
- **Rethink Regulatory Approaches**: Adapt and modernize regulations to accommodate the unique characteristics of AVs, enabling their safe integration with existing traffic.

II.4 Question 1: Stakeholders and responsibilities

We asked: If we agree that in order to get full benefit from CAVs we need cooperation across sectors and actors – what are the different stakeholders responsibilities?

Group 1 – Stakeholders and Responsibilities

Key Stakeholders Identified:

- Public sector (policymakers, infrastructure planners)
- Automotive companies
- Transport operators
- Research institutions and academia

Stakeholder Responsibilities:

- Public sector: Policy design, infrastructure development
- Automotive companies: Ensuring technology safety and reliability
- Transport operators: Managing safe fleet operation
- Universities/Research Institutions: Research, development, education, and innovation

Collaboration Strategies:

- **Setting Common Goals**: All stakeholders need alignment on objectives for AV development and deployment.
- **Transparency and Information Sharing**: Open communication across sectors to share data and findings.
- **Public-Private-Research Partnerships**: Formal collaboration for knowledge transfer and resource sharing.

Group 2 – Stakeholders and Responsibilities

- **Shifting Public Role**: The public sector moves away from comprehensive traffic management towards primarily providing data.
- **Mixed Traffic Management**: AV development must be compatible with a mixed-traffic environment, requiring investment in physical infrastructure (e.g., lane markings).
- **Need for Harmonisation**: Cross-border collaboration, especially within Europe, is essential for harmonizing infrastructure and laws.
- **Evolving Vehicle Testing**: Type approval processes must adapt to include software updates, recognizing the dynamic nature of AV technology.
- **Authority-OEM-Industry Collaboration**: These are the key stakeholders for establishing cooperation.
- **Predictable Innovation Environment**: OEMs desire a clear roadmap for cooperation, allowing innovation in a predictable regulatory framework.

Group 3 – Stakeholders and Responsibilities

- **Scaling Up**: Advocacy for removing EU legislative limits on the number of AVs in commercial deployment (increase from 1,500).
- **Commercialisation**: Allow for more key commercial players to invest in European AV development.
- **Infrastructure Integration**: Seamless integration of AV technology with existing and future infrastructure is key.
- **Global Standards**: Harmonizing standards across regions is necessary to ensure safe cross-border operations.
- **Building Consumer Trust**: Demonstrating that AVs offer enhanced safety compared to human-driven vehicles.
- **Funding and Investment**: Attract significant funding for large-scale AV deployment.

Group 4 – Stakeholders and Responsibilities

- **Shifting Responsibility**: The group believes too much responsibility currently lies with vehicle creators and suggests transferring a portion to other stakeholders.
- **Liability vs. Risk Responsibility**: There's a need to differentiate between the two and increase cooperation to define roles.
- **Public Perception**: It's crucial for public authorities or local governments to handle AV communication to ensure the public doesn't perceive autonomous driving as dangerous.
- **Role of Public/Private Sector**: The public sector should establish a minimum level of responsibility. Harmonisation of laws across regions/countries is needed to ease the burden on private actors (OEMs).

- **Challenges of Scaling**: Small use cases might limit AV potential to solve large-scale transportation problems.

Group 5 – Stakeholders and Responsibilities

- **OEM Cooperation**: The need for data sharing among OEMs is emphasized, especially regarding road conditions and incidents for mutual benefit.
- **Cooperation on Standardisation**: Standardisation is crucial for data such as weather/road conditions and ODD (Operational Design Domain) standards.
- **Lack of Standards**: There are no clear standards for HD maps and ODD, which limits where AVs can operate. Communication technology standards are also needed.
- **Data Ownership (GDPR)**: The car owner's right to their vehicle data is highlighted. Questions raised about large-scale data collection—who oversees it, and who benefits?
- **Logistics Operators' Responsibilities**: Define the scope of logistic operator responsibility (e.g., parcels, accidents, network connectivity, vehicle condition).

Group 6 – Stakeholders and Responsibilities

- **Shift in Transportation**: Emphasis on reducing private vehicles in favor of increased autonomous transport solutions.
- **Road Development and Maintenance**: Invest in building new roads and adapting existing ones to accommodate AVs (physical and digital infrastructure).
- **Equitable Access**: Ensure infrastructure is accessible to all.
- **Industry-Government Communication**: Establish clear communication between industry stakeholders and the government.
- **Legislation as Infrastructure**: Governments must establish legal frameworks for AV development and deployment.
- **Sustainability Focus**: Prioritize long-term sustainable solutions in infrastructure investment for AVs.
- **Digital Infrastructure**: Enhance digital infrastructure alongside physical roads.

II.5 Question 2: The Role of Government

We asked: How and what should the government do in relation to facilitating infrastructure for automated transport?

Group 1 – The Role of Government

- **Strategic Prioritisation**: Governments should identify critical locations for infrastructure upgrades to support CAVs.
- **Digitalisation and Real-Time Updates**: Modernize existing infrastructure to be digitally integrated, enabling real-time road condition updates.

- **Localized Research**: Governments should support research initiatives tailored to local contexts, addressing specific regional needs.

Group 2 – The Role of Government

- **Learning from Private Sector and Global Leaders**: The government should adopt best practices from businesses and other countries.
- **Focus on Supporting Systems**: Prioritize infrastructure development for vital systems like telecommunications and charging networks.
- **Defining Responsibilities**: Clarify stakeholder responsibilities (telecom, OEMs, road authorities).
- **Society-Centric Approach**: Ensure that private traffic management solutions benefit society as a whole.
- **Strategic Roadmap**: Governments must develop area-specific roadmaps for AV deployment.

Group 3 – The Role of Government

- **Road Markings and Signage**: Ensure markings and signs are optimized for CAV digital readability.
- **Data Quality and Management**: Prioritize the quality of digital traffic data and clarify responsibility for maintaining and updating maps.
- **Cost-Benefit Analysis**: Governments must conduct cost-benefit analyses for CAV-ready infrastructure.

Group 4 – The Role of Government

- **Charging & Fuel Infrastructure**: Prioritize government investment in charging stations along major transportation routes like TEN-T corridors.
- **Risk Mitigation**: Governments should share responsibility for infrastructure investment risks with the private sector.
- **Digital Infrastructure**: Invest in robust digital infrastructure, including V2X technologies and 5G networks.

Group 5 – The Role of Government

- **Cross-Border Standardisation**: Advocate for standardisation across countries, following vehicle type approval models.
- **Vehicle Intelligence**: Intelligence should primarily reside within the vehicle, reducing reliance on infrastructure.
- **Liability and Behavior**: Clarify responsibility for AV behavior, especially in incident scenarios. Avoid focusing on fault-finding.

Group 6 – The Role of Government

- **Public Data and Standards**: Governments should provide a high-quality digital representation of physical infrastructure and develop standards for this data.
- **Digital Traffic Rules**: Create machine-readable descriptions of traffic regulations for easy integration with AV systems.

II.6 Question 3: Next steps

Based on what you just heard about national strategies what important actions is needed in the next 2 to 3 year? We would like you to discuss concrete problems/challenges that needs to be solved.

Group 1 - Next Steps 1

- **Strategy and Funding**: Develop a comprehensive public strategy for CAV deployment, ensuring sufficient funding.
- **Standardisation**: Promote harmonisation of technical standards and regulations internationally.
- **Prepare for Scaled Deployment**: Focus on infrastructure adaptations for large-scale CAV deployment.

Group 2 - Next Steps

- **Testing Framework and Type Approval**: Develop robust frameworks for testing and type approval processes, verifying CAV safety.
- **Industry Roadmap**: Create a roadmap outlining future regulatory directions to align industry development with planned changes.
- **Stakeholder Cooperation**: Foster collaboration between all stakeholders in the CAV ecosystem.

Group 3 - Next Steps

- **Standards and Digital Traffic Data**: Continue harmonizing standards and digital traffic regulations.
- **Nudging Shared AV Models**: Encourage OEMs to develop CAVs as shared services, promoting safety and sustainability benefits.

Group 4 - Next Steps

- **Foundation for AV Integration**: Lay the groundwork for CAV integration and potentially advanced vehicle technologies.
- **Data Handling and Regulation**: Address complexities in data sharing regulations, ensuring responsible and secure data use.

Group 5 - Next Steps

- **Focus on Standards and Legislation**: Prioritize the development of robust standards and update legislation for CAV deployment.
- **Cross-Border Standardisation**: Advocate for standardisation across European countries, following the vehicle type approval model.

Annex III: Workshop on HD maps

A leap towards SAE L4 automated driving features

MODI workshop on HD-maps

Meeting Minutes

25th June 2024

Online meeting

Document Summary Information

Grant Agreement No	101076810	Acronym	MODI
Full Title	A leap towards SAE L4 automated driving features		
Project URL	https://www.modiproject.eu		
Meeting ID	Online, 25062024		
Purpose/Title	MODI workshop on HD-maps		
Venue	Teams		
Document Date	04.07.2024	Version	draft v0.1
Distribution	Meeting participants for review and circulation to all partners		
Minute taker	Trond Storrønning (NMA)		

III.1 Meeting overview

The purpose and goal of the HD map workshop meeting is:

- Purpose
  - Understand the need and role of HD Maps for L4 driving
- Goal
  - Collect requirements from the MODI-project and add to Book of Recommendation

Meeting material is found here: MODI HD-Maps Workshop 1.pptx

https://inlecom.eu.teamwork.com/

25th June 2024		
13:00	Welcome Purpose and Goal Background Input from City of Hamburg on HD Maps	Viktor Johanson (AZ) Henning David (City of Hamburg)
13:30	Workshop intro	Simen Rostad Sæther (SIN)
13:40	Group discussion 1 - Sector perspectives and requirements	ALL
14:05	Plenary summary	
14:15	Group discussion 2 - Providing the data for HD maps	ALL
14:50	Wrap-up & Conclusions	Viktor Johanson (AZ) Simen Rostad Sæther (SIN)

III.2 List of participants

Online participation

	Name	Organisation
1	Viktor Johansson	AZ
2	Lars-Ole Raimond Johnsen (External)	
3	Henrik Lund Pedersen (External)	NMA
4	Guus Arts (Unverified)	DAF
5	Stein-Helge Mundal (External)	NPRA
6	Thor Gunnar Eskedal (External)	NPRA
7	Pascal Hernandez (External)	QFREE
8	Sveinung Himle (External)	NMA
9	Terje Moen (External)	SIN
10	Per Johan Lillestøl (External)	SIN
11	Maria Backlund (External)	LIN
12	Schade, Rando	HAMBURG
13	Claus Lund Andersen (External)	VEJ
14	Vinith Balasingam (External)	NMA
15	Simen Rostad Sæther (External)	SIN
16	Dierke, Jens (External)	BAST
17	Henrik Gillgren	AZ
18	Trond Storrønning (External)	NMA
19	Bo Ekman (External)	VEJ
20	Kjersti Leiren Boag (External)	NPRA
21	Solveig Meland (External)	SIN
22	Sunniva Frislid Meyer (External)	TOI
23	Mads Skovsgaard Rasmussen (External)	DFDS
24	Gjermund Clements Jakobsen (External)	NPRA

25	Petter Arnesen (External)	SIN
26	Runar Søråsen (External)	ITSN
27	Per Einar Pedersli (External)	NPRA
28	Burak Derecik (External)	APM
29	Adityen Sudhakaran	DAF
30	Verhaeg, G.J.A. (Geert) (External)	TNO
31	Petr Pokorny (External)	TOI
32	Helene Correale (External)	CLEPA
33	Thierry Kabos	DAF
34	Joakim Møyholm (External)	NPRA
35	Knut Jetlund (External)	NMA
36	Trond Hovland (External)	ITSN
37	Bjor Grønnevet (External)	NPRA
38	Jan Kristian Jensen (External)	NPRA
39	Hamid (Unverified)	STA
40	Siri Vasshaug (External)	NPRA
41	Wolfgang Hoefs (External)	ERTICO
42	Gunnar Deinboll Jenssen (External)	SIN
43	Polyxeni Fragkiadaki (External)	NMA
44	Tore Abelvik (External)	NMA
45	Anders Vaernholt (External)	RORO
46	Trond Foss (External)	SIN
47	Lubrich, Peter (External)	BAST

III.2.1 Key Outcomes

This section summarises the key outcomes from the discussion across all the groups.

First Group discussion: Sector perspectives and requirements

For the first group discussion we want to give everyone a chance to give their input based on their unique sector/stakeholder perspective and which requirements they believe are needed solved for wider integration of HD maps solutions for L4 driving

We therefore want you to reflect, share and discuss on the following three questions:

1. Where do your organisation as an; OEM, logistics actor, authorities see the role of HD maps?
2. What are your organisation requirements as an; OEM, logistics actor, authorities to use HD maps?
3. What can your organisation/stakeholder provide to the development of HD maps?

Summary from group discussions:

1. **Role of HD Maps:** The groups highlighted diverse roles for HD maps, ranging from supporting autonomous vehicle testing and urban planning (Groups 1, 3) to enabling precise positioning in logistics (Group 2).
2. **Requirements for HD Map Use:** A consistent need for standardisation, high accuracy, and up-to-date information emerged across all groups, regardless of their specific sector. Additionally, concerns about data security and the need for clear business cases were raised (Groups 3, 4).
3. **Stakeholder Contributions:** Groups identified numerous potential contributions to HD map development, including data provision (e.g., base maps, dynamic data, risk assessments), technical expertise (testing, research), and feedback mechanisms between stakeholders (Groups 1, 2, 3, 5). The importance of collaboration between authorities and OEMs was emphasized.

Second Group discussion: Providing the data for HD maps

If we accept the take from the introduction and look at the Figure III-1; is it enough that the authorities stick to the base layer and what does this base layer look like?

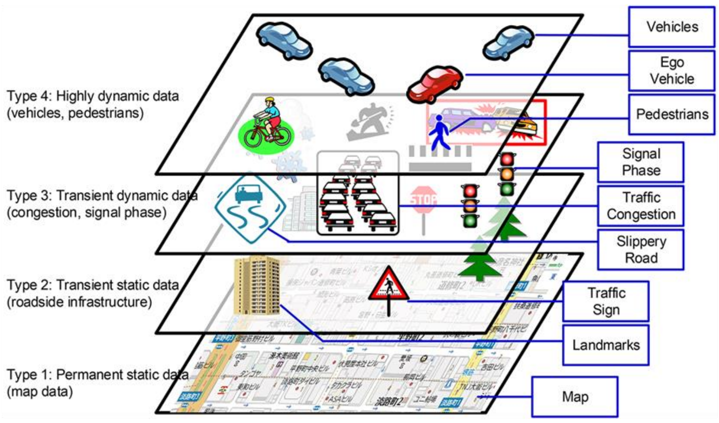


Figure III-1: from Shimada et al., 2015

Please reflect, share and discuss on the following points:

1. Where does the base layer end and what data can the authorities be the trusted source of?
2. What about the map providers? The vehicles themselves?
3. How do we ensure harmonisation?
4. Requirements for; quality? accuracy? “freshness”/“up-to-date-ness”? content?

Bonus discussion point:

- What are the next steps (i.e., in the short term) for the authorities and infrastructure regarding HD maps?

Summary from group discussions

1. **Base Layer and Authority Data:** Groups agreed that authorities should provide the foundational static data for HD maps, including road infrastructure, traffic regulations, and legally binding information. This base layer should be enriched with metadata to ensure reliability and accuracy.
2. **Map Providers and Vehicles:** While authorities manage the base layer, map providers and vehicle sensors can contribute dynamic data, such as real-time traffic conditions. Collaboration and data sharing between these stakeholders are crucial for a comprehensive HD map.
3. **Ensuring Harmonisation:** Standardisation of data formats, architectures, and validation processes emerged as critical for harmonisation. Learning from existing initiatives like ISA were suggested to test and refine these standards.
4. **Data Requirements:** Across all groups, the need for high-quality, accurate, and up-to-date information was emphasized. Data should be trustworthy, certified, and meet the specific requirements of autonomous vehicles and other users.

Bonus discussion point – Next steps for authorities:

- Data standards: Develop and adopt clear data standards for various types of data (e.g., static infrastructure, traffic conditions).
- **Investment in infrastructure: Harmonisation between physical and digital infrastructure** to support the sharing of base layer data to HD maps

III.3 Discussion Notes – Summary

This section outlines what was discussed in each of the groups.

First Group discussion: Sector perspectives and requirements

For the first group discussion we want to give everyone a chance to give their input based on their unique sector/stakeholder perspective and which requirements they believe are needed solved for wider integration of HD maps solutions for L4 driving

We therefore want you to reflect, share and discuss on the following three questions:

1. Where do your organisation as an; OEM, logistics actor, authorities see the role of HD maps?
2. What are your organisation requirements as an; OEM, logistics actor, authorities to use HD maps?
3. What can your organisation/stakeholder provide to the development of HD maps?

Group 1

The participants in Group 1 believe HD maps are crucial for various roles. Q-FREE sees them as essential for testing autonomous vehicle products and emphasizes standardisation. Authorities, such as those in Hamburg, recognize their role in future city planning and compliance, stressing the need for data collection and technical permits. NMA highlights HD maps as vital infrastructure, advocating for collaboration and acknowledging the potential for both open and non-open data. The NPRA and TØI emphasized dynamic data and the need for high-quality maps for accident risk assessment and alternative solutions.

In terms of requirements, Q-FREE and stress standardisation and vehicle data for verification. The City of Hamburg needs HD maps for planning and management, while NMA and NPRA focus on high-accuracy and dynamic data. TØI highlights the necessity of high-quality maps for evaluating risks. For contributions, QFREE can provide testing expertise, Hamburg offers local insights, German federal states contribute data collection mechanisms, NMA provides base mapping data, NPRA supplies dynamic data, and TØI offers risk assessment data.

Group 2

Group 2 recognizes the critical role of HD maps for precise positioning in terminal operations. TNO and APM emphasize the need for high accuracy under cranes and for parking, while the NPRA questions if HD maps alone can meet the 5 cm accuracy requirement, suggesting sensor fusion. They prioritize updatability and availability, with unique maps for each terminal, but raise concerns about data conflicts and standardisation.

TNO focuses on research and technical expertise for HD map development, while APM relies on third parties for specialized technology. The NPRA acknowledges the importance of providing relevant data as an authority and road owner, but points out challenges in determining future data needs and standardisation. The group underscores the necessity of resolution mechanisms for data conflicts and maintaining accurate, updated maps.

Group 3

Group 3 sees a future need for HD maps to provide traffic regulations, with SINTEF stressing the importance of standardisation and high-quality maps with varying accuracy levels. DFDS doesn't currently need HD maps but recognizes their value for OEMs. The NPRA emphasizes accurate and up-to-date data from authorities. Requirements include standardisation, accuracy, and timely updates, with a focus on different levels of accuracy for various applications.

SINTEF highlights the need for authorities to provide essential data for HD map development and explores specific applications. Concerns about security and reliability are raised. The group emphasizes HD maps' importance for traffic information, road conditions, and the need for standardisation, accuracy, and clear business cases.

Group 4

The group acknowledges the high cost of delivering data for HD maps and stress the need to explore societal and business benefits to justify this expense. They raise questions about taxpayer funding and emphasize understanding OEM requirements for accuracy and safety. Noting limited past interest from authorities, they call for greater engagement between authorities and OEMs for data sharing.

Possible solutions include closer collaboration and highlighting public benefits like safety and reduced congestion. Conducting cost-benefit analyses and exploring alternative funding sources are suggested. RA's existing road data is recognized as a valuable base layer for HD maps. The group emphasizes the need for careful consideration of costs, benefits, and requirements for HD map funding and data provision.

Group 5

The discussion in group 5 recognizes the availability of road data and the importance of redundancy in HD maps. TRA highlights authorities' role in providing traffic regulations, while DAF suggests HD maps should encompass high precision and other features. Requirements include authorities taking responsibility for traffic regulations and including undetectable information in HD maps.

Contributions to HD map development emphasize feedback loops between OEMs and authorities, with TRA highlighting L4 driving and OEMs' role in providing feedback. The group stresses the need for clear definitions, consistent data, and various types of maps for different applications. They underscore the importance of collaboration between authorities and OEMs to ensure accuracy and effectiveness.

Second Group discussion: Providing the data for HD maps

If we accept the take from the introduction and look at the Figure III-2; is it enough that the authorities stick to the base layer and what does this base layer look like?

Please reflect, share and discuss on the following points:

1. Where does the base layer end and what data can the authorities be the trusted source of?
2. What about the map providers? The vehicles themselves?
3. How do we ensure harmonisation?
4. Requirements for; quality? accuracy? "freshness" / "up-to-date-ness"? content?

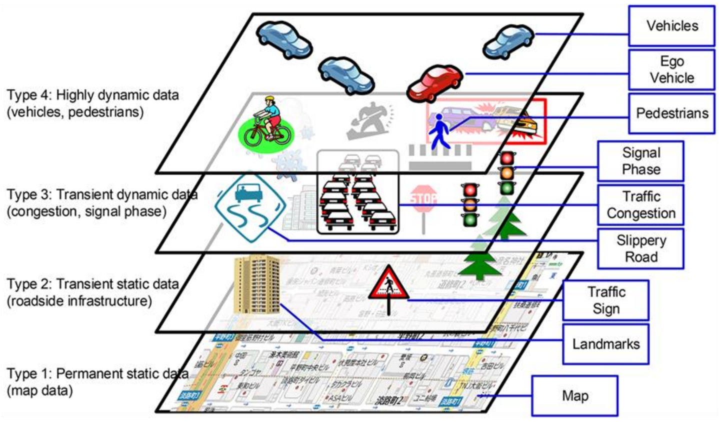


Figure III-2: from Shimada et al., 2015

Bonus discussion point:

- What are the next steps (i.e., in the short term) for the authorities and infrastructure regarding HD maps?

Group 1

Group 1 highlights the importance of collaboration between authorities and OEMs for HD map development. They stress that OEMs should share collected vehicle data with authorities to enhance map quality and efficiency. The base layer should include legally required data, enriched with metadata for reliability, and dynamic data from fleets and private vehicles.

The group also emphasizes clear data quality distinctions and robust validation processes. They propose a subscription model for data sharing, ensuring that contributing entities gain access to more data. Trust and harmonisation are key, with governmental entities providing authoritative base layer data and promoting open data regulations.

Group 2

Group 2 advocates for a collaborative approach where authorities provide static data, like infrastructure and traffic regulations, while vehicle operators contribute dynamic data. Hamburg's model exemplifies this, combining landmark data from authorities with real-time updates from vehicles.

Emphasizing the need for accurate and standardized data. Building trust through consistent, validated data is crucial, learning from successful initiatives like Intelligent Speed Adaptation (ISA). They call for standardized data formats and architectures to ensure reliable HD map development.

Group 3

The discussion focuses on the need for authorities to provide reliable static data, such as speed limits and traffic regulations, while private providers handle dynamic data like travel times and queues. They discuss transitioning from informative to legally binding data, emphasizing the necessity of formal approvals for road works signage.

Questions about the accuracy of data from sources like Google Maps are raised, highlighting the need for trusted sources. Predictive information about road conditions should be included in HD maps, with a balance between data from authorities and vehicles ensuring comprehensive coverage.

Group 4

Group 4 underscores the role of authorities in providing base layer data for HD maps, stressing harmonisation between physical and digital infrastructure. They highlight the importance of trusted, certified data from authorities and address liability concerns. Costs of HD maps are justified if data benefits all drivers, not just autonomous vehicles.

They advocate for standardisation to ensure data quality and accuracy. Collaboration between authorities, map providers, and OEMs is essential to define requirements and build trust. Map makers are keen to contribute but emphasize the need for openness and shared standards for effective HD map development.

Group 5

The group emphasizes that authorities should provide both static and dynamic data, particularly information that onboard sensors cannot detect. OEMs must determine their specific data needs and assess the sufficiency of data provided by authorities. Harmonisation across counties remains a challenge, with lane markings detected better by vehicles than drivers.

The group calls for authorities to identify roads suitable for Level 4 (L4) autonomous operations and focus on a broader audience. Future HD map development should involve data partnerships, ensuring comprehensive data provision beyond just authorities, to meet the needs of all drivers.

Annex IV: Simulation of GNSS Dilution of Precision (DOP) for Automated Mobility along the MODI Road-Corridor using High-Resolution Digital Surface Models

IV.1 Introduction

The accuracy of Global Navigation Satellite Systems (GNSS) is vital for the implementation of Cooperative, Connected, and Automated Mobility (CCAM) solutions, particularly for advanced driver assistance systems and automated vehicles. This study, conducted by Kristian Breili and Carl William Lund, focuses on the simulation of GNSS performance using Dilution of Precision (DOP) analysis along road corridors in Europe, including sections in Norway, Germany, and the Netherlands.

DOP is a critical measure used to evaluate the quality of GNSS positioning by assessing the geometry of satellite constellations. Lower DOP values represent better satellite positioning, resulting in more accurate GNSS readings. The MODI project, which aims to accelerate the deployment of CCAM in Europe, serves as the framework for this analysis. The main goal is to identify areas along major European roadways where GNSS signal performance is poor due to environmental obstructions, such as buildings, trees, and terrain.

IV.2 Methodology

To simulate GNSS DOP, the researchers utilized high-resolution Digital Surface Models (DSMs), which represent the surface elevation, including man-made structures and natural elements like trees. These DSMs were combined with almanac data from several GNSS constellations— BeiDou, Galileo, GLONASS, and GPS—to evaluate satellite visibility and the subsequent DOP values.

The study focused on three European road sections:

1. **Oslo to Svinesund** (Norway),
2. **Hamburg city center** (Germany),
3. **Rotterdam to the Dutch-German border** (Netherlands).

The emphasis was placed on **Horizontal DOP (HDOP)**, as horizontal positioning accuracy is critical for vehicle navigation. Various GNSS constellations were tested alone and in combination to assess how system performance might improve in challenging environments. The combination of multiple constellations offers redundancy and more visible satellites, improving positioning accuracy.

IV.3 Key Findings

1. Overall GNSS Performance The study found that GNSS performance in the three study areas is generally good or excellent, with HDOP values better than 5 at nearly all study points. Even when GPS alone was used, 99-100% of the BeiDou, Galileo, GLONASS, and GPS points achieved a median (calculated over one complete day) HDOP categorised as either "excellent" or "good".

2. Challenges in Urban Environments However, urban areas such as Hamburg city center pose significant challenges to GNSS signal accuracy. Buildings obstruct satellites' signals, leading to higher DOP values for parts of the day. When using GPS alone, as much as 8% of the study points in Hamburg experienced "weak" or "poor" maximum HDOP values. In some locations, GPS availability was lower than 50% of the time.

Despite these issues, the inclusion of multiple GNSS constellations dramatically improved the results. For example, when GPS was combined with BeiDou, Galileo, and GLONASS, system availability exceeded 95% for 99% of the study points in Hamburg, mitigating the effects of signal blockage from tall buildings.

3. Validation and Accuracy To validate the simulation results, GNSS data were collected using a survey vehicle in Hamburg. Initially, the correlation between simulations and real-world data was low, likely due to non-line-of-sight (NLOS) signals, where satellite signals are reflected off buildings rather than directly received. By excluding satellites with weak signal-to-noise ratios, the correlation between simulated and real-world HDOP values improved significantly, demonstrating the robustness of the simulation model in predicting GNSS performance.

IV.4 Impact of Digital Surface Model (DSM) Resolution

The spatial resolution of DSMs plays a crucial role in accurately simulating satellite visibility. The study compared 1-meter and 10-meter resolution DSMs in Hamburg. While the 10-meter DSM offered significant computational efficiency, the 1-meter DSM captured more detailed variations in terrain and obstructions, making it more suitable for high-precision GNSS analysis, particularly in urban environments.

Despite this, the researchers found that the 10-meter DSM provided sufficiently accurate results for identifying major problem areas, though some small details affecting GNSS visibility were lost. For rural areas, the 10-meter DSM was adequate, but in complex urban environments like Hamburg, a higher resolution DSM is recommended for greater accuracy.

IV.5 Advantages of Combining Multiple Constellations

The study highlighted the advantages of combining multiple GNSS constellations. In rural areas, GPS alone often provides sufficient accuracy, but in urban settings where satellite visibility is frequently obstructed, adding constellations like BeiDou, Galileo, and GLONASS greatly improves GNSS performance. For example, in Hamburg, GPS alone provided a mean of eight visible satellites, while combining two constellations increased this number up to 19, significantly lowering the DOP values and improving accuracy.

BeiDou proved especially beneficial in increasing satellite availability, as it consists of more satellites than Galileo or GLONASS. This demonstrates that multi-constellation approaches are key for urban environments, where signal blockage is common.

IV.6 Conclusion

The study successfully demonstrated the utility of simulating GNSS DOP using high-resolution DSMs to assess GNSS performance along major European road corridors. The simulations identified areas where GNSS performance may be limited, particularly in urban environments with obstructed views of satellites.

Combining multiple GNSS constellations significantly improves satellite availability and positioning accuracy, making it a crucial approach for automated mobility and advanced driver assistance systems. In addition, while coarser DSMs offer computational advantages, higher-resolution DSMs are recommended for more precise urban analyses.

Overall, the study provides valuable insights into GNSS performance for automated vehicles, identifying both strengths and potential challenges along the MODI corridor.

Annex V: Geodetic reference frames

V.1 Geodetic reference frames for ITS

A leap towards SAE L4 automated driving features

7th August 2024

V.2 Summary

This document presents a detailed analysis of the challenges associated with geodetic reference frames for the MODI project and ITS applications. Theoretical analyses and practical tests highlight the complexities arising from discrepancies between national and global reference frames, particularly at borders along the MODI corridor. The findings confirm a strong alignment between theoretical predictions and real-world observations, emphasizing the critical need for alignment and harmonization of reference frames.

Key results demonstrate horizontal discrepancies ranging from 0.01 m to 0.024 m, corresponding closely to calculated differences of 0.015 m to 0.017 m in the same regions. These differences, validated through GNSS data collected at the Norwegian-Swedish border, confirm that end-users will experience slight misalignments in navigation systems when crossing borders. This underscores the importance of adopting consistent reference frames and minimizing the complexities of cross-border transformations.

Reliable and user-friendly reference frames are essential for both professionals and non-specialists. However, the complexity of geodetic systems should remain the responsibility of geodetic professionals, ensuring accessibility and reducing the risk of errors for end-users. Simplifying reference frames and minimizing the number of available reference frames and transformations are critical steps in supporting seamless navigation and geospatial data usage across borders.

This document outlines recommendations to address these challenges. These include transforming data to a common reference frame before deployment, standardizing metadata, and ensuring alignment between national and global systems. By implementing these solutions, ITS applications can achieve the consistency, accuracy, and simplicity required for effective cross-border operations.

V.3 Background and Introduction

The MODI use case demands high-accuracy geographic data, including maps and GNSS positions. The project aims to accelerate the introduction of automated vehicles navigating across several countries, each with its own reference frame implementation. This introduces complexities, including the need for multiple transformations at borders and challenges in aligning data from various sources.

Reference frames underpin GNSS satellite systems, supporting navigation, positioning, and mapping globally. Effective handling of geospatial data is critical for ITS, navigation, environmental monitoring, and cadastral systems. Collaboration between geodetic professionals, software developers, and geospatial data managers is essential to ensure reliable, standardized systems.

National reference frames adapt global systems like ETRS89 to local conditions, leading to variations at borders. For ITS, minimizing reference frame transformations and simplifying geospatial data handling for non-specialists is critical. Challenges such as outdated reference frames, unclear usage guidelines, and discrepancies between global systems (e.g., WGS84) and national databases (e.g., EUREF89) must be addressed.

This document aims to:

- Highlight the implications of reference frame discrepancies for ITS.
- Provide theoretical and practical analyses of these challenges and validate what the implications are for the end-user.
- Offer actionable recommendations to improve the usability of geodetic reference frames for ITS.

Readers unfamiliar with concepts introduced in this report are encouraged to consult Chapter 4 of the TEAPOT project report [1], which provides an accessible introduction to the topic of geodetic reference frames.

V.4 Geodetic reference frames for the MODI corridor

Countries in Europe refine the general European reference frame, ETRS89, into more precise national variants to meet specific geodetic needs. While this approach ensures improved accuracy within each country, it introduces inconsistencies at borders. This practice aligns with the INSPIRE Directive, which promotes harmonized geospatial data across Europe but does not eliminate regional variations.

For the MODI project, the driving route crosses multiple borders, spanning from Rotterdam to Moss. Each country's use of distinct national reference frames creates challenges, particularly when transformations between global and national systems are inaccurate or inconsistent. Misaligned transformations can lead to errors in navigation systems and mismatches between maps and positioning data.

Table V-1 summarizes the available transformations from national reference frames to global systems such as ITRF2014/ITRF2020 for the countries along the MODI corridor.

Table V-1: National reference frames on the MODI corridor

Nation	Source ref. frame	Target ref. frame	Accuracy
Germany	ETRS89 (ETRS89/DREF91/2016)	ITRF2014	0.100 m
Netherlands	RD New – Netherlands - Holland - Dutch	ITRF2014	0.102 m
Sweden	SWEREF99 (ETRS89)	ITRF2014	0.010 m
Denmark	ETRS89	ITRF2014	0.020 m
Norway	ETRS89	ITRF2014	0.020 m

Germany and the Netherlands have transformation accuracies listed as 0.100 m and 0.102 m, respectively. This relatively high error margin reflects the fact that national reference frames are not always fully integrated or updated in geodetic transformation frameworks, for example Proj, limiting their precision. Germany's national variant was only recently added to Proj, and the listed accuracies have not yet been adjusted to reflect this update.

In contrast, Sweden, Denmark, and Norway report significantly higher transformation accuracy, with differences around 0.010–0.020 m, largely due to more mature integration of national variants with global systems.

V.5 Theoretical and Practical Analysis of Reference Frames

This section presents the results of theoretical analyses of discrepancies between geodetic reference frames along the MODI corridor. These analyses are validated by practical tests conducted at the Norwegian-Swedish border, utilizing RTK services from both countries to assess and confirm the calculated discrepancies.

V.5.1 Theoretical analysis

The differences between reference frames used in various countries can vary along the border between two countries and depend on the specific border in question. To analyse the discrepancies between the official national reference frames along the MODI corridor, the following theoretical computations were conducted:

Demonstration 1: Analysis of National ITRF2014-ETRS89 Transformations at Common Borders

The objective of this test is to examine the differences in national ITRF2014-ETRS89 transformations at shared border polygons. The following steps were undertaken:

- Retrieval of country borders in Europe from the EuroGlobalMap [14] dataset.
- Transformation of the shared borders using national ITRF2014-ETRS89 transformations available in the Proj framework.
- Identification and analysis of gaps resulting from the transformations along the borders.
- Plotting of error vectors to visualize the discrepancies identified during the gap analysis.

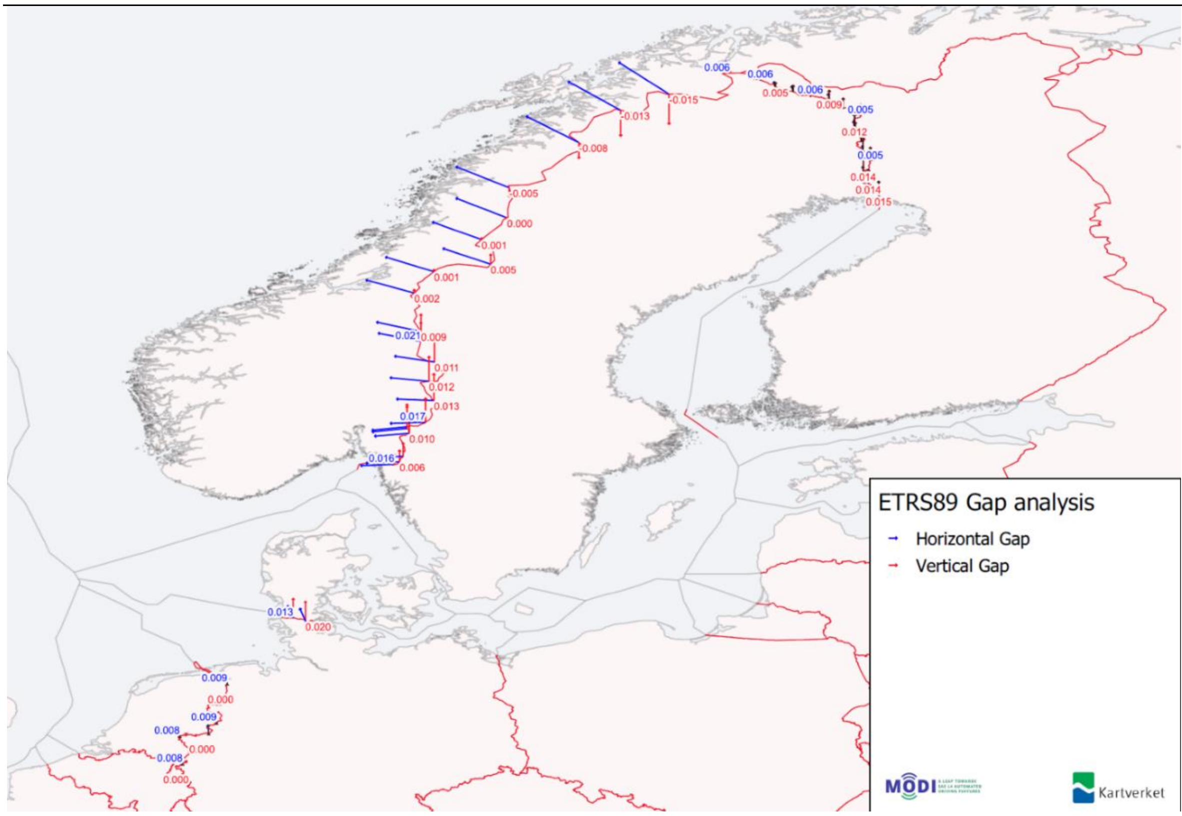


Figure V-1: Differences between national reference frames in the MODI corridor. Blue arrow is horizontal difference while red is vertical difference.

Figure V-1 displays discrepancies in horizontal (blue) and vertical (red) gaps along the borders on the MODI corridor. The long Norwegian-Swedish border shows varying discrepancies due to rotational differences between the Norwegian ETRS89 and the Swedish SWEREF99, which are discussed in more detail later in the second theoretical analysis in this report.

Table V-2: Average differences on the border crossings on the MODI corridor

From	To	Average north diff	Average east diff
NOR	SWE	0,0047 m	0,0198 m
DEN	GER	0,0124 m	0,0054 m
GER	NL	0,0086 m	0,0008 m

Discrepancies along the MODI corridor are generally lower in the southern regions, reflecting the reduced impact of land uplift and tectonic deformation. In contrast, greater discrepancies are observed in the northern parts of the corridor, due to land uplift and local geodynamic variations in Scandinavia. In other parts of Europe, such as Italy, Greece, and Turkey, seismic activity contributes to larger differences in reference frames, highlighting regional variations caused by local geodynamics.

Demonstration 2: Differences Between National ETRS89 Realizations compared to ETRF2000

This demonstration investigated the differences between national ETRS89 realizations and the European reference frame ETRF2000. ETRF2000 is essentially ITRF2014 adjusted for the continental drift of the Eurasian plate but does not account for intraplate deformation, land uplift, or seismic events.

The following steps were conducted:

- Gap analyses were performed for Norway, Sweden, Denmark, and Germany.
- Error vectors resulting from the analyses were plotted to visualize discrepancies.

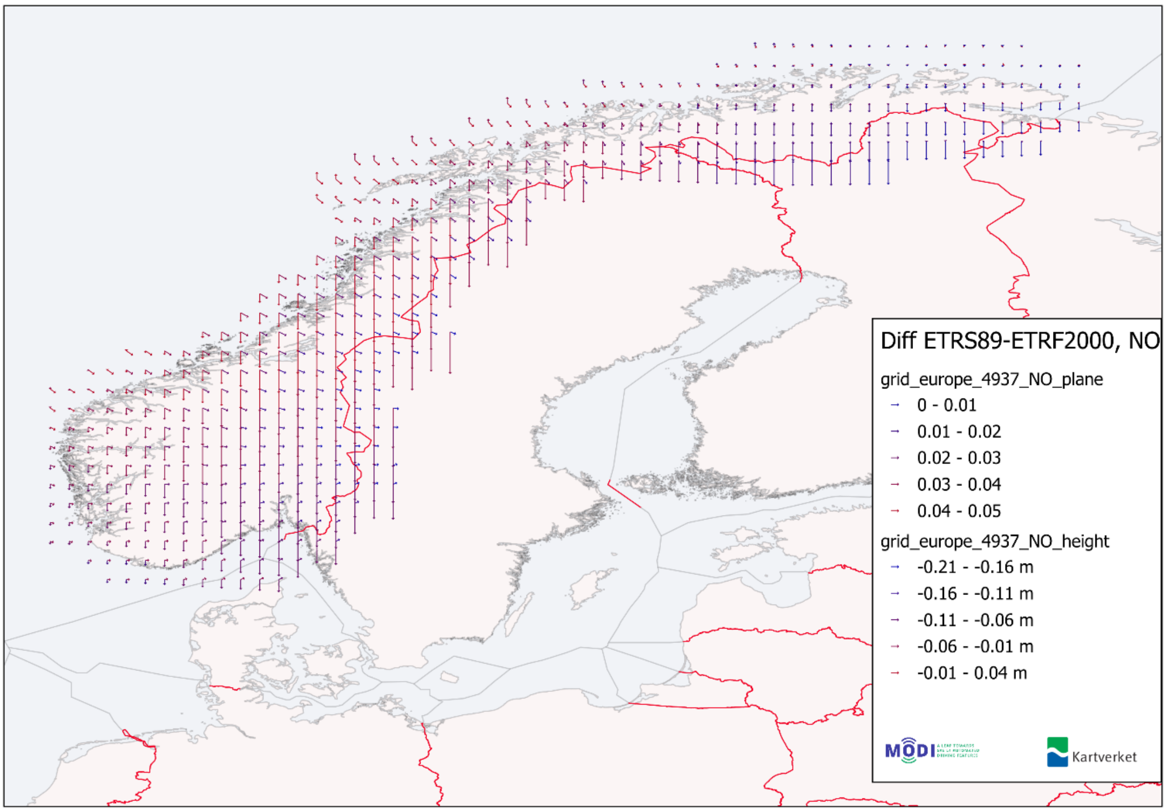


Figure V-2: Difference between Norwegian EUREF89 and ETRF2000.

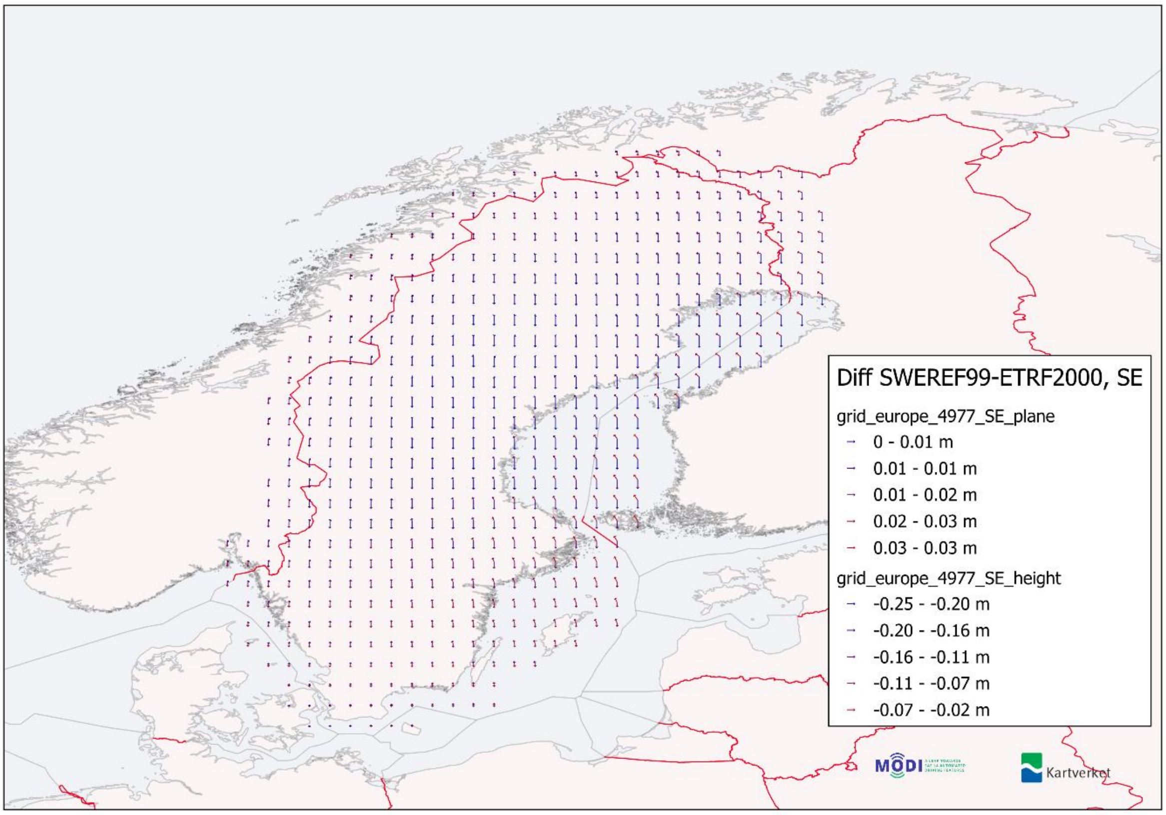


Figure V-3: Difference between Swedish SWEREF99 and ETRF2000.

Figure V-2 illustrates differences between the Norwegian national reference frame (ETRS89) and ETRF2000, while Figure V-3 shows the corresponding differences for the Swedish national reference frame (SWEREF99). The patterns reveal distinct characteristics:

Norway: Figure V-2 indicates more rotation, as indicated by the varying directions of the small arrows. This rotational difference suggests that the Norwegian realization of ETRS89 includes adjustments that diverge more significantly from ETRF2000 in terms of orientation.

Sweden: The arrows in Figure V-3 predominantly point in a uniform direction, reflecting translational differences where shifts occur in the east, north, and height directions with minimal rotation. The magnitude of these shifts is represented by colour intensity.

The differences in Norway show a greater degree of rotation, whereas the Swedish example demonstrates more straightforward translational shifts. Further south along the MODI corridor, the pattern aligns more closely with the Swedish example, showing little rotational difference between national translations and ETRF2000.

Similar patterns of translational differences, as seen in the Swedish example, are observed in Denmark, Germany, and the Netherlands. These patterns indicate that adjustments in these regions involve minimal rotation, focusing more on uniform shifts relative to ETRF2000.

There are two primary reasons for the differences observed between national reference frames:

- Each country refines the general European reference frame ETRS89 by incorporating data from additional GNSS reference stations, allowing for more precise modelling of deformations and tectonic plate movements within their territory. However, these refinements are conducted independently by each country, without harmonization across borders or adjustments for neighbouring countries.

- Variations in the realizations of ETRS89. These differences originate from how each country determines its national realization, including variations in the computational approaches, adjustment models, and the epoch (time of realization). These differences can lead to discrepancies such as rotations or translations between reference frames.

V.5.2 Practical data collection and analysis

A practical demonstration of the theory was conducted through GNSS data collection at the Norway-Sweden border at three different locations:

- Skjeberg - Strømstad, data collected on June 4th 2024
- Ørje - Töckfors, data collected on June 5th 2024
- Magnor - Charlottenberg, data collected on June 6th 2024

GNSS positions were captured using two high-precision NRTK GNSS positioning services:

- CPOS, provided by the Norwegian Mapping Authority, with positions referenced to the Norwegian EUREF89 reference frame.
- SWEPOS, provided by the National Land Survey of Sweden, with positions referenced to the Swedish national reference frame, SWEREF99.

These positioning services are practical implementation of different reference frames and can be used to both demonstrate the practical consequences and verify the theory as described in this document. CPOS and SWEPOS utilize Galileo, GPS, Beidou and GLONASS satellites.

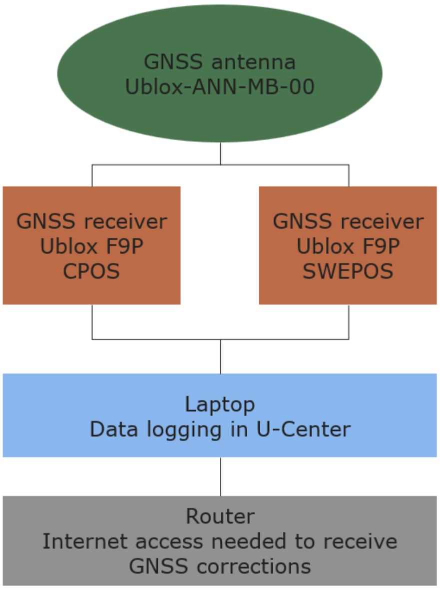
At each location, data was logged twice on both sides of the border, with a time gap between the logging sessions to ensure accuracy and consistency. Equipment used:

- GNSS antenna: Ublox ANN-MB-00
- GNSS receivers: Ublox F9P (one receiver for each positioning service)
- Router: Used to provide internet access for receiving GNSS corrections

The instruments used in the demonstration are illustrated in Figure V-4. All GNSS receivers were of the same model, equipped with the same firmware, and paired with the same GNSS antenna. This uniformity ensures that any differences in computed positions can be attributed solely to the different reference frames used by the positioning services.

All data was logged using U-Center software from Ublox to ensure consistency in data capture and analysis.

Figure V-4: Instruments used in data capture.



The tables V-4, V-5 and V-6 present the differences observed between the positioning services at each location. CPOS and SWEPOS denote the respective positioning services used, while NOR and SWE indicate the side of the border where the data was captured. The abbreviations SVI, CHA, and ORJ correspond to the data capture locations (Skjeberg-Strømstad, Charlottenberg-Magnor, and Ørje-Töckfors, respectively). The final number in each identifier refers to the data capture session. Findings from the theoretical study (ref) at the same location is shown in each table.

Table V-3: Difference between services at Svinesund

From	To	North diff	East diff
CPOS_NOR_SVI_1	SWEPOS_NOR_SVI_1	0.005 m	0.015 m
CPOS_NOR_SVI_2	SWEPOS_NOR_SVI_2	0.002 m	0.012 m
CPOS_SWE_SVI_1	SWEPOS_SWE_SVI_1	0.001 m	0.016 m
CPOS_SWE_SVI_2	SWEPOS_SWE_SVI_2	-0.002 m	0.015 m
Calculated values at Svinesund		0.006 m	0.016 m

Table V-4: Difference between services at Ørje.

From	To	North diff	East diff
CPOS_NOR_ORJ_1	SWEPOS_NOR_ORJ_1	-0.006 m	0.010 m
CPOS_NOR_ORJ_2	SWEPOS_NOR_ORJ_2	-0.004 m	0.013 m
CPOS_SWE_ORJ_1	SWEPOS_SWE_ORJ_1	0.013 m	0.019 m
CPOS_SWE_ORJ_2	SWEPOS_SWE_ORJ_2	0.008 m	0.021 m
Calculated differences at Ørje		0.010 m	0.016 m

Table V-5: Difference between services at Charlottenberg

From	To	North diff	East diff
CPOS_NOR_CHA_1	SWEPOS_NOR_CHA_1	0.014 m	0.024 m
CPOS_NOR_CHA_2	SWEPOS_NOR_CHA_2	0.008 m	0.016 m
CPOS_SWE_CHA_1	SWEPOS_SWE_CHA_1	0.000 m	0.018 m
CPOS_SWE_CHA_2	SWEPOS_SWE_CHA_2	0.001 m	0.019 m
Calculated differences at Charlottenberg		0.013 m	0.017 m

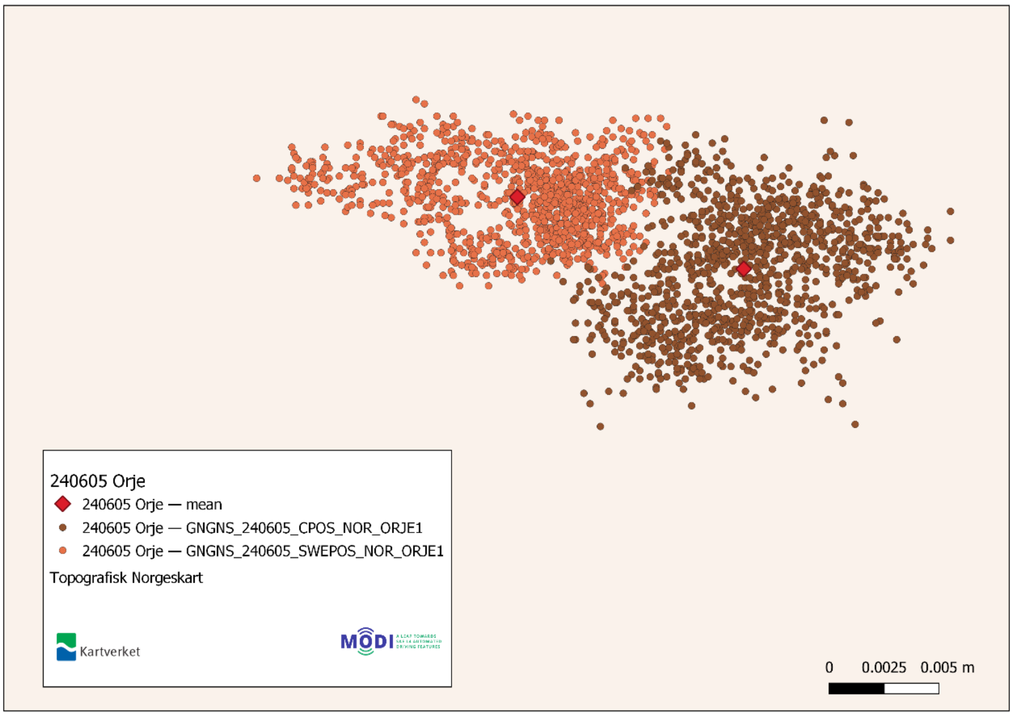


Figure V-4: Scatter plot from practical test

Figure V-4 shows a scatter plot of CPOS, SWEPOS at Ørje, Norway. The red squared dot symbolizes the meamvalue from both services.

V.6 Conclusion

The results from Tables 2–4 and Figure 4 demonstrate that the discrepancies between the Norwegian positioning service CPOS and the Swedish positioning service SWEPOS closely correspond to the calculated differences between the Norwegian ETRS89 and the Swedish SWEREF99 reference frames. Implicating that there is a strong alignment between theoretical calculations and practical observations.

The findings confirm that end-users relying on positioning services will experience discrepancies close to what is shown in Table 1 when crossing borders, resulting in slight misalignments between navigation systems and geographic data.

V.6.1 Discussion

Reliable and user-friendly reference frames are essential for both professionals and non-specialists. However, managing their inherent complexity should remain the responsibility of geodetic professionals and relevant organizations, reducing risks for end-users and ensuring accessibility.

Collaboration among geodetic professionals, geospatial data managers, software developers, and standardization bodies is critical for achieving interoperability. Reference frames and metadata must be properly handled in software and sharing platforms. Simplifying reference frames and minimizing transformations should be a priority to avoid unnecessary complexity. These steps are vital for enabling non-specialists to work effectively with geographic data, maps, and positions sourced from multiple providers.

The responsibility for developing future reference frames rests primarily with public-sector institutions, which play a key role in maintaining the global geodetic infrastructure. These reference frames are foundational for GNSS satellite systems, supporting positioning, navigation, and mapping for critical applications such as transportation, environmental monitoring, defense, and cadastral systems. Simplified, standardized, and updated geodetic frameworks are essential for ensuring reliability and usability across diverse applications.

V.6.2 Recommendations

To address the challenges of reference frames in the MODI project and ITS applications, actionable solutions are required to ensure consistency, accuracy, and simplicity for end-users. By harmonizing data transformations, adopting widely recognized reference frames, and standardizing metadata, the complexities of cross-border operations can be significantly reduced. Below are key recommendations to support the effective use of geodetic reference frames in the MODI corridor and beyond:

Table V-6: Recommendations on how geodetic reference frames should be handled

Recommendation	**Rationale**
Transform all geographic data to a common reference frame before deployment, using an EPSG code to define the reference frame.	Ensures consistent and accurate geographic data alignment across providers.
Perform real-time transformations of GNSS positions during operation to align with the reference frame of geographic data.	Maintains accurate positioning throughout operation, especially when crossing borders.
Use the WGS84 (G2139) reference frame, defined by EPSG code 9755, as the standard for automated vehicles operating across multiple countries.	WGS84 (G2139) is widely recognized, closely related to ITRF2014, and integrates well with EGM08. *NOTE: G2296 was released in Nov 2024, defined by EPSG code 10606*
Adopt the EGM08 geoid model, defined by EPSG code 3855, for height referencing, as it provides sufficient accuracy (5–10 cm) and simplifies data handling.	EGM08 is globally available and simplifies processes by avoiding complex national models while maintaining acceptable accuracy.
Standardize reference frames and metadata, including time stamps, to ensure seamless integration of geospatial data.	Standardized metadata reduces complexity for users and ensures consistency across systems.
Rely on official registries, such as the ISO Geodetic Registry, IOGP's EPSG registry, and OGC standards, for published and continuously updated transformations.	Official registries provide reliable, authoritative data and transformations for use in ITS systems.

V.7 References

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Annex VI: Corridor assessment of physical infrastructure

VI.1 Introduction

The aim of this document is to assess the physical infrastructure along the MODI corridor, with a specific focus on how road authorities from the MODI countries evaluate the road sections they are responsible for. The assessment involved collecting pain points through an online mapping tool. A pain point has been defined as an area or point where the road authorities expect that L4 vehicles may encounter challenges to their ODD, either because of the road itself or the surrounding infrastructure. This work was primarily conducted as a desktop study, utilizing various national data sources for road images and data, including Google Maps and national road databases. In the case of The Netherlands, a dedicated visual inspection was undertaken, while other countries based their insights on ongoing activities and daily operational experiences.

The task was carried out iteratively, with close collaboration between road authorities during a series of meetings. Although the subjective nature of the task may have introduced individual biases, when aggregated, the data highlighted significant patterns and provided valuable insights into how road authorities perceive the current condition of the corridor's infrastructure.

The identified pain points were grouped into seven key categories:

- Markings
- Signage
- Road geometry
- Entrances and exits
- Dynamic signage
- Tunnels
- Bridges, toll stations, ferries and other infrastructure elements

A more comprehensive analysis of the MODI corridor's readiness for Level 4 freight transport will be performed by further examining the collected pain point data alongside results from multiple data collection efforts. Together, these insights will offer a detailed understanding of the corridor's current state and its future infrastructure needs. The full results of this expanded analysis will be documented in later MODI deliverables.

VI.2 Corridor assessment

VI.3 Norway

The selected road in Norway runs from the Swedish border in the south to Alnabru in Oslo. This is a 120 km long highway with several entrances and exits. The corridor assessment assumes an advanced ADS is capable of handling the road conditions.

Markings

Most of the road has good to adequate lane markings. Some sections are worn, which the NPRA presumes could create slight uncertainty for L4 vehicles relying solely on visual input. One curious observation is that acceleration lanes in Norway do not have lane markings all the way, unlike in some other European countries. This may pose a challenge for L4 vehicles, depending on how their ADS algorithms are trained. Another notable fact is that Norway uses yellow dividing lines between driving directions. This should not pose an issue for L4 vehicles.

Signage

The corridor features several variable speed limit signs, mainly LED-based. Due to sampling frequency, these may cause issues for camera-based systems. Currently, there is no digital representation of the content of the variable message signs. Access to a digital representation would mitigate this problem. Additionally, two physical variable signs along the test route have malfunctioned. An ADS might also struggle to differentiate partially covered signs. Aside from these issues, other signs along the corridor are in good condition and are not expected to pose a problem for the ADS.

Road Geometry

The only notable issue is at Ulvenspliten, where there is a downward slope combined with a 270-degree turn and a low-speed segment (30 km/h), indicated by static advisory reduced speed limit signage.

Entrances, Interchanges, and Exits

The challenges with entrances, interchanges, and exits are mostly related to lane markings, as described in the previous section. All entrances and exits in the corridor have adequate acceleration lanes, and there are no interchanges on the Norwegian section from the border to Alnabru. Apart from the lane markings not covering the entire length of acceleration lanes, no significant challenges were observed with entrances, interchanges, or exits.

Dynamic Signage

In addition to the variable speed limit signs, there are several variable message signs that may provide relevant information for automated vehicles.

Tunnels, Bridges, Toll Stations, and Ferries

Tunnels, bridges, toll stations, and ferries are included in the national road database and have therefore not been manually evaluated. However, the variable message signs in tunnels have been manually verified. It has been observed in the MODI project that objects blocking GNSS signals, such as tunnels, may cause issues for L4 vehicles.

Other Infrastructure Elements

There are a few spots along the corridor that may pose challenges. One example is a complex lane change where a public transport lane transitions into an entrance lane. However, these instances are few and far between. These complex infrastructure elements are only located in the right lane and can be avoided if necessary by the ADS. Nevertheless, they are marked as high severity, as complex situations may arise at these locations.

VI.4 Sweden

The Swedish Transport Administration has identified several challenges for autonomous driving along the route, which is E6 starting at Svinesund at the Norwegian border towards the Öresund bridge at the Danish border. The observations refer to road markings, signage, road geometry, intersections, dynamic signage, weather conditions and features like bridges and toll stations.

Generally the road markings are of good quality along E6, but as the traffic is heavy, road markings deteriorate over time and can be of lower quality at some places for some periods before they are repainted again.

The most challenging stretch of the road is when passing Gothenburg where the road geometry and lane markings makes it necessary to change lanes at several places. A specific challenge is exit ramps to the left which is not so common elsewhere. Passing Gothenburg there is also need to read the content on quite a number of variable message signs at MCS-portals along the road. Traffic congestions appears frequently when passing Gothenburg and Malmö. At several locations E6 has short entrance ramps which will be challenging for HVG:s specifically at heavy traffic conditions. One known example is at Helsingborg.

The toll station for the Öresund-bridge is located on the Swedish side and will of course give specific challenges for automated vehicles. E6 in Sweden has only one tunnel and it is under the river when passing Gothenburg. This tunnel has several lanes and lane changes and also heavy traffic. Several high bridges exist, these are often located close to the sea, which means that large vehicles can be affected when strong winds are blowing from the west. Between Halmstad and Helsingborg is the steep ridge "*Hallandsåsen*" situated, where heavy vehicles can have problems if the road is slippery. Dedicated lanes for HVG:s exist there and also emergency staging areas. Generally the weather conditions can be challenging during winter time with heavy snowfall and wind from the west as E6 quite often goes rather close to the sea.

VI.5 Denmark

The Danish Road Directorate has identified several challenges for autonomous driving along the route starting at Rødbyhavn towards the Øresund Tunnel. The observations focus on road markings, signage, dynamic signs, and tunnels.

Key issues include the condition of road markings, which are generally in good shape, though at major interchanges, the use of barrier field markings requires accurate detection by autonomous systems. Signage presents another challenge, with visibility issues at exits and some HGV restrictions, especially near tunnels, potentially confusing autonomous systems. Most signs present light severity challenges, though areas with flashing lights and warnings for tunnel closures pose more significant risks.

Dynamic elements, such as variable message signs and dynamic barriers, provide real-time updates but require precise interpretation under conditions like slippery roads and high winds. These elements, particularly near the Øresund Tunnel, are rated as medium to high severity and demand quick responsiveness from autonomous vehicles. Emergency features like red flashing lights further add complexity near tunnels.

As observations from April to June 2023 indicate, factors like weather variations, traffic conditions, and seasonal impacts on sign readability significantly influence infrastructure interpretation, highlighting the need for robust autonomous vehicle handling capabilities. Looking ahead, ongoing road maintenance and the planned ITS-system enhancement at The Farø Bridges by 2024, coupled with a new tolling scheme for trucks from January 2025, will require additional signage and equipment deployment to support safe autonomous navigation.

VI.6 Germany

The German segment of the Rotterdam-Oslo corridor consist of ca. 460km on the highways A30 and A1 and the European route E47 from Enschede to Puttgarden. The route assessment was conducted as a desktop study based on a national database. Possible challenges along the route include areas without hard shoulders, tight curves, tunnels, bridges, and possible road works. Automated systems must manage these situations with careful adjustments and adaptability ensuring smooth operation across a variety of conditions.

Markings: Markings are consistent with the road types along the route. Cases of faded or worn out markings could present a challenge, especially in roadworks areas and merging/exit areas. Night visibility and adverse weather conditions were not part of the assessment.

Signage: Along the route, many standard signs include additional information in German language, such as time- or weather-specific prerequisites. Those have to be correctly recognised by the vehicle.

Road Geometry: In general the road geometry corresponds to the road class. Sharp curves in interchanges and segments lacking hard shoulders could present a challenge and demand sufficient speed control as well as steering precision.

Entrances, Interchanges, and Exits: Due to the routing of the German part of the MODI corridor with most of the route on the A1, there are few transitions at interchanges expected. Transitions may need to be addressed with measures such as speed control and sufficient headway.

Dynamic Signage: Dynamic signage (VMS) is used on the route to harmonise traffic in traffic jams, as well as for incident management, maintenance and road works. The dynamic signage (eg. variable speed limit, lane closure) must be correctly detected by the vehicle as the content is currently not available digitally.

Tunnels, Bridges, Toll Stations, and Ferries: The route includes bridges and one 250m tunnel (under railway), which could present challenges. There are no toll stations along the route. The German part of the MODI corridor ends with the ferry terminal at Puttgarden, where the vehicle should correctly position itself.

VI.7 The Netherlands

The Dutch segment of the Rotterdam-Oslo corridor, considered in MODI, includes the A15 motorway between Maasvlakte (Port of Rotterdam) and the Valburg interchange, the A50 between Valburg and Apeldoorn, and the A1 between Apeldoorn and the Dutch-German border, connecting to the German A30 motorway. The total length of this route is 245 km (see Figure VI-1). The entire route is designed as a motorway according to the Dutch standards[5], with separate carriageways consisting of two to six lanes in each direction and featuring grade-separated intersections. Below are several features of this route that may be of specific interest for automated driving.

Figure VI-1: The Dutch part of the MODI corridor

Markings

[5] Richtlijnen Ontwerp Autosnelwegen (ROA), https://standaarden.rws.nl/link/standaard/1474

On the A50 between Arnhem and Apeldoorn, in both directions the hard shoulders are used as peak-hour lanes. Due to high traffic volumes, these lanes, with special markings, are open for most of the day. These lanes have very narrow lines on the right-hand side, and drivers using them, must cross several continuous lines, which deviates from standard traffic regulations. This is particularly relevant for heavy vehicles considered in MODI, as they are expected to keep to the right, and therefore, use the peak-hour lane.

Signage

On many standard signs along the route, additional text (in Dutch) has been added to indicate specific conditions under which the signs apply. For example, on the A15, the sign prohibiting heavy vehicles from overtaking is only valid during daytime hours. This additional text may be difficult for automated systems to process. In many places along the route, there are also signs visible that are not intended for traffic on the main carriageway. These include signs meant for exit traffic or, for instance, signs prohibiting entry onto service roads adjacent to the motorway.

Road Geometry

For tight curves, speed limit signs are not usually applied by default. Consequently, there can be situations where the desired speed does not align with the speed limit in effect. For example, at the Valburg cloverleaf interchange on the west-to-east route, there is a tight curve where the appropriate speed is lower than the posted speed limit.

Entrances, Interchanges, and Exits

The MODI route in the Netherlands is complex, featuring multiple interchanges and variations in the number of lanes. Assuming that heavy vehicles remain in the far-right lane, several lane changes will be necessary, particularly south of Rotterdam (where lanes are added and reduced along the route), at the Valburg interchange (change of direction), and near Arnhem (merging motorways), Apeldoorn (change of direction), and Hengelo (merging motorways).

Dynamic Signage

Most of the route is equipped with gantries displaying dynamic signage. The distance between these gantries ranges from approximately 500 to 800 meters. These signs are used for incident management, the protection of traffic at the tail end of traffic jams, and during roadworks. The status of these dynamic signs is centrally available in digital format. In addition to these gantries, there are also some stand-alone dynamic signs.

Tunnels and Bridges

The route includes three tunnels under waterways with special traffic lights, markings and barriers. In the Rotterdam port area, these include the Caland Tunnel and the Botlek Tunnel, and southeast of Rotterdam, the tunnel under the river Noord. Further east, there are several wildlife crossings over the A50 and A1 motorways. The bridges on the route, including the large bridges over the rivers Rhine and IJssel, are all fixed with no special traffic lights or barriers.

VI.8 Corridor Assessment Summary

Table VI-1: Assessment of the Physical Infrastructure on the MODI corridor

	Norway	Sweden	Denmark	Germany	Netherlands
Markings	Good condition overall, but some sections are worn. Acceleration lanes are not marked to the end, as is common in other European countries.	Generally in good condition, normal wear and tear to be expected.	Good condition overall. Interpreting barrier markings at intersections can be challenging.	Generally good, possible sections with worn out markings	Peak-hour lanes (A50; Arnhem-Apeldoorn), with narrow, non-standard markings, complicate lane discipline
Static signage	Signs are in good condition overall.	No specific challenges noted.	Signs with HGV restrictions may confuse CAVs.	Along the route, many standard signs include additional textual information, such as time- or weather-specific prerequisites.	Additional Dutch text on signs (A15, A50)e.g., heavy vehicle overtaking restrictions and signs intended for exits or service roads, could be confusing
Dynamic signage	Frequent VMSs along the E6, but no digital representation of the information is publicly available. LED speed limit signs may cause sampling issues for camera detection systems.Currently, two physical variable signs have malfunctioned.	VMSs around Gothenburg must be accurately interpreted by CAVs.	VMSs near the Øresund Tunnel regulate speed, lane usage and emergency warnings.	Sections with dynamic signage (VMS) present. No digital content available.	Frequent dynamic signage along the A15 and A50, with gantries spaced 500-800 meters apart, provides real-time updates.
Road geometry	No sharp curves or other special challenges on the motorway between Ulvensplitten and Svinesund.	Challenging around Gothenburg due to lane changes and tight geometry.	No challenges identified.	Overall the road geometry corresponds to the road class.	Tight curves at interchanges (e.g. Valburg) lack specific speed limits
Entrances, interchanges, and exits	There are no interchanges on the motorway. No challenges regarding entrances and exits noted.	A specific challenge is the exit ramp to the left in Gothenburg, which are not so common elsewhere. Short entrance lanes, such as those near Helsingborg, might cause problems.	On entry, vehicles on the motorway are obligated to adjust their speed as needed to ensure safe merging with entering traffic.	Very few transitions on the route. Transitions paired with lack of hard shoulders and tight curves in exit/entry ramps might be challenging.	Complex interchanges near Rotterdam, Valburg, Arnhem and Hengelo require frequent lane changes by heavy vehicles. Challenging for lane management and navigation
Tunnels, bridges, toll stations, and ferries	Seven tunnels and several bridges, including the Svinesund Bridge on the E6. No additional challenges were noted for these road sections.	One tunnel runs under the Gothenburg River, with several lanes. Lane changes might be necessary for correct navigation. High bridges near the sea pose wind challenges.	Dynamic barriers near the Øresund Tunnel require real-time decision-making.	Ferry terminal at Puttgarden. Bridges and one tunnel along the route.	Tunnels in Rotterdam (Caland, Botlek, Noord) have special traffic lights and barriers. Wildlife crossings over the A50 and A1 add variability.
Other infrastructure elements	The right lane is used for multiple purposes in urban areas close to Oslo; Signs indicate when the right lane changes from a bus lane to a entry/exit lane.	HGV lanes exist on steep sections. Weather near Hallandsåsen often causes problems for HGVs.	No additional elements noted	No additional elements noted	No additional elements noted

Annex VII: Data Types and Provision of Data for HD Maps

VII.1 Introduction

The development of automated logistics operations relies on accurate and up-to-date data from national authorities. This chapter outlines an initiative by the Norwegian Public Roads Administration (NPRA) that defines key data types crucial for these systems, supported by a discussion on standardisation related to the provision of data for HD Maps. These data types, sourced from public authorities' databases, support the implementation of automated driving systems and can help expand the operational design domain of vehicles (See Chapter 3.2.4 Expanding the Operational Design Domain).

VII.2 Context and Background

As part of the MODI project, road data from five countries along the MODI corridor was collected and analysed using an online mapping tool. This work revealed significant discrepancies in how road data is stored, managed, and shared across the nations involved. Variations in data accuracy, collection methods, update frequency, and documentation practices present ongoing challenges. Standardised information models are needed to formalise how the real world and its properties shall be represented digitally, including vocabularies, geometry representations, location references and other properties. Information from public authorities' data systems should be shared according to the information models and through standardised exchange technologies.

The analysis is this chapter focuses on identifying the data types that public authorities should prioritize for developing the digital infrastructure required to support L4 freight transport on public roads across Europe. Norwegian databases were used as a case study to explore these issues. The primary objective of the case study is to identify the data types essential for supporting the PDI requirements outlined in Section 2.2 Requirements for PDI on Public Roads. The data types discussed are intended to complement vehicle sensors, providing critical information to enable and ensure the safe operation of CAVs.

Annex III MODI Workshop on HD maps presents findings supporting the vital role of data from public authorities and offers insights into the MODI consortium's perspective on roles and responsibilities within the HD map ecosystem. However, this analysis does not explore those roles in detail. Additionally, the quality requirements for each data type are beyond the scope of this work.

In the context of the analysis described in this annex, the term "data type" refers to the content level of data collected from various sources. Each data type may include multiple data points that provide more detailed information, and multiple data types may describe the same object, feature, or service. Since the structure and complexity of data types can vary between standards like DATEX and TN-ITS, the data types have been generalized and harmonized to offer a comprehensive and aligned list, independent of provider or standard.

VII.3 Case study

VII.3.1 Method and Approach

The MODI literature review, semi-structured interviews, and MODI Use Cases identify a wide variety of relevant static and dynamic data types that are highly useful for supporting the operation of an L4 vehicle. Examples of requested data types include traffic regulations, access restrictions, and descriptions of dynamic changes in the road network.

Most of the identified data types can be shared from national databases in accordance with international standards and are available at the National Access Point (NAP). The static data types consist of road-related data from the National Road Database (NVDB) and geospatial information from the Common Map Database (FKB). The dynamic data types are based on relevant publications and classes from the DATEX standard. Currently, Situation publications are distributed from the Traffic Management Central (TMC) in Norway and are available at the NAP. Data types from DATEX publications and TN-ITS have been included in this analysis. A further description of the Norwegian public data infrastructure is provided in Annex VIII in this report.

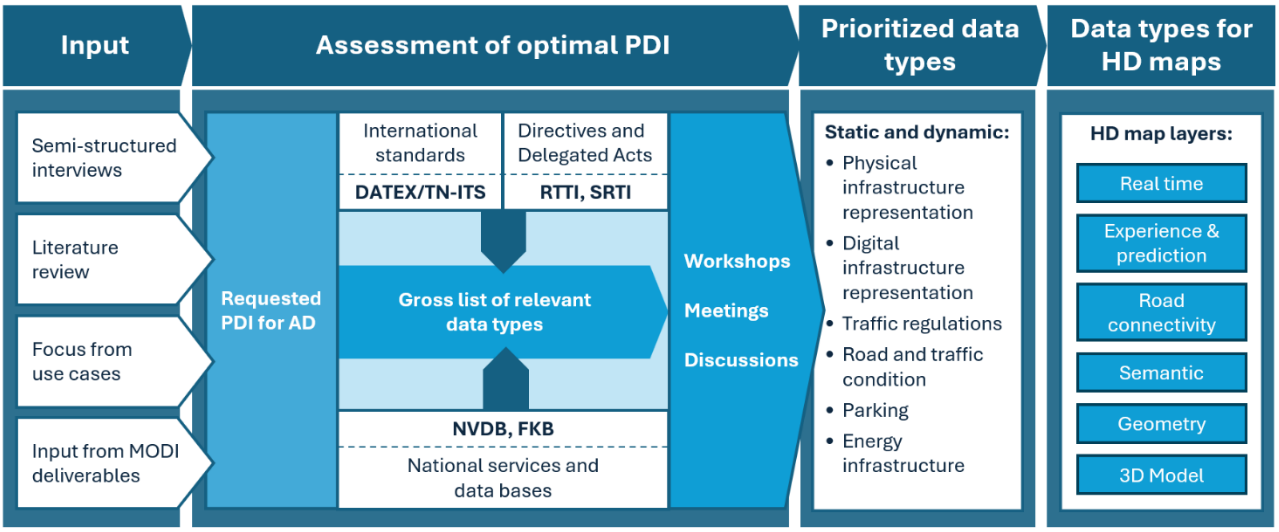

Figure VII-1: Assessment of data types to support optimal PDI (adopted from Annex VII: Data Types for HD Maps)

All four data sources – DATEX, TN-ITS, FKB, and NVDB – are shown in Figure VII-. Directives and delegated acts, such as the ITS Directive, SRTI, and RTTI, provide guidance on how the data types should be prioritized, with a focus on enabling SAE Level 4 on public roads. The analysis has identified more than 700 data type records, and additional records may be added in the future.

The next step in the assessment process was to prioritize each data type to support PDI for automated driving and extend vehicle ODD. The importance and relevance of each data type vary. Some are prerequisites or highly important for automated driving, while others may be relevant in the future. To highlight the most important data types, a prioritisation was conducted through *meetings, workshops, and consultations with experts* based on the following priority criteria:

1. Data types that are prerequisites for driving on SAE L4, according to international and national regulations.
2. Data types that provide relevant and important information to support an SAE L4 vehicle.
3. Data types that may offer useful information to support an SAE L4 vehicle.
4. Data types that may become relevant in the future.

The data types can be static, semi-static, or dynamic, and some static data types may also vary dynamically. Speed limits are one example, where the posted speed limit on a road section is generally static, but it may change during roadworks (semi-dynamic data) or through variable speed limits used to optimize traffic safety and flow (dynamic data). For an SAE L4 vehicle, as for human drivers, the most important information is the currently applicable speed limit at the actual time and location of the transport operation.

All static and dynamic data types can be presented as information in an HD map, providing relevant ODD information for an SAE Level 4 driving task. Elghazaly, Frank et al. (2023) [1] proposed a generic model of HD maps consisting of six layers. The model was adapted for the purpose of this analysis, as listed in Table VII-1. The final part of the assessment process was to verify that all data types could be represented in one or more of these HD map layers.

Table VII-1: Generic model of HD map layers (adapted from Elghazaly, Frank et al. 2023)

Layer	Description	Example data types
Real-time	Real-time updated map information	Location and speed of other vehicles, location and status of traffic signals, and the presence of construction areas or other obstacles and blockages
Experience and prediction	Updates from learned data from experiences enabling predictive behaviour and learning	E.g. data on the status of traffic flow and accident zones for more efficient and predictive driving behaviours
Road Connectivity	Defines how geometric primitives of the geometric layer are connected	Layout and connectivity of roads, including lane borders and centre lines, as well as intersections
Semantic	Information about road features (traffic lights, road signs, pedestrian crossing, POIs)	Speed limits, lane boundaries, intersections, crosswalks, traffic signs, traffic lights, parking spaces, and bus stops
Geometry	High-precision lane-level geometric primitives (points, lines, multi-lines, polygons)	Road width, number of lanes, the centreline of each lane, borders of lanes in each road and the elevation of the road surface
3D Model	The base map layer is the foundation of an HD map and is considered a reference layer on which all other layers are built	Contains a highly accurate 3D geospatial representation of the environment, such as the location and shape of roads, buildings, and other structures. Raw georeferenced data created by sensors like LIDAR and camera

VII.3.2 Results and Discussions

Table VII-2 provides a summary of selected data types, categorized by their priority level and relevance for automated driving. A complete list of all identified data types is available in Annex VIII. These data types can be grouped into five main categories: Physical Infrastructure Representation, Traffic Rules and Regulations, Road and Traffic Conditions, Parking, and Charging Infrastructure. The prioritisation ensures that the most critical data types are given higher precedence, while future-relevant or less critical data types are also acknowledged for long-term development.

Category	Data type	Pri.	Layer
Physical Infrastructure Representation	Road network geometry and topology	1	Road connectivity
	Sign plate	1	Geometry
	Road marking	1	Geometry
Digital Infrastructure Representation	Address / Point of interest	1	Semantic
Traffic regulations	Speed limit	1	Semantic
	Height restrictions	1	Semantic
	Direction of travel	1	Semantic
	Restricted driving manoeuvre	1	Semantic
	No overtaking	1	Semantic
Road and traffic conditions	Weather-related road conditions	1	Real-time
Physical Infrastructure Representation	Pedestrian crossing	2	Semantic
	Tunnel	2	Geometry
	Bridge	2	Geometry
	Light poles	2	Geometry
	Guard rail	2	Geometry
	Curb	2	Geometry
	Hard shoulder width	2	Geometry
Road and traffic conditions	Roadworks	2	Real-time
	Accident	2	Real-time
	Obstruction	2	Real-time
Physical Infrastructure Representation	Acoustic barrier	3	Geometry
Road and traffic conditions	Travel time data	3	Real-time
	Infrastructure damage obstruction	3	Real-time
	Winter maintenance class	3	Semantic
Parking	Parking site / Occupancy	3	Real-time
	Rest area	3	Semantic
Energy infrastructure	Electric charging point status	3	Real-time
Physical Infrastructure Representation	Playground equipment	4	Geometry
	Public transport hub	4	Semantic
Road and traffic conditions	Avalanche point	4	Semantic

Table VII-2: Examples of data types for HD maps

Some data types may consist of both static and dynamic information. **Speed limits** provide a clear example of this, as they can either be posted on static signs or dynamically updated via variable speed limit signs. Information on the location of both static and variable traffic signs within the road network, as well as detailed information on the specific sign content (including the posted speed limit), is available from road authorities' databases. Speed limits will also be represented as linear objects within the HD map, live-updated according to current traffic regulations and the situation on the road. Additionally, vehicle sensors must be capable of detecting and interpreting both static and variable speed limit signs, using this information to determine the applicable speed.

Traffic signs, along with other elements such as **light poles**, **guardrails**, and **curbs**, can also be used by vehicle sensors and software for additional reference positioning within the road network.

Another example of data types with both static and dynamic characteristics is **accident** and **incident information**. Automated vehicles will likely need access to static information such as accident risk or historical data on events like landslides, avalanches, and the winter maintenance level. These types of data can be integrated into the semantic layer of HD maps for use in route planning. However, real-time data on events like accidents, **roadworks**, and **weather-related road conditions** is equally important. This dynamic information is crucial for supporting the vehicle's real-time automated driving tasks and is typically transmitted via digital infrastructure or displayed on roadside Variable Message Signs (VMS).

Tunnels and **bridges** are special road segments that may require specific data types for automated vehicles to operate safely. One significant challenge for tunnels is the lack of GNSS (Global Navigation Satellite System) positioning signals. In these environments, vehicles should rely on alternative systems and sensors. Tunnels and bridges are also often associated with narrow hard shoulders and height restrictions, making it necessary to provide specific data types addressing these features in addition to access restrictions and hard shoulder width.

VII.3.3 Conclusion

The results of this analysis provide clear guidance for advancing digital infrastructure to support L4 vehicles. Considering the high costs of maintaining accurate databases, it is wise to concentrate investments on data types with the highest potential impact for L4 deployment—those offering the most value for the cost. The next steps will involve determining the necessary data quality, update frequency, and maintenance standards for these prioritized data types. According to the research in this deliverable, this approach will directly support efforts to enhance automation levels on public roads. Together with other strategic and operational priorities, it contributes to building a sustainable, safe, and efficient transportation system.

VII.4 Standardisation

VII.4.1 The need for standards

Standards are needed for the full production chain for HD Maps, from data collection and exchange to HD Map production, sharing, updating, and maintenance. Specifications of the content and exchange technologies for HD Maps should be developed and standardised in collaboration between authorities and industry stakeholders. This will help to harmonise the final product across administrative and functional borders. Figure VII- illustrates the ecosystem of standards involved in HD Maps for automated driving.

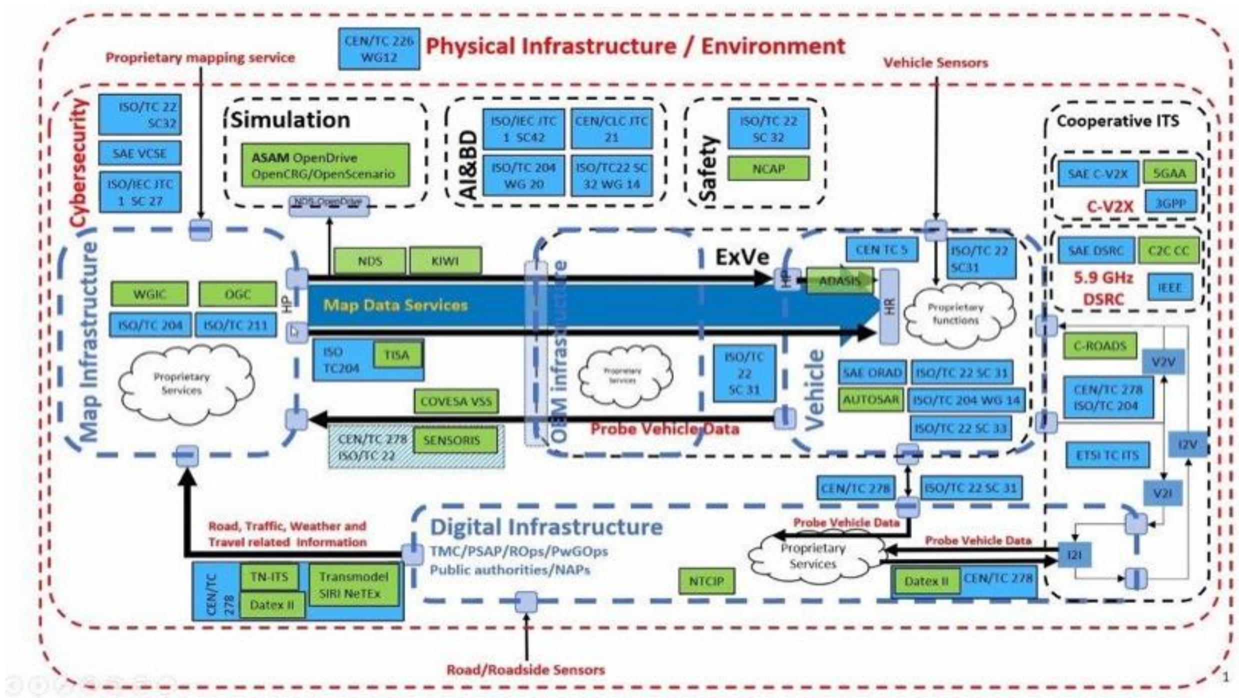

Figure VII-2 The ecosystems of map standards for automated driving. Source: András Csepinszky, ISO/TC 204

VII.4.2 Development of standards

Official standardisation bodies and consortiums at the International, European, and national levels are developing standards related to the production of HD Maps. The most relevant official standardisation bodies concerning HD Maps are:

- The ISO Technical Committee 204 (ISO/TC 204) develops standards for Intelligent Transport Systems, where several are pivotal for HD Maps:
  - The ISO 17572 series defines concepts for location referencing.
  - The ISO 20524 series (Geographic Data Files – GDF) defines a conceptual model for the content of geospatial databases for ITS
  - The ISO 22726 series defines a model for dynamic events and map database specifications for applications of automated driving systems, cooperative ITS, and advanced road/traffic management systems
  - The ISO 21219 TPEG2 series standardises the communication of traffic and travel information
  - The ISO 24315 series will standardise the management of electronic traffic regulation (METR)
- The ISO Technical Committee 211 (ISO/TC 211) develops fundamental standards for describing and sharing Geographic Information, which also lay the fundament for ISO/TC 204 and CEN/TC 278 standards
- ISO/TC 211 and ISO/TC 204 Joint Working Group 11 is developing a new version of GDF based on concepts from ISO/TC 211 standards.

- The CEN Technical Committee 278 (CEN/TC 278) develops European standards for Intelligent Transport Systems, where two standards for sharing information from authorities are essential for HD Maps:
  - The CEN/EN 16157 DATEX II for road and traffic information such as events.
  - CEN/TS 17268 TN-ITS for road attributes such as restrictions for navigation.
  - DATEX II and TN-ITS are now being merged through the European NAPCORE project.
- National standardisation bodies are developing standards that are later brought further to the European and International levels.
  - One example is the British Standards Institution (BSI) and the standard BSI PAS 1883 Taxonomy ODD, which provides a taxonomy that can be used to specify ODDs for automated driving systems.

Several consortiums are developing standards and specifications related to HD Maps. The most prominent consortium in Europe is probably the Open Autodrive Forum (OADF), an umbrella organisation that connects more specifically focused organisations such as:

- ADASIS for standardising data for Advanced Driver Assistance Systems (ADAS), including a standardised data model to represent map data and other georeferenced data ahead of the vehicle (the so-called ADAS horizon).
- The Navigation Data Standard (NDS) Association maintains the NDS.Live standard for map data in automated systems.
- SENSORIS standardises the interface for information exchange from in-vehicle sensors.
- TISA for the TPEG2 traffic and travel information standards, which are put forward to ISO/TC 204 for formal standardisation in the ISO 21219 series.
- TN-ITS for the exchange of spatial road data between authorities and map makers, formalised by CEN/TC 278 as CEN/TS 17268 and pointed out as one of the standards used for the RTTI delegated regulation.

Other prominent consortiums besides OADF are:

- DATEX II develops the DATEX II Standards for road and traffic information, which are put forward to CEN/TC 278 for formal standardisation in the CEN 16157 series and pointed out as one of the standards used for the RTTI delegated regulation.
- The Association for Standardization of Automation and Measuring Systems (ASAM) maintains the OpenDRIVE specification for describing road networks, particularly for use in simulation.
- Overture Maps standardises schemas for open geospatial data, where Transportation is one of the themes that may support the need for data on the infrastructure and restrictions for navigation.

VII.4.3 Legislative fundament

In the legislative area, EU Regulations mandate the sharing of data according to standards. Some relevant legislations related to HD Maps are listed below:

- The INSPIRE Directive 2007/2/EC mandates authorities to share spatial data, including Road Transport Networks with properties, according to specific information models and services.

- The ITS Directive 2010/40/EU and its amendment 2023/2661 establish a framework for deploying Intelligent Transport Systems (ITS) across Europe, with delegated regulations to ensure standardized data sharing. These include:
    - Real-Time Traffic Information (RTTI) – on the provision of EU-wide real-time traffic information services (Delegated Regulation 2015/962).
    - Minimum Universal Traffic Information Services (SRTI) – on the provision, where possible, of road safety-related minimum universal traffic information free of charge to users (Delegated Regulation 886/2013).
    - Multimodal Travel Information Services (MMTIS) – on EU-wide multimodal travel information services (Delegated Regulation 1926/2017).
    - Safe and Secure Parking Information – Information services for safe and secure parking. (Delegated Regulation 885/2013).
- The Open Data Directive 2019/1024 mandates authorities to share high-value datasets, including general geospatial data and mobility data.

Besides the European legislations, the Roling plan for ICT Standardisation is a vital part of the standardisation landscape related to HD Maps. The part on ITS, CCAM and Electromobility requests several standardisation actions, including:

- Action 1.2: Revise DATEX II standards to support a wider range and approaches to publishing data.
- Action 10: Develop standards/specifications to steer and manage the exchange of accurate (public) road data in navigation-oriented maps and of the timely integration of such updates in ITS digital maps for navigation and more advanced in-vehicle applications, including ITS applications for CCAM services and automated driving support, and for non-vehicle ITS applications.

Annex VIII: Public data infrastructure in Norway

A leap towards SAE L4 automated driving features

The Norwegian Public Data Infrastructure

29th Mar 2023

Table of Contents

VIII.1 Introduction

In MODI, identifying physical and digital infrastructure (PDI) needs, is an important task. Both from a general L4 perspective and for developing and conducting the MODI demonstrators. In this project note we focus on available data sources from the authorities in Norway, in particular for the Norwegian use case, E6 Svinesund – Oslo, including Patterød junction to the Port of Moss.

Existing data could be valuable digital infrastructure for the future of automated vehicles, but they need to be available, accurate and reliable. In addition, support from the infrastructure could provide redundancy for the in-vehicle sensors, extending the ODD (operational design domains) of the vehicles. For this to happen, there needs to be dialogue and collaboration between authorities, data providers, and vehicle industry on what is needed and the requirements. In MODI, this is a topic in several other tasks, in addition to UC Norway, including task 4.2 and the CCAM corridor use-case. This note is from the Norwegian authorities (The Norwegian Public Roads Administration, Viken County Council and The Norwegian Mapping Authority) perspective input to these discussions, providing an easy-to-read overview and guidance on how to access the available data sets.

The data described here can have multiple usage, including planning of demonstration, simulation of scenarios, and analysis of gaps that needs to be closed for future implementations, both the availability of data, data collection processes, meta data descriptions and attribute inclusions. In

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Co-funded by the European Union

essence this note aims to describe what is available now, including a section describing available measuring vehicles that can be utilized for a more targeted data collections within the MODI-project.

VIII.2 Static Data

VIII.2.1 NVDB – National Road Database

National Road Database is a database that contains information about national and county roads, municipal roads, private roads, and forest roads. The database is actively used in Norway's road management and contains the following information:

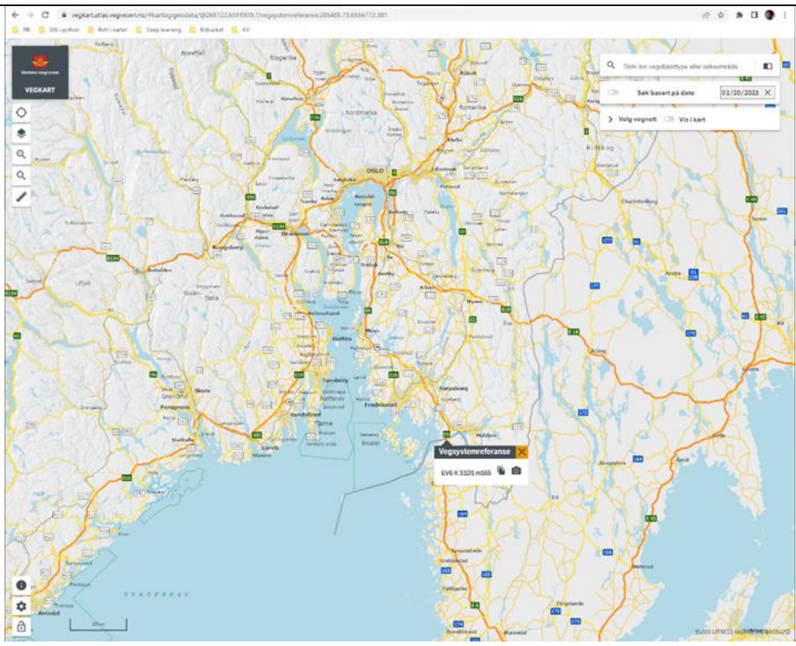
- Road network with geometry and topology that forms the basis for online mapping solutions and route planners.
- Overview of equipment and drainage along the road.
- Accidents and traffic volumes.
- Basic data for use in noise calculation and traffic modelling.

The API is based on REST and can be used to retrieve most of the basic data in the National Road Database (NVDB). The data is delivered in XML or JSON format. As the NVDB API Read is open under the Norwegian license for public data, it does not require a user account. However, you need a user account with write access to register and modify data in the NVDB.

Examples of content in the NVDB include signs, culverts, lighting points, manholes, guardrails, landslides, rest areas, tunnels, ferry terminals, and traffic accidents.

Currently, there are more than 16 million objects available for retrieval, divided into over 400 object types. All object types in the NVDB are described through a separate data catalogue. Note that it is the object types' ID, not their name, that is used in queries against the API. Most of the data is associated with the European, national, and county roads. A few object types are registered on other roads, such as speed limit. All object types have a coordinate for display on the map.

The information is also available on vegkart, the Norwegian Public Roads Administration's map application for presenting data from the NVDB.



Road and traffic data, road closures and weather condition are supported in DATEX II format, which may be useful for the trucks. REST based API's can be used to connect to NVDB, for more information visit: Dataut. More detailed information about NVDB, NVDB API, and related datasets can be found at NVDB atlast, which is in Norwegian.

API documentation for NVDB:

NVDB-API

Pypi module for working with NVDB api-v3 and a github page for documentation:

Pypi – Module – Python

Github - Documentation & example code

The following is an example of how to extract speed limits *(geometry included)* on European roads for all municipalities between Svinesund and Moss.

```
# Create a variable for speed limits data with Fagdata ID 105
# The object catalog for Fagdata 105 can be found here: https://labs.vegdata.no/nvdb-datakatalog/
fart = nvdbapiv3.nvdbFagdata(105)

# Filter the data to include only the following municipalities: Halden, Sarpsborg, Fredrikstad, Råde, Moss
fart.filter({
    'kommune' : [3001, 3003, 3004, 3017, 3002]
})

# Further filter the data to include only European routes
fart.filter({
    'vegsystemreferanse' : 'E'
})
```

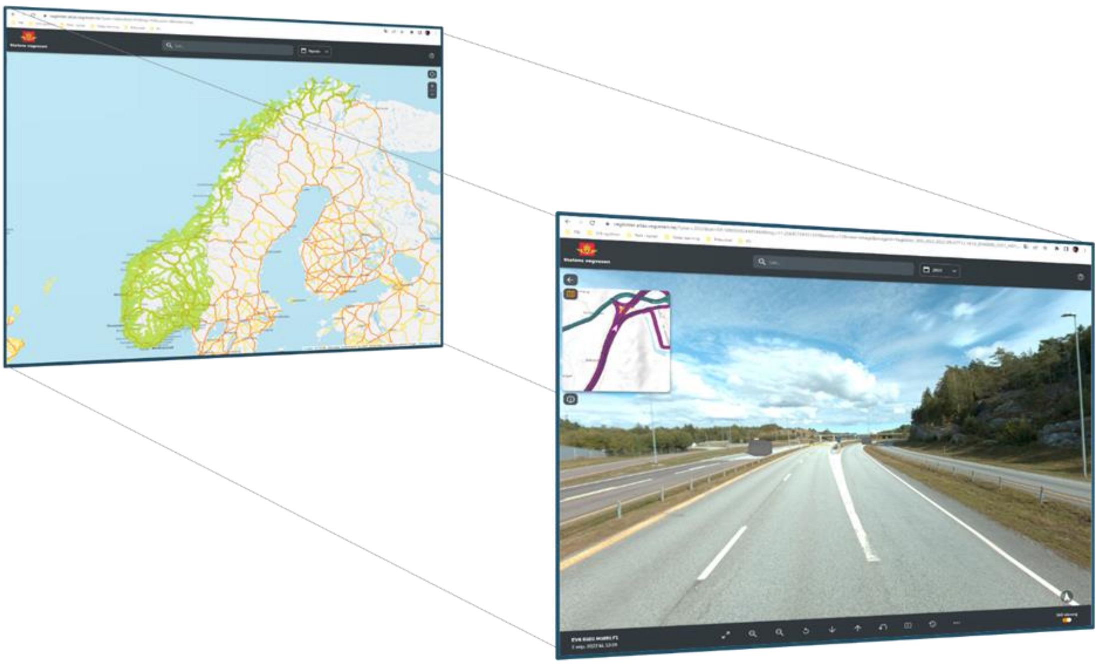
Contact who can provide further information and assistance:

Vinith Balasingam, Vinith.Balasingam@kartverket.no

VIII.2.2 Vegbilder – Road Images

Vegbilder is a web-based application developed and maintained by The Norwegian Public Roads Administration (NPRA) for displaying images of the Norwegian road network. The purpose of this application is to provide a visual representation of the road network in Norway to the public. The data presented in the application may contain errors.

Vegbilder allows users to view images of the Norwegian road network, which are taken on a yearly basis and continuously made available in the application. The user can click on the map to initiate a search for the most recent image taken at the selected point. If an image is found, a preview of the image is displayed. In cases where no images are found within 300 meters of the selected point, the map will zoom in to make the selection process easier. Additionally, at most locations on the European road, there is an option to turn on 360-degree view for a given location.



The search bar in Vegbilder can be used to look for specific location names or road references. Users can also select a specific year to narrow their search. The year selector can also be used to look for images from other years in a selected image point. NPRA is working on an API solution to make it easier for people to get road images from Vegbilder.

Contact who can provide further information and assistance:

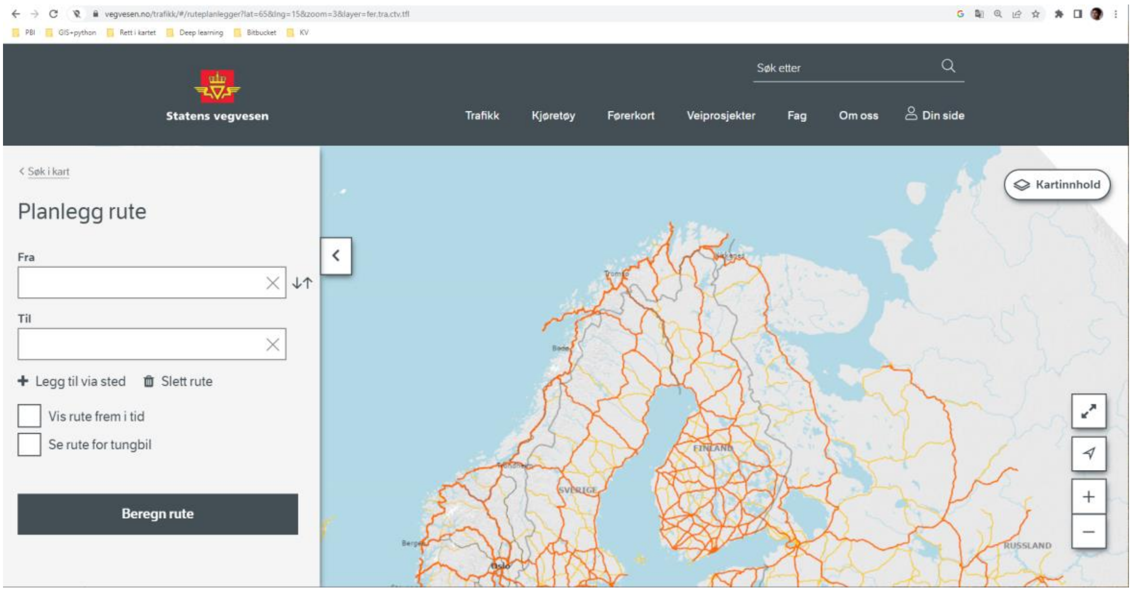
Doreen Siebert, doreen.siebert@vegvesen.no

VIII.2.3 Route planning for cars

Navigable road network from NVDB, and API that provides travel routes between two points with detours.

The routing service for driving calculates up to three different travel routes between two points. You can also define up to eight detour points. The service is intended for developers who want to use the route calculator in their web or mobile applications. The service is a REST-inspired API and should be sufficiently well-documented to be used if you have sufficient programming knowledge.

A web-solution for route planning:



Data is available in open formats such as XML and JSON. Coordinates are delivered by default in the proprietary but publicly available ESRI compact geometry standard, but with the geometry format parameter, more conventional formats such as GML and ISO can also be chosen. Add z (GMLZ, ISOZ) to include altitude coordinates in the route proposals' geometry.

To use the service, you need to get in touch with the NPRA (ruteplan@vegvesen.no) and request the creation of a username and password. The URL for accessing the service is: https://www.vegvesen.no/ws/no/vegvesen/ruteplan/routingservice_v2_0/routingservice/

Documentation for the route planner is available here:

https://labs.vegdata.no/ruteplandoc/

Contact who can provide further information and assistance:

Jan Kristian Jensen, jan.kristian.jensen@vegvesen.no

VIII.2.4 Høydedata – Elevation Data

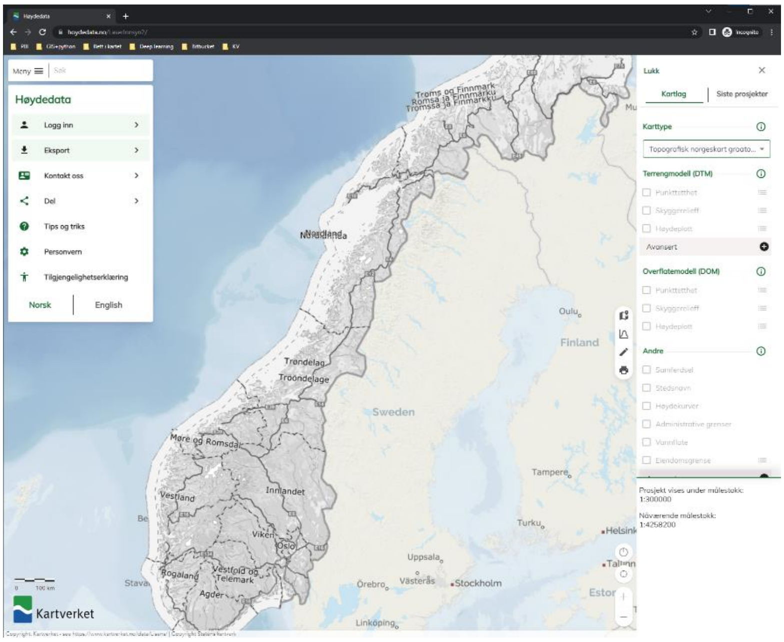
All height data is accessible at høydedata.no. It was collected through the National Detailed Height Model project, which started in 2016 and was completed in 2022. The project has now ended, and the result is a comprehensive height model for the entire country with one-meter resolution. In addition to the laser data collected through the project, høydedata.no also contains data from other Norge digitalt partners. Norge digitalt is a partnership between all public entities with responsibility for geodata or who are major users of such data.

Terrain data can be downloaded in the following formats:

- Original point clouds in LAZ or ZLAS format
- Terrain models (DTM) in grid format (Geotiff)
- Surface models (DOM) in grid format (Geotiff)
- Depth data can be downloaded in ENH (East North Height), NED (North East Depth), and XYZ formats.

The maps are also available as APIs: WCS, WFS, and WMS. We also have REST services for machine-based data downloads and metadata searches from høydedata.no. An overview of all APIs can be found here: https://www.geonorge.no/verktoy/APIer-og-grensesnitt/

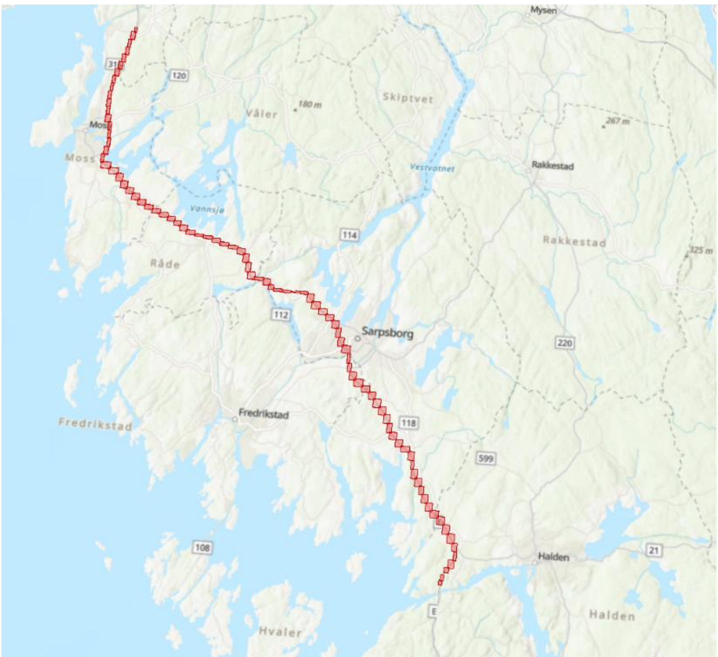
URL link to høydedata: https://hoydedata.no/LaserInnsyn2/



VIII.2.5 Point clouds relevant for UC Norway:

E6, Svinesund – Moss

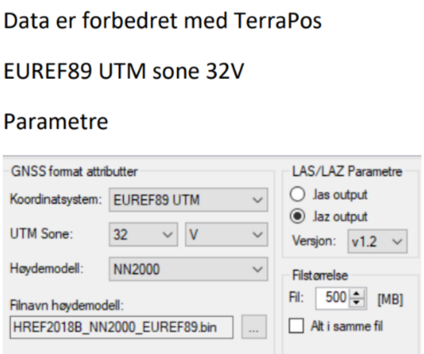
The point cloud for the stretch Svinesund-Moss is collected by The Norwegian Public Roads Administration. These points were gathered on 25.08.2022 using a mobile mapping scanner. Images were taken while the vehicle was scanning the road, providing a model of the terrain with images and point clouds. The figure below provides a visual representation of the mapped route.



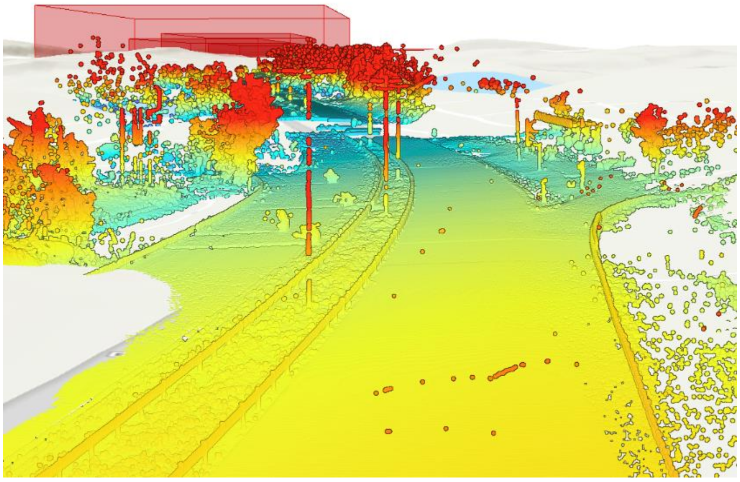
The following features are available from the point cloud:

> *[X, Y, Z, intensity, return number, number of returns, scan direction flag, edge of flight line, classification, synthetic, keypoint, withheld scan angle rank, user data, point source id, gps time]*

Parameters from the scan:



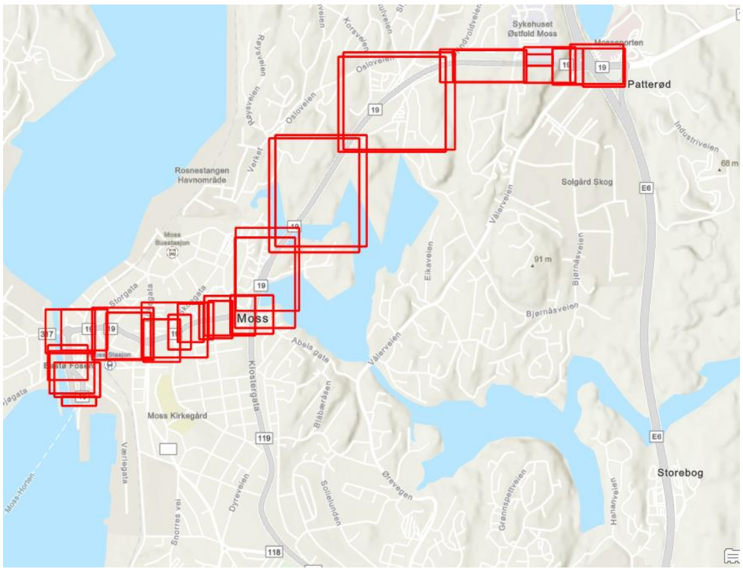
Visualisation example:



RV19, Patterødkrysset – Port of Moss

The point cloud for the stretch Patterødkrysset – Port of Moss is collected by The Norwegian Public Roads Administration. These points were gathered on 26.08.2022 using a mobile mapping scanner. Both images and point clouds were collected simultaneously.

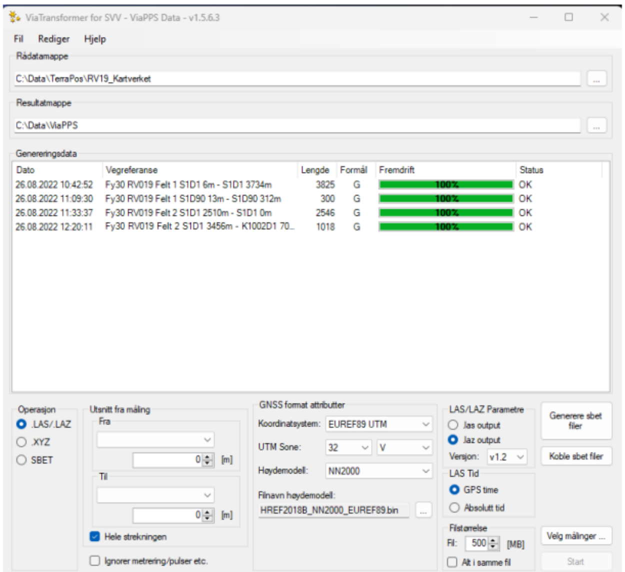
These areas show the coverage of overlapping point cloud collection on RV19:



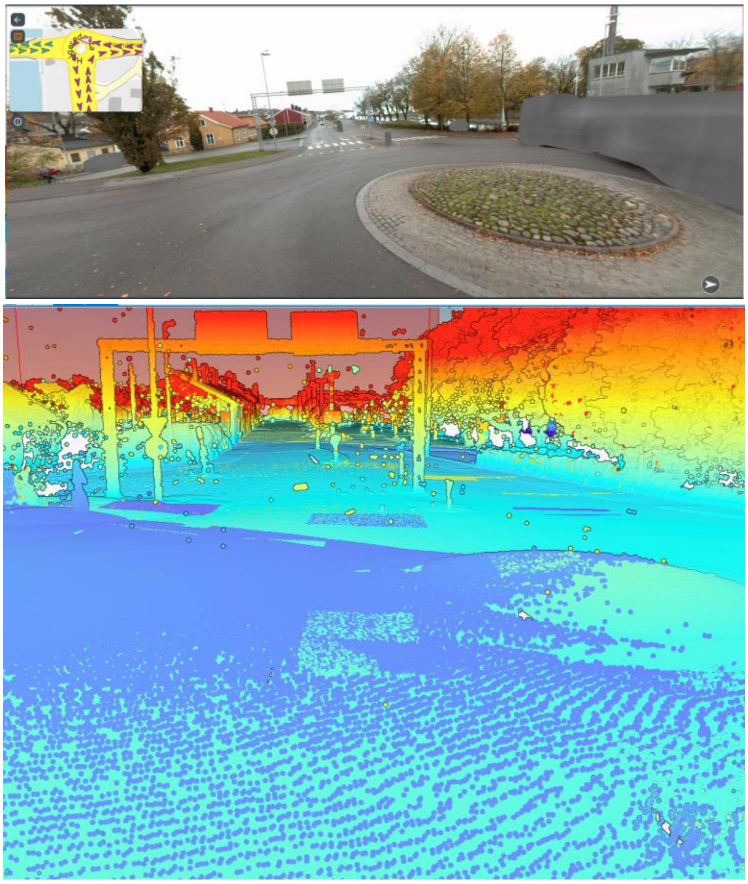
The following features are available from the point cloud:

> *[X, Y, Z, intensity, return number, number of returns, scan direction flag, edge of flight line, classification, synthetic, keypoint, withheld scan angle rank, user data, point source id, gps time]*

Parameters:



Visualisation example (Road images and Lidar point clouds):



Contact who can provide further information and assistance:

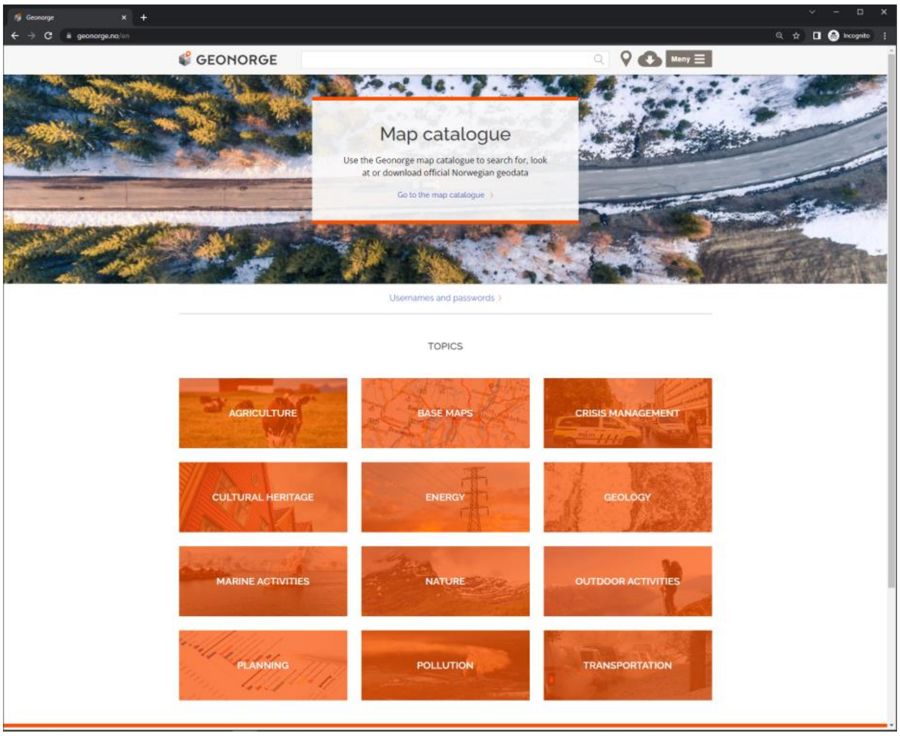
Jon Moe, Jon.Moe@kartverket.no

VIII.2.6 Geonorge – Geospatial Data Portal

Geonorge is the national website for map data and other geospatial information in Norway. Users of map data can search and access available information.

Geonorge is a part of Norge digitalt, a collaboration between public entities responsible for establishing and managing map data and other geospatial information. Geonorge is developed and maintained by The Norwegian Mapping Authorities on behalf of the partners in the Norge digitalt collaboration. Geonorge has numerous kinds of data and information sources. These can be accessed through APIs. Software developers can use APIs for direct access to data sources, and to make applications more functional and user-friendly.

URL to Geonorge: https://www.geonorge.no/en



These APIs are a collection of rules on how to execute requests relating to data and information sources, and they describe how different requests may give responses with different data selection variants. APIs can usually be linked, making it possible to join data requests and ensure richer use of the information and data available in the Norwegian spatial data infrastructure.

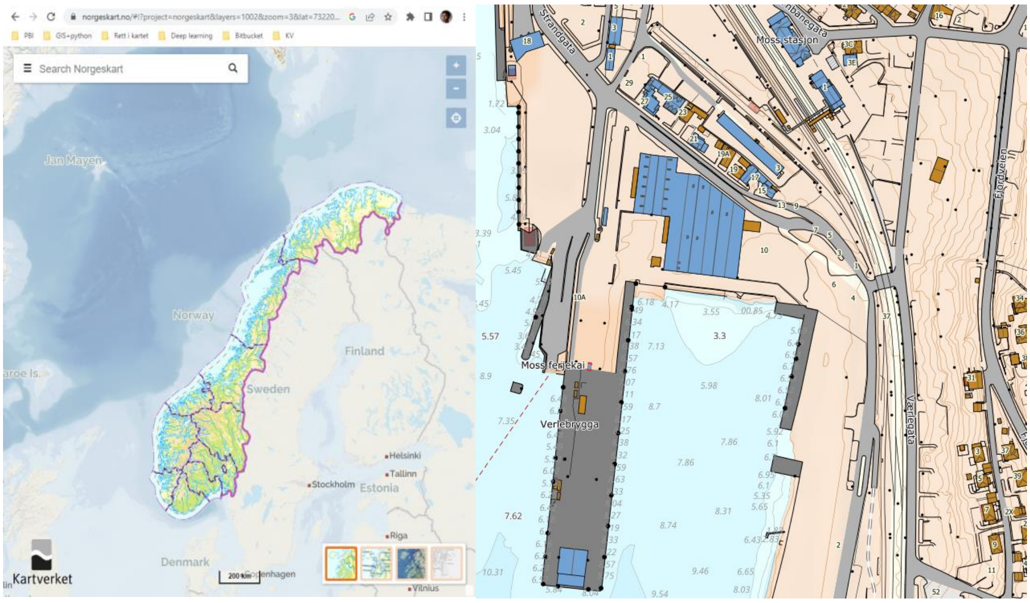
The following Geonorge APIs are available:

- APIs for the Norwegian metadata catalogue
- APIs for the Norwegian Feature Catalogue
- APIs for the Geonorge/Norwegian NSDI registers – registry services
- API for the Geonorge/Norwegian NSDI service validation and status function
- Norwegian Geoportal Atom Feed
- Norwegian Geoportal metadata service – CSW (catalogue service web)
- Norwegian Geoportal metadata API – rest
- ID references and linked data
- Norwegian Geoportal download API

VIII.2.7 FKB – Common Map Database

The Common Map Database (FKB) is a collection of data sets with some of the most detailed and accurate geospatial information about the country's terrain, buildings, and infrastructure. FKB data is managed by the Norwegian Mapping Authority (Kartverket) and is widely used by various public and private organisations for mapping, planning, and analysis purposes. The FKB data includes both vector and raster data and is updated frequently to ensure that the information is up-to-date and reliable. The data is largely constructed based on periodic aerial photography and continuously updated.

The Norwegian Mapping Authorities has developed a web-map solution to visualize FKB data. Link to the web mapping solution, Norges kart. FKB data for Port of Moss as an example:



FKB data is adapted for use at scales of 1:500 to 1:30,000. The FKB database is classified into four standards, namely FKB-A, FKB-B, FKB-C, and FKB-D. The different standards of the FKB database address varying degrees of map detail, with FKB-A containing the most comprehensive and in-depth information, followed by FKB-B, FKB-C, and finally FKB-D. FKB data can be downloaded for a fee and is available through Geonorge.no. NMA can provide FKB data free of charge for the MODI project.

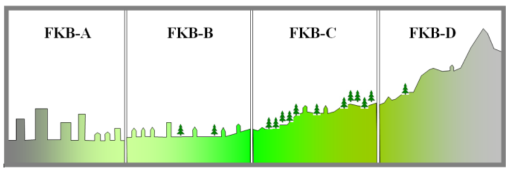


Figure 0-I: The different Standards of FKB data

Contact who can provide further information and assistance:

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VIII.3 Dynamic Data

VIII.3.1 DATEX II

The Norwegian Public Roads Administration (NPRA) offers weather data, travel times, camera images and traffic information via DATEX II.

Traffic information (DATEX-format) - Dataset - Dataportalen (vegvesen.no)

The Norwegian Public Roads Administration offers real-time weather data, travel times, camera images, and road messages containing information on incidents, roadworks, and driving conditions via DATEX II version 2.3 and 3.1. DATEX (specification for DATa EXchange between traffic and travel information centres) is a European standard for exchanging traffic information between different actors and is based on XML messages.

Access to DATEX is provided at this page: Request DATEX NPRA

VIII.3.2 Weather data

This publication contains meteorological measurements from weather stations along national and county roads. We update it every 10 minutes. The road weather data publication publishes updated information every 10 minutes.

The publication consists of meteorological measurement values from weather stations located along the national and county road network. All weather stations have a connected web camera that shows a regularly updated still image, possibly video. The weather data publication is updated every 10 minutes.

You must order access to the Norwegian Road Administration's DATEX node before you can connect to the publication.

VIII.3.3 Webcams

The webcam publication transmits updated images from roadside cameras. These provide an impression of traffic flow, weather and road surface conditions.

The Norwegian Public Roads Administration has deployed a number of webcams along the road network. They are mostly located in places with challenging weather, at ferry quays, mountain passes and in urban areas with heavy traffic.

The images from the cameras are updated with varying frequency. This has to do with the type of camera and how communication with the cameras is set up. Some cameras are set up to alternate between different directions and lanes. This means that they can change image details between updates

VIII.3.4 Travel times

This publication contains travel times in seconds between two measurement points. We update travel time for all road sections every five minutes.

The publication contains travel times for

the main road network around Oslo, Bergen, Stavanger, Kristiansand and Trondheim

- E18 from Oslo to Aust-Agder
- E6 from Ås to Kolomoen
- E8 from Skibotn to the Finnish border

VIII.3.5 Road traffic information

This publication shows information about situations on or along roads that may cause delays or increased risk of accidents in traffic.

Roadworks, temporary traffic control measures such as closures, traffic accidents, storms, slides and floods are among the things that may affect traffic flow. Information we receive about such issues is continuously published as traffic messages in the DATEX II format.

Relevant pages about DATEX from NPRA:

- What is DATEX? | Statens vegvesen
- How to use DATEX | Statens vegvesen
- DATEX publications | Statens vegvesen
- Information and news | Statens vegvesen

Contact who can provide further information and assistance:

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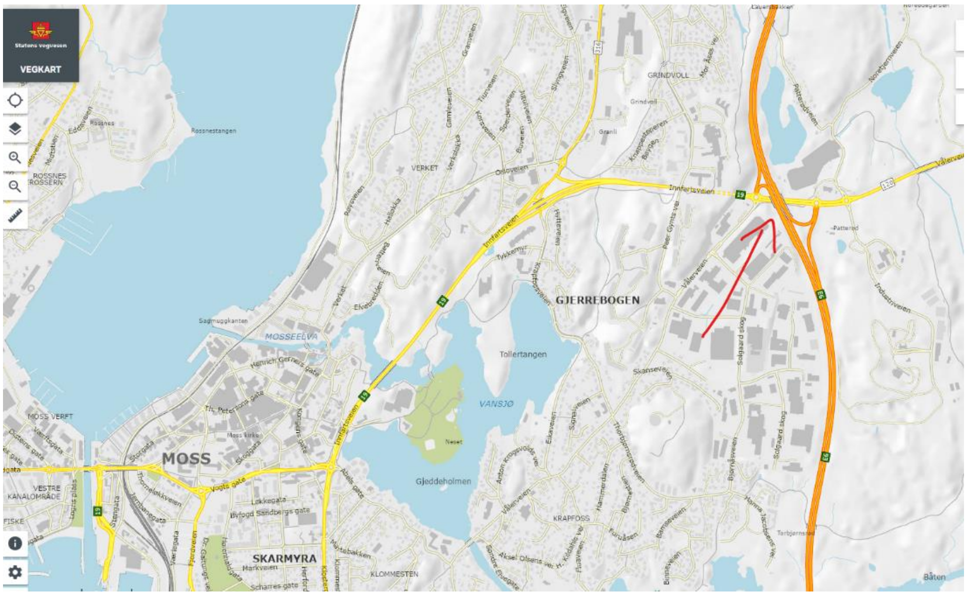
VIII.3.6 ITS G5

The ITS Pilot initiative, situated at Patterødkrysset (E6) and highlighted on the Vegkart website of Vegvesen.no, represents an intersection solution. The system boasts two roundabouts and a fully articulated two-level intersection, between the E6 and RV19.

Patterødkrysset with the exit to Moss has a large amount of traffic and challenges with back-blocking on the E6. Combined with high speed (110 km/h) on the E6, this leads to the risk of serious accidents. This also applies to vehicles driving in the opposite direction up the ramps. In order to prevent accidents and provide road users with better information, ITS-G5 solutions have been developed and installed which are being tested at the intersection, while a traditional queue warning system using inductive loops has also been installed.

This is not publicly available, but access and use of the physical and digital infrastructure can be arranged after further discussions with NPRA, Aventi and Qfree.



- 4 permanently mounted RSUs (roadside units) with ITS-G5 (from Aventi)
- 4 fixed RSUs with ITS-G5 (from QFree), hang from the same masts as Aventi's but lower
- 2 mobile RSUs with ITS-G5 technology that can be used in trials and placed where you want to test
- About. 40 OBU (onboard units) with ITS-G5
- Inductive sensors on the exit ramp from the south
- Camera owned by VTS - Fiber network and cabinets in which equipment can be stored

Contact who can provide further information and assistance:

Christina Skaftnes Nicolaisen, christina.nicolaisen@vegvesen.no

VIII.3.7 Traffic Data

Trafikkdata (vegvesen.no)

Visual map solution Trafikkdata (vegvesen.no)

The Norwegian Public Roads Administration's Traffic Data API contains traffic data from public roads in Norway. Traffic data is registered in traffic registration points from around the country on state and county roads, and some points are located on municipal roads.

The Norwegian Public Roads Administration's aim is to be able to deliver traffic data of known quality and the right level of detail, and that this data is requested and collected from the correct road network.

All available data are on an aggregated level, where one hour is the shortest time interval. Vehicle by vehicle data is not available to the public.

As of now, all data is for traffic volume. The spatial resolution is per lane, direction or registration point, where each point is limited to one unique road reference. The vehicles are classified according to their measured length.

Speed and distance are also recorded for each lane.

All data has quality parameters associated with it, indicating their uncertainty and relevance. All use of the data must take the quality parameters into account.

Traffic data API:

- Traffic data

Read more on traffic data and data quality under Om trafikkdata (Norwegian only).

Contact who can provide further information and assistance:

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VIII.3.8 Traffic management & information:

Vei- og trafikkinformasjon | Statens vegvesen (Information only in Norwegian)

The Norwegian Public Roads Administration has national preparedness on roads The road traffic centers (five each with their own area) are an example of a national area of responsibility) The Vegtrafikksentralene (VTS) is the NPRA’s operational unit to look after traffic management and traffic information on European, national and county roads. They are the hub of traffic preparedness. VTS continuously monitors using cameras and other installations - which provide support for traffic management They warn and convey information about status and events on the road network, in road traffic and in the road's immediate surroundings

VIII.4 Publicly owned vehicles with sensor platforms

VIII.4.1 NPRAs measuring vehicle:

The Norwegian Public Roads Administration (NPRA) has several measuring vehicles with advanced equipment to collect data on the condition of roads. These vehicles are equipped with lidar, GNSS, and cameras for accurate and comprehensive data collection.

Lidar:

- One of the lidar systems used by NPRA is the Z+F PROFILER® 9012, a compact high-speed phase-based laser scanner that offers great precision, a 119 m range, and a 360° field of view. It has a high scan rate of over 1 million points/ sec. and a scanning speed of up to 200 profiles/sec. This makes it possible to achieve very short distances between profiles even at high platform speeds.
- NPRA also uses ViaIRI texture laser to collect data on road surface irregularities and provide accurate measurements of the International Roughness Index (IRI).

GNSS:

- The NPRA's measuring vehicles use Applanix POS LV, a fully integrated and turnkey Position and Orientation System that utilizes integrated inertial technology to generate stable, reliable, and repeatable positioning solutions for land-based vehicle applications. It also utilizes CPOS service for added accuracy.

Cameras:

- The measuring vehicles are equipped with two camera systems: ViaPhoto Wide and Ladybug 360. These camera systems help in collecting visual data for detailed analysis of the road condition, including wear and tear, cracks, and other damages.

Contact who can provide further information and assistance:

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VIII.4.2 NMAs measuring vehicle:

The vehicle equipped with a sensor platform provides advanced mapping capabilities with the help of its high-end navigation equipment and lidar. NMAs vehicle with a sensor platform is an excellent tool for accurate and efficient data collection and analysis.

Figure 0-II: The Norwegian Mapping Authority vehicle with sensor platform

Sensors on vehicle platform:

- GNSS receiver: Septentrio AsteRx 4
- GNSS antennas: Trimble Zephyr Geodetic 2
- IMU: SBG Systems Apogee-D
- Odometer: Pegasem WSS2
- Lidar: Ouster OS1-128

Navigation and georeferencing of point cloud are post-processed to ensure optimal accuracy.

Contact who can provide further information and assistance:

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