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ULTIMO

Advancing Sustainable User-centric
Mobility with Automated Vehicles

DELIVERABLE

D3.4 Common Platform and HD map

First version

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Acronyms

ADS	Automated Driving Systems
ADAS	Advanced Driver Assistance System
AI	Artificial Intelligence
AM	Automated Mobility
API	Application Protocol Interface
AV	Automated Vehicle
BMM	Business Modelling Manager
CAV	Connected and Automated Vehicles
CB	Consortium Body
D7.1	Deliverable 7.1
DI	The department of infrastructure (Swiss Canton of Geneva)
DMP	Data Management Plan
EAB	External Advisory Board
EC	European Commission
ECSEL	Electronic Components and Systems for European Leadership
EM	Exploitation Manager
ESRI	Environmental Systems Research Institute
EU	European Union
EUCAD	European Conference on Connected and Automated Driving
FEDRO	(Swiss) Federal Roads Office
FM	Fleet Management
FOT	(Swiss) Federal Office of Transport
GDPR	General Data Protection Regulation
GNSS	Global Navigation Satellite System
IPR	Intellectual Property Rights
IT	Information Technology
LA	Leading Author
LIDAR	Light Detection And Ranging
MEM	Monitoring and Evaluation Manager
MIF	MapInfo interchange Format
OCT	General Transport Directorate of the Canton of Geneva
ODD	Operational Domain Design
OEDR	Object And Event Detection And Response
PC	Project Coordinator
PEB	Project Executive Board
PGA	Project General Assembly
PRM	Persons with Reduced Mobility
PTO	Public Transportation Authority
PTO	Public Transportation Operator
PTS	Public Transportation Services
QRM	Quality and Risk Manager
QRMB	Quality and Risk Management Board
RN	Risk Number
SA	Scientific Advisor
SAE Level	Society of Automotive Engineers Level (Vehicle Autonomy Level)
SDK	Software Development Kit
SMB	Site Management Board
SoA	State of the Art
SOTIF	Safety Of The Intended Functionality
SWOT	Strengths, Weaknesses, Opportunities, and Threats.
T7.1	Task 7.1
TM	Technical Manager
TPG	Transport Publics Genevois
UITP	Union Internationale des Transports Publics (International Transport Union)
V2I	Vehicle to Infrastructure communication
WP	Work Package
WPL	Work Package Leader

Executive Summary

This version of the deliverable presents an analysis of the current landscape of High-Definition (HD) maps utilized by autonomous vehicles, with a particular focus on the target use cases and partner project technologies.

The advancement of autonomous vehicle technology significantly hinges on the development and application of High-Definition (HD) maps. These maps, distinguished by their precision and comprehensive detail, serve various crucial roles across the spectrum of autonomous driving, urban planning, and beyond. This report delves into the current state of HD map technology, categorizing them by types and uses, and further explores the descriptions of maps utilized by different partners within the ULTIMO project.

HD maps are segmented into several types, each designed to fulfil specific functions such as road network mapping, lane-level details, semantic interpretation, 3D environmental modelling, dynamic data integration, and more. These maps are indispensable for autonomous vehicles, providing essential information for localization, navigation, and complex decision-making processes. The report also outlines the creation and maintenance challenges of HD maps, including data collection, processing, and the necessity for regular updates due to dynamic road conditions.

A significant portion of the deliverable is dedicated to examining the HD maps used by ULTIMO project partners. Each partner utilizes HD maps tailored to their specific operational needs, reflecting the diversity in requirements across different applications of autonomous technology. The report highlights the advanced features of these maps, such as centimeter-level precision, AI-assisted processing, and integration with vehicle-specific behaviors.

Furthermore, the deliverable discusses the relationship between HD maps used by fleet orchestrators and autonomous vehicles. It emphasizes the need for synchronization and compatibility between these maps to ensure efficient fleet management and route optimization. The challenges of achieving this synchronization in the context of public transportation are also addressed, proposing a hybrid model that combines pre-scanned maps with dynamic updates.

In conclusion, HD maps represent a foundational element of the autonomous vehicle ecosystem, with their development and refinement being key to the future of autonomous driving. Despite the challenges, ongoing efforts towards standardization, collaboration, and innovation are critical to unlocking their full potential. The ULTIMO project's exploration of HD maps underscores the importance of these tools in achieving a seamless and safe autonomous driving experience.

1 Introduction

During the past few years many projects and initiatives were undertaken deploying and testing Automated Vehicles (AVs) for public transportation and logistics. However in spite of their ambition, all of these projects stayed on the level of elaborated experimentation and never reached the level of a large-scale commercial deployment of transport services. The reasons for this are many, the most important being the lack of economically viable and commercially realistic models, the lack of scalability of the business and operating models, and the lack of user oriented services required for large end-user adoption of the solutions.

The ULTIMO project will create the very first economically feasible and sustainable integration of AVs for MaaS public transportation and LaaS urban goods transportation. ULTIMO aims to deploy in three sites in Europe 15 or more multi-vendor SAE L4 AVs per site. A user centric holistic approach, applied throughout the project, will ensure that all elements in a cross-sector business environment are incorporated to deliver large-scale on-demand, door-to-door, well-accepted, shared, seamless-integrated and economically viable CCAM services. We target the operation without safety driver on-board, in a fully automated and mission management mode with the support of innovative user centric passenger services.

ULTIMO's innovative transportation models are designed for a long-term sustainable impact on automated transportation in Europe, around the globe and on society. The composition of the consortium ensures the interoperability between multiple stakeholders by making adoption of new technology at minimum costs and maximum safety. The integration of the ongoing experiments of previous AV-demonstrator projects ensures highest possible technical and societal impacts from the very beginning of the project, as well as during the project lifetime and even long after its completion.

1.1 On-demand Mobility

Public transportation is a key element of a region's economic development and the quality of life of its citizens. Governments around the world are defining strategies for the development of efficient public transport based on different criteria of importance to their regions, such as topography, citizens' needs, social and economic barriers, environmental concerns, and historical development. However, new technologies, modes of transport and services are appearing, which seem very promising to the support of regional strategies for the development of public transport.

On-demand transport is a public transport service that only works when a reservation has been recorded and will be a relevant solution where the demand for transport is diffuse and regular transport is inefficient.

On-demand transport differs from other public transport services in that vehicles do not follow a fixed route and do not use a predefined timetable. Unlike taxis, on-demand public transport is usually also not individual. An operator or an automated system takes care of the booking, planning and organization.

It is recognized that the use and integration of on-demand Automated vehicles has the potential to significantly improve services and provide solutions to many of the problems encountered today in the development of sustainable and efficient public transport.

1.1.1 Fully Automated Vehicles

A self-driving car, referred in the ULTIMO project as a **Fully Automated Vehicle** (**AV**), is a vehicle that can sense its environment and moving safely with no human input.

The terms *automated vehicles* and *autonomous vehicles* are often used together. The Regulation 2019/2144 of the European Parliament and of the Council of 27 November 2019 on type-approval requirements for motor vehicles defines "automated vehicle" and "fully automated vehicle" based on their autonomous capacity:

An "automated vehicle" means a motor vehicle designed and constructed to move autonomously for certain periods of time without continuous driver supervision but in respect of which driver intervention is still expected or required

"Fully automated vehicle" means a motor vehicle that has been designed and constructed to move autonomously without any driver supervision

In ULTIMO we operate ***Fully Automated mini and micro shuttles for shared public transportation***. In relation to the SAE levels, the ULTIMO project will operate SAE Level 4 vehicles.

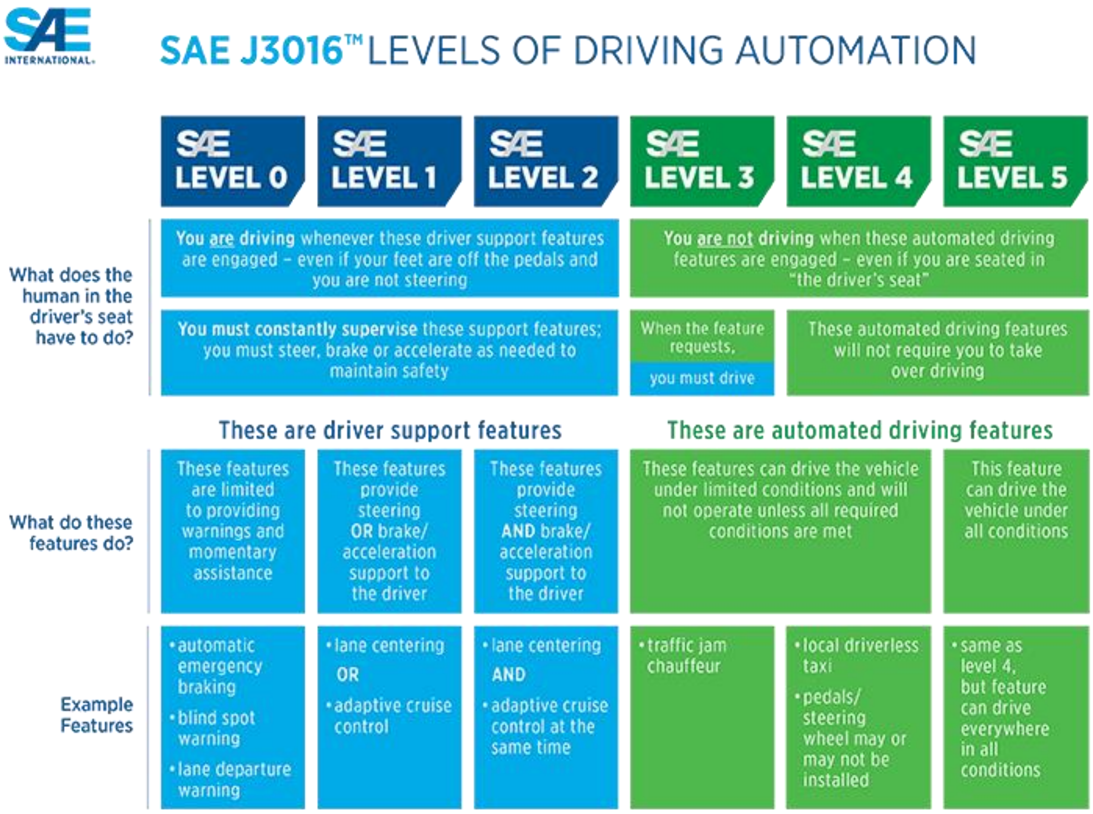

Figure 1: SAE Driving Automation levels (©2020 SAE International)

1.2 The ULTIMO dream for public transportation

Our city has a population of 700.000, and the local PTO (Public Transport Operator) deploys 3.000 Km of public transportation services' routes, with 4 backbone tram lines, 8 backbone large bus/trolley lines, and 340 fully automated multi-manufacturer mini and micro-shuttles in an on-demand, door-to-door shared public transport service. The fleet of the 340 automated mini-busses is composed of different vehicle generations and models from different manufacturers, as it was purchased in different batches during the last 12 years (it all started with the first 15 bought by a European project in 2023/24). It is today composed of the first 15 twelve-years old vehicles from manufacturer A, 160 eight-years old vehicles from manufacturer B and 160 two-years old vehicles from manufacturer A, which are the new generation of manufacturer's A vehicles. These last 160 vehicles re-placed the last 70 old, driver based, thermic busses that reached the end of their life after 18 years in operation. The change from driver large busses to automated mini-buses and from fixed line service to on-demand, door-to-door, for the last area of the city, was decid-ed 6 years ago, and was based to the great success of the already deployed AV-based ser-vices in the other parts of the city.

The integration of new vehicles in the PTO fleet was done within just a few days, thanks to the now standardised APIs of the automate vehicles' connection with the AV fleet management and orchestration service, that allows a plug-and-operate functionality, but also enables the combination of AVs with all other means of transport, offering a seamless citizen centric journey to the users. Similarly, the now standardized High Definition (HD) maps between the vehicle manufacturers, allowed us to reuse the maps created in the past for the 3.000 Kms of routes of the city, with small adaptations for the new vehicle capabilities. At the same time of the purchase of the last 160 AVs, we also switched to a new AV fleet management and orchestration service, from another provider, which offers more precise trip time estimations, considering also traffic jams in the city and weather conditions (that affect traffic in the city). The replacement was made within just two weeks, thanks to the new standardised interfaces between AV fleet management and PTO MaaS services.

Passengers are now able to reserve, via their mobile phone app, on the fly or with pre-reservation trips from one side of the city to another, using the optimal transport mode available for them, with a combination of different transport modes, and having the automated vehicle arriving next (or almost) to their door entrance and bringing them to their final destination or to a backbone transport connection. All trips are offered with highly reliable and accurate transport and arrival times, based on real time, dynamic route changes of the vehicles, responding to the passenger needs. Many passenger services are available in the AVs via a mobile phone app, adapted to all passengers' needs, from special needs passengers (visually impaired, wheel-chair users, pregnant women, elderly, children), to persons transporting suitcases or a baby-stroller, providing adapted information of their trip (where to get-off, PTO general information, and even infotainment, like city related information and historical facts and anecdotes, related to their current position).

With the full suppression of on-board operators, automated in-vehicle monitoring provides a multitude of passenger services, which were, and are developed with a continuous collaboration and innovation between users and the PTO. An on-board unit identifies locally (that is, in the bus) incidents and events, like aggressions, vandalism, forgot-ten objects, littering, accidents, etc., and raises incident alarms to the PTO back-office. The PTO officer at the back-office evaluates the incident and decides, based on the operator policies, what action to take: dismiss the incident, or stop the vehicle and call one of the intervention teams to go the vehicle and take the required action. The back-office operator, based on the number of incidents and intervention time legal obligations, can deploy any of the 15 intervention teams available in the city, ready to reach within a few minutes any AV. At the back-office, service operators are able, with one set of screens linked to the fleet management, to follow the vehicle status, trip reservations, routes chosen, open and closed road segments (due to works, accidents, etc. thus adapting dynamically the trip routings), while in a second set of screens, the back-office operators can follow the passenger services' incidents and the status and location of the intervention teams. The two systems, although independent, are linked so that the back-office operator can transfer incidents to intervention teams and turn-on, when possible and under the local legal re-strictions, video connection to inspect the incident.

The public transport services are operating 24/7 with different active vehicles, de-pending on passenger transport demands. The PTO, being eco-sensible, has defined that the vehicle must have an average occupancy of at least 3 passengers. This of course has implications, especially in off-peak hours, in the transport delays, but it is fully justified for an optimal and eco-responsible operation. Exceptions are made for people with special needs or when the passenger is ready to pay an additional price.

While at peak-hours the full 340 strong fleet of AVs is in service for public transportation, in the off-peak and night hours, due to the reduced transportation needs, part of the fleet is not serving passenger transportation. However, because having a vehicle waiting idly is a waste of resources, the PTO has signed an agreement with Logistics as a Service (LaaS) Service providers. During the off-peak hours the unused vehicles are dynamically chartered by the different LaaS providers to be used for other types of incidental transport of goods or even non-public transportation of passengers. Local shops and enterprises use the service, on demand with dynamic reservation, to offer home delivery of on-line purchases, or B2B delivery of goods from an urban consolidation center to the distribution center (hub, many to one or one to many, or even transport their VIP customers directly to their offices or exposition centers. This way they can deliver the goods to their customers in the city, with a delay of just 60 minutes with affordable prices, as the last mile is the most inefficient part of the goods delivery chain. The goods send can include books from local bookshops or libraries, supermarket bags or even documents exchanged between companies or waste. The local shops are even using the service in the early hours (5 o'clock in the morning) for re-provisioning their shops for the day. The so chartered AVs are "returned" to the PTO for public transport at the peak-hours automatically, at the end of the chartered time period.

1.2.1 A layered approach for the deployment of fully automated shuttles for public transportation

The realisation of the above described dream requires the integration and interoperation of different technologies. In the ULTIMO project we have defined a layered approach, where we distinguish four layers, each providing a specific service, and namely

- micro-navigation,
- macro-navigation
- fleet orchestration and
- passenger services

The **Micro-navigation** is fully integrated in the vehicle and implements the road behaviour of the vehicle; micro-navigation will provide the required obstacle recognition and bypassing, lane changing (when authorised), turning points, speed control, breaking, turning a the right point etc. The micro-navigation is effectively the automated driver of the vehicle.

The **Macro-navigation** controls the vehicle routing, that is which path to follow to from point A to point B, as well dynamic path changes. This is the same function as the widely used GPS navigators that provide to the driver of the individual vehicle instructions of the road to take, but are not interfering to the on-road driver decisions. The macro-navigation will take into account road conditions (like traffic jams) and adapt dynamically the path to the destination.

In the operation of a public transportation service we will have a large number of vehicles operating within the designated service area. Which vehicle will serve which trip request is done by the **fleet orchestration** system, which manages (among others) the choice of the specific vehicle that will be used in reply to a specific passenger trip request, based on the transport policies defined by the operators, vehicle loads, passenger needs (ex. Require wheel chair support) and road conditions.

Once the vehicle has been selected, then the information to go to a destination will be received by the Macro-navigation which will decide the exact path to follow.

The fleet orchestrator tracks the position and status of each vehicle and will dynamically decide to new assignments depending on new trip requests, changing street/weather conditions, changes in the vehicle status and operator policies to respect.

The last layer is the **passenger services**, providing the required user experience services to the passengers, like trip reservation, in- and out- of-vehicle services, comfort services etc. These services are a key element in the provision of public transportation, since we need, from one side cover the absence of driver in the vehicle (and the services to passengers offered by the driver) and from the other side provide the required tools to improve user experience with fully automated vehicles.

1.3 Preamble – Towards a viable model for HD maps management

WP3 contributes in the definition of the overall system and services that need to be implemented for the creation and deployment of the target public transportation services.

The target of this deliverable series (D3.4, D3.5, D3.6) is to define in detail the common HD map model for fully automated vehicles. The deliverable is based on the work performed in T3.3 and T3.4.

A large number of HD maps are today available commercially by various map providers. However, fully automated vehicle manufactures create and use their homemade custom HD maps for their vehicles. This is due to the fact that the ADS systems are strongly linked with the details and structure of the used HD maps, to achieve the needed performance. Although the basic components of an HD map are similar to all manufactures, the internal details can drastically differ. In fact, each ADS provider needs to optimize the HD map for its own ADS system, so it has an internal model highly tailored to its specific ADS.

Considering now that in a large scale deployment of AVs in a city, the mobility services' operator will surely end up using vehicles from different manufactures, each however requiring its own HD map model. Although this, per-se, is not an issue for the services quality, does create major problems, considering the full life-cycle of the HD maps.

From one side, a city is living organisation where roads are changed daily. Existing commercial HD-maps do update their city representations, the delay for the updates can take weeks or even months. This can be acceptable for overall city urban design, but it is unacceptable for the AVs that need live updates of the roads. Considering that a mobility operator will need to update several models of HD maps for each change in the city, creates a major administrative and economic burden that can seriously hinder the deployment of AVs and degrade the service quality.

From the other site, the mobility operator will need to deploy the services and map hundreds or even thousands of Kms on city roads. Performing this for every new model of AV, can become a major economic obstacle in the selection of a new type of vehicle (that will need its own HD Map), as the cost of creating a new HD maps can be a few thousand EUR per KM (taking into account the road scanning, the cleaning of the data, the restructuring, the integration of annotations, and the final deployment and maintenance).

The target of the work in the ULTIMO for HD Maps, is to propose viable solutions for the creation, deployment and use of HD maps for AVs in public transportation.

The target of the ULTIMO work in HD maps is investigate and propose solutions for an economically viable use and deployment of HD maps for a multi-vendor, large scale mobility service. Although we will concentrate in the technical aspects on how HD maps can be standardised, the economic issues related with possible solutions, taking into account the complete life-cycle of HD-maps will also be addressed.

In our approach we will take into account the different parts composing the HD-maps used by AVs and identify, first the common parts of the different HD maps used by vehicle manufactures, and second whether the custom-made parts can be possibly converted from one manufacture representation and model to another. The questions of HD-map life-cycle will also be investigated, always from the point of view of multi-manufacturer fleets and the need for fast modification and update propagation.

This first version of the deliverables series (D3.4) identifies and describe the HD maps, identifying the common parts and differences between the different HD maps in the market and where each model is used and what are the related needs.

2 HD maps: types and usage

High-Definition (HD) maps come in various types, each serving specific purposes and applications. These different types of HD maps cater to specific needs and play crucial roles in the development and deployment of autonomous vehicles, smart cities, and various other applications related to spatial understanding and navigation.

1. Road Network Maps:

These maps focus on providing detailed information about the road infrastructure, including lane markings, road signs, traffic signals, and the overall geometry of road networks. They are essential for autonomous vehicles to navigate and make informed decisions on the road.

2. Lane-Level Maps:

Lane-level maps provide detailed information about individual lanes within a road. This includes lane width, curvature, and specific lane markings. These maps are crucial for precise lane-keeping and lane-changing manoeuvres in autonomous vehicles.

3. Semantic Maps:

Semantic maps go beyond geometric details and include information about the semantic meaning of the environment. This includes object classifications (e.g., buildings, pedestrians, vehicles), enabling better understanding and interaction with the surroundings.

4. 3D Maps:

3D maps provide a three-dimensional representation of the environment. They include elevation data, enabling better modelling of road slopes, overpasses, and other topographical features. 3D maps are valuable for enhancing the perception capabilities of autonomous vehicles.

5. HD Maps with Dynamic Data:

Some HD maps incorporate real-time or dynamic data, such as current traffic conditions, construction zones, and temporary road changes. These maps are continuously updated to reflect changing road scenarios, making them adaptable to evolving conditions.

6. HD Maps for Urban Planning:

These maps focus on providing detailed information about urban environments, including building structures, parking spaces, and other city-specific details. They are valuable for city planning, infrastructure development, and optimizing urban mobility.

7. HD Maps for Specific Use Cases:

Some HD maps are designed for specific use cases, such as parking maps that provide information about available parking spaces, or maps tailored for logistics and delivery services to optimize routes and deliveries.

8. HD Maps for Augmented Reality (AR):

These maps are designed to enhance augmented reality experiences, providing additional context and information about the environment to users. AR maps may include overlays of virtual information onto the real-world surroundings.

9. HD Maps for Geospatial Analytics:

These maps are used for advanced geospatial analytics, allowing for detailed analysis of the environment. They may include additional layers of information relevant to research, planning, and decision-making.

10. HD Maps for Indoor Spaces:

While HD maps are commonly associated with outdoor environments, there are also maps designed specifically for indoor spaces. These maps provide detailed information about the layout of buildings, including rooms, hallways, and points of interest, and are useful for applications like indoor navigation.

11. HD Maps for Autonomous Vehicles:

Autonomous vehicles rely on highly detailed maps tailored to their unique needs. These maps include not only road network information but also lane-level details, such as precise lane markings, road curvature, and traffic signs. Additionally, these maps often incorporate semantic information about the environment, such as the classification of objects and dynamic elements. HD maps for autonomous vehicles play a critical role in localization, providing a reference for the vehicle to accurately determine its position in real-time. These maps are essential for safe navigation, decision-making, and planning complex manoeuvres, making them a foundational component of autonomous driving systems.

In the rest of the document, we will concentrate in HD maps for autonomous vehicles, and thus any further reference to HD maps, should be considered are referring exclusively to the HD maps are needed for the operation of Autonomous vehicles.

3 HD maps : components and creation

A High-Definition (HD) map is a specialized type of map designed for use in autonomous vehicles systems (ADS) and advanced driver assistance systems (ADAS). It provides highly detailed and accurate information about the road environment and surrounding infrastructure to enable precise localization, navigation, and decision-making for self-driving cars. High Definition Maps are today available and commercialised by many companies, but they are not always adapted or sufficient for being used with automated vehicles. A review of the production and uses of maps for autonomous driving and a synthesis of the opportunities and challenges can be found in [WONG20].

During the last few years new vehicles appeared in the market claiming full autonomy, but offering in reality “simple” driver assistance (though sophisticated!). As a result a confusion was created in what we mean with HD maps for autonomous driving.

The existing commercially available vehicles are operated with an ADAS (Advanced Driver Assistance System) which provides an implementation of L3 vehicles. On the other hand the under development fully automated vehicles operate with and ADS (Autonomous Driving System), providing an implementation of L4 vehicles. The needs and use for the HD maps between the two systems are very different.

On the other hand, we have large number of commercially available HD maps whose prime target it to provide for the needs of ADAS systems, thus providing for example “low” road precision of 10ths of cms, where this precision is sufficient for ADAS (for which the driver is in control), but is not sufficient for ADS where centimetric precision is needed for a safe fully autonomous driving [MENGM24].

In this deliverable we will describe the existing HD maps and identify their common elements, regarding their use for automated vehicles.

3.1 Components of HD maps

HD maps include different types of information, providing a comprehensive and detailed representation of the road environment, supporting the safe and efficient operation of autonomous vehicles by offering precise localization, navigation, and context-aware decision-making capabilities.

In the following list we provide the most important elements that constitute a High-Definition map. To be noted each HD map can include a part of the elements described below, depending on its target usage. For example, some AVs do not need information on lanes, having the vehicle operating in a virtual line based on high accuracy of geolocation (using GNSS or GPS).

A. Topology layer

The topology layer includes the rather immutable components of a city. Changes are very slow and are related to city evolution over time (new roads creation etc).

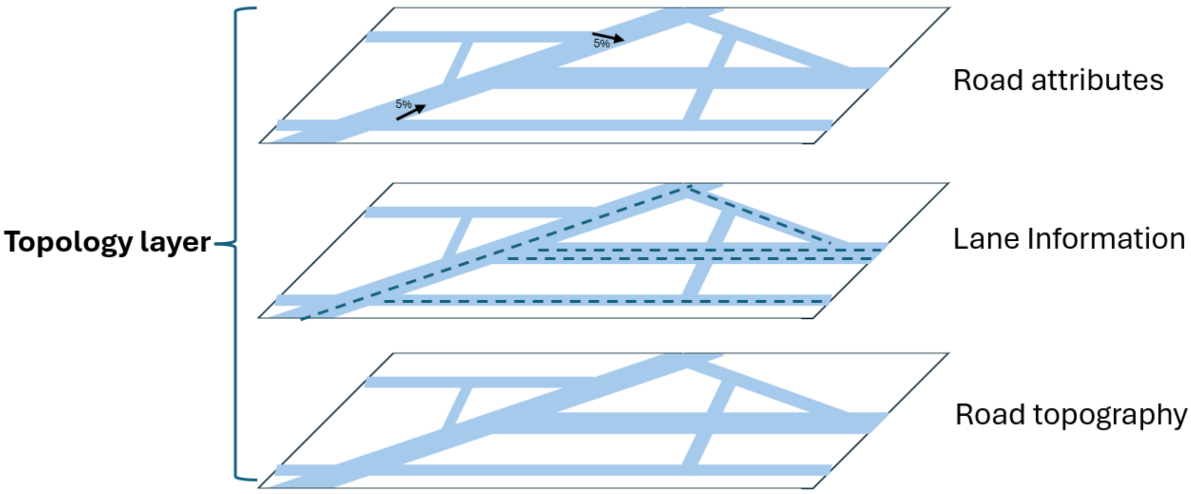

Figure 2 Topology layer of HD maps

1. Road Topography (Geometric information):

HD maps include detailed geometric information about the road geometry, such as lane boundaries, curves and intersections. This what we call *Road Topography*, which defines the geometric disposition of the roads (road network), buildings and other city elements. The accuracy of this geometric data is often obtained through technologies like LiDAR (Light Detection and Ranging) sensors, which generate point clouds representing the 3D structure of the environment. The topology layer is used by fleet orchestrators for the definition of the optima itinerary of the vehicle.

The geometric information is relatively static, changing though out the time with the construction of new roads or modifications of existing ones.

2. Lane-Level Detail:

The map provides information at the lane level, specifying the number of lanes, their width, and any special lane markings or designations. This level of detail is essential for autonomous vehicles to make accurate decisions about lane changes and maneuvers. Point clouds contribute to capturing fine details in lane geometry.

3. Road Attributes:

Detailed information about road attributes, such as road curvature, slope, and elevation changes, is included. This data helps autonomous systems anticipate and adapt to variations in the road environment. Point clouds can provide a rich representation of the road surface and its features.

B. Traffic control layer

This layer contains static elements that provide information on traffic or localisation. The information can change through out time (new road signs, new traffic lights etc).

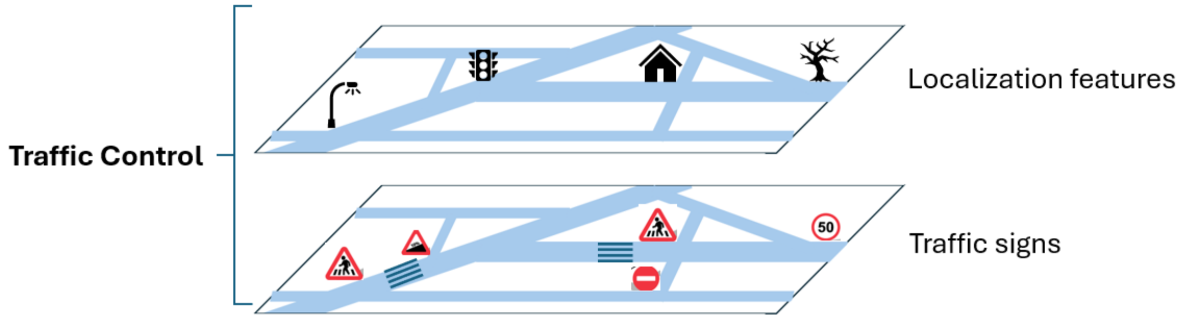

Figure 3 Traffic Control layer

4. Traffic Control Devices:

HD maps contain information about traffic signs, signals, and other traffic control devices. This data is crucial for the vehicle to understand and respond to traffic rules and regulations. Point clouds can enhance the detection and recognition of these devices by capturing their 3D characteristics.

5. Localization Features:

Special features for vehicle localization, such as landmarks, unique road features, and reference points, are integrated into the map. These features, when represented in point clouds, assist the vehicle in accurately determining its position within the mapped environment.

C. User information – Semantic information layer

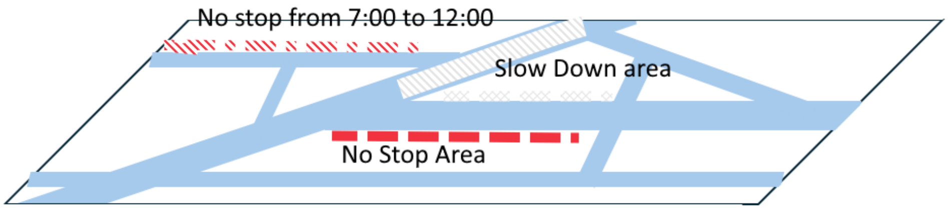

Figure 4 User defined Semantic Information

6. Semantic Information:

Beyond geometric details, HD maps may include semantic information about the operational environment, which is defined by the service users (in our case the PTO/PTAs). This semantic information (provided in the form of annotations by the PTO or PTA), requires direct human intervention to specify, for example, areas that the vehicle need to slow down due to possible regular presences of vulnerable road users, authorised or restricted stop zones, time of the day depended information related to the mobility and transport services etc. This information can be modified dynamically.

D. Road Status Information layer

A road in a city is a "living" entity, changing dynamically due to human activities. AVs and fleet orchestrators will need to be aware of the changing road status and conditions, so as to optimize routing and trips. The road status information is very dynamic, changing every minute.

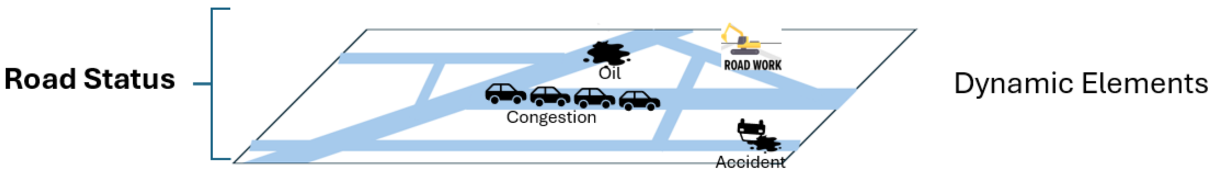

Figure 5 Road Status information

7. Dynamic Elements:

Some HD maps can incorporate real-time or dynamic data, such as current traffic conditions, construction zones, and temporary road changes. This dynamic information, when combined with point clouds, helps autonomous systems adapt to changing road scenarios in a more detailed and accurate manner. This is information is highly dynamic and requires continuous updates.

E. HD Map usage

All the above described elements constitute "just" the ingredients of an HD map. However, the ingredients are not enough on their own. The HD map will be used with a specific ADS (or ADAS) system, which is a highly sophisticated software that requires very precise response time to all possible situations. In order to achieve this high performance, all elements of the ADS system must be highly fine tuned to optimize the system operation. The format and encoding of the HD maps is there highly personalised and adapted to the specific ADS system, (systems which are by definition proprietary, with their own internal representations).

8. Data Format:

HD maps are stored in a digital format suitable for machine interpretation, that is for the specific ADS (or ADAS). A commonly using format is vector-based. Additionally, point clouds are utilized to represent the detailed 3D information of the environment in a way that can be efficiently processed by the vehicle's ADS. Specialised data fusion algorithms merge the different types of information in optimised format for the given ADS.

9. Updating Mechanism:

Due to the fact that each ADS has its own internal representation of the HD map, specialised mechanisms have been implemented by the different ADS providers for introducing updates, triggered by changes in the road infrastructure, construction projects, or other relevant events. Point clouds, when acquired regularly, contribute to keeping the map information up-to-date by capturing changes in the physical environment. Different methods are used for the updates, raning form manual updates, to automatic updates provided by each AVs during its daily operation.

3.2 Construction of HD maps

Creating an HD map is a complex process that relies on advanced technologies, data fusion, and ongoing maintenance to ensure the map's accuracy and relevance in dynamic environments. Here's a general overview of the steps typically involved in creating an HD map. (more details can be found in [BAO23].

We distinguish four main stages for the creation of an HD map: data collection, data processing for feature extraction, fusion and annotation, and map generation.

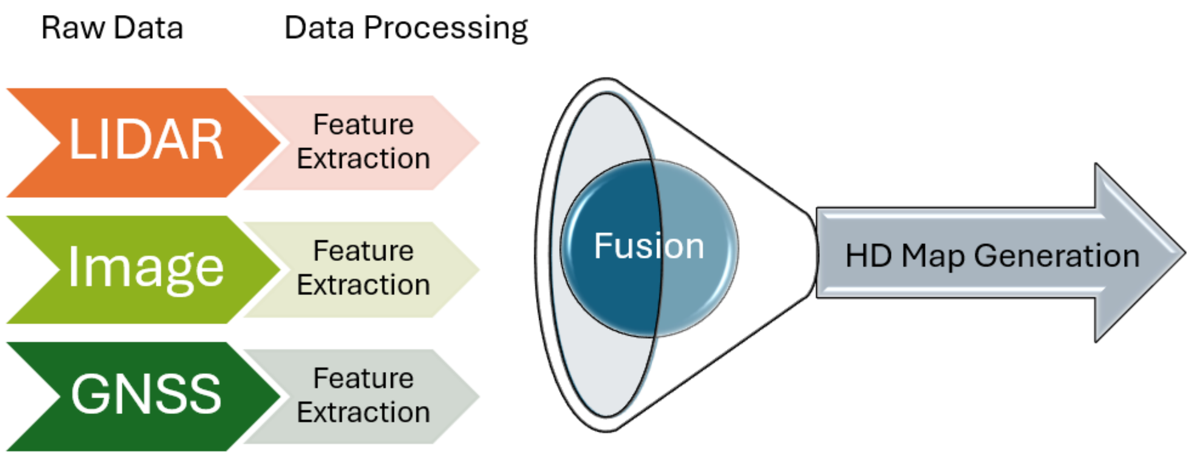

Figure 6 Stages of HD map creation

1. Data Collection:

Different technologies are required to collect the data for the HD map. In the following we present the key technologies, keeping in mind that the different HD map providers might use any combination of them, as required by the target use case.

LiDAR (Light Detection and Ranging): LiDAR sensors mounted on vehicles or drones are commonly used to collect highly accurate 3D point cloud data. LiDAR emits laser beams and measures the time it takes for the laser to bounce back, creating precise distance measurements. This results in a detailed 3D representation of the environment.

Figure 7 Point Cloud raw data (image from Navya)

Camera Imagery: High-resolution cameras capture images of the surroundings, providing additional contextual information. Images are used (in the next phase of data processing) for texture mapping and object recognition.

GPS and IMU (Inertial Measurement Unit): Global Positioning System (GPS) receivers and IMUs are used to determine the vehicle's position and orientation. This data is essential for accurately geo-referencing the collected point cloud and imagery.

RADAR and other Sensors: Depending on the requirements, other sensors like RADAR may be used to capture specific information, such as object detection and velocity.

The ADS manufactures are a using different methods and technologies to collect the above raw data. Depending on the ADS, the collected data can drastically differ, like for example the LIDAR density and resolution. The higher the LIDAR Density and Resolution is, the more accurate are the representations of complex surfaces. However in the next phase of feature extraction, higher processing power will be required for the identification of minor features, which can result to a reduction of the ADS performance. For this reason the data processing, that will fuse the information and adapt it to the specific ADS is a crucial element of the process.

Here we should note that the data collection is made by commercially available technologies and therefor the raw data collected are stored in standard well known formats and therefor can be considered as reusable. However we must underline that the collected data are massive, in the order of hundreds or thousands of TBs.

2. Data Processing:

The data processing is a critical part of the creation of HD maps for ADS. It is at this point that where the differentiation of the HD maps of the ADS manufactures starts. Each ADS has its own internal structure and optimised algorithms and therefor the HD map internal representation should be adapted to the specific ADS model, in order to achieve the required performance.

Machine learning is used to identify and extract features relevant to navigation and localization, such as lane markings, road signs, traffic signals, and other infrastructure details.

In addition, Human annotators may be involved to verify and annotate specific features in the map, ensuring accuracy and completeness.

Point Cloud Processing: The raw LiDAR data is processed to create a detailed 3D point cloud of the environment. Algorithms filter out noise, segment objects, and classify points to represent different features like road surfaces, buildings, and vegetation.

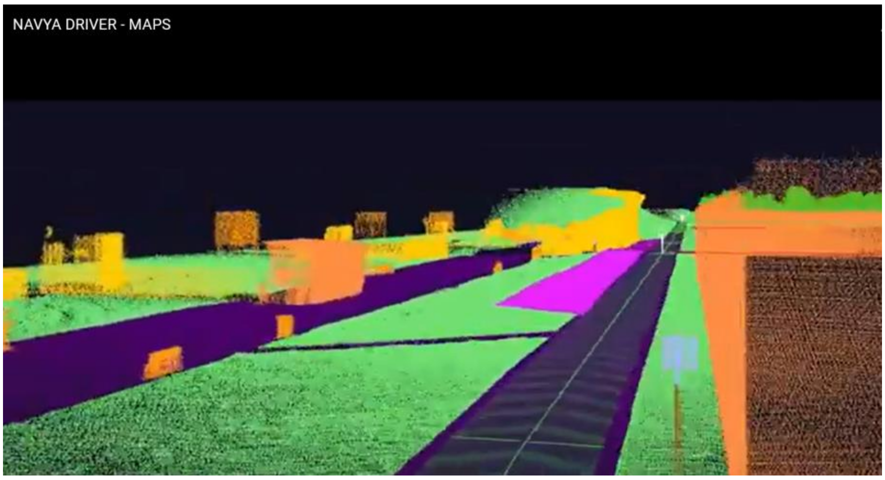

Figure 8 Navya LIDAR image Proccessing – example of identification of elements

Image Processing: Images captured by cameras are processed to extract features, detect objects, and perform image recognition. This information is integrated with the point cloud data.

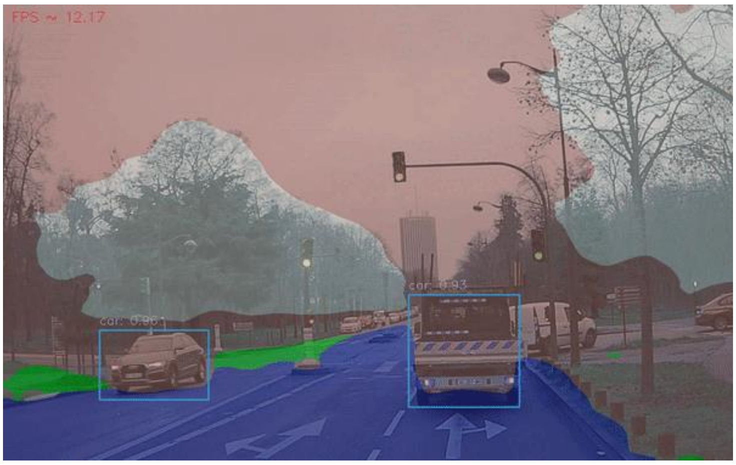

Figure 9 Image processing - contextual environment recognition (Image from Navya)

3. Fusion

Data from various sensors (LiDAR, cameras, GPS, IMU, etc.) is fused to create a comprehensive and accurate representation of the environment. Sensor fusion helps overcome limitations and enhances the overall quality of the map.

4. Map Generation:

The processed data, including the 3D point cloud, imagery, and extracted features, is used to generate a detailed HD map. The map may consist of multiple layers, as they described in the previous section, such as a base map layer with road geometry and topology, a semantic layer with object classifications, and additional layers for dynamic elements [KWAG24].

The generation of maps is a vital component for Automated Driving Systems (ADS). As previously discussed, ADS is an advanced and highly efficient system that demands extensive optimization to promptly respond and make decisions. Map generation involves optimizing and tailoring the various elements of the HD map to align with the specific internal architecture and algorithms of the ADS. Each ADS manufacturer employs proprietary algorithms that form the core of their expertise, necessitating the adaptation of the HD map to ensure compatibility with the ADS. Consequently, this adaptation process reflects the internal algorithms of the ADS and is protected by the ADS manufacturer (as is the internal format of the HD map).

5. Map Life cycle

The generated and optimized HD map is integrated into the ADS of autonomous vehicles. Different versions of the same map may be available, depending in he ADS version of the specific vehicle. We underline once more that the HD map is tightly linked and optimised for the specific ADS and can even differ from one version to another.

The final element in HD map is the updates and the simplicity in the installation. ADS manufactures provide different tools allowing the distribution of updates to the AVs, in most cases by remote uploading of the new map version of map segment.

4 HD maps in the market

4.1.1 Overview of commercially available HD maps

Several companies were actively working on commercially available or commercially used High-Definition (HD) maps for autonomous vehicles. Please note that the autonomous vehicle industry is dynamic, and new developments are introduced by the manufactures. Furthermore, by no means the following list should considered as exhaustive, other providers can exist in local markets. More information can be found in the literature [LIU19],

Following are some notable companies that were involved in providing HD maps for ADS and ADAS.

1. *Here* Technologies:

Here is a leading provider of location-based services and mapping solutions. They offer HD Live Maps [HERE24], which include detailed information about roads, lanes, and various objects relevant to autonomous driving.

- **Detailed Road Geometry:** Here Technologies provides HD Live Maps with comprehensive road geometry details, ensuring accurate representation of the road network.
- **Lane-Level Information:** The maps include information about lane markings and lane-level specifics, allowing for precise lane-keeping by autonomous vehicles.

- **Real-Time Updates:** Here emphasizes real-time updates, ensuring that the maps reflect changes in the environment promptly and accurately.
- **Integration:** The HD maps are designed for integration with various automotive platforms, making them accessible for a wide range of autonomous vehicles.

2. TomTom:

TomTom provides navigation and mapping products, and they have been working on HD maps for autonomous vehicles [TOMTOM24]. Their maps include information about road geometry, lane-level details, and traffic signs.

- **Road Geometry and Navigation:** TomTom's HD maps provide detailed road geometry information, supporting accurate navigation for autonomous vehicles.
- **Lane-Level Details:** The maps include information about individual lanes, including turn lanes, helping in lane-keeping and navigation.
- **Traffic Sign and Signal Information:** TomTom's maps incorporate data about traffic signs and signals, enhancing the understanding of traffic regulations.
- **Real-Time Updates:** TomTom focuses on real-time mapping updates to adapt to dynamic and changing road conditions.

3. Waymo (Alphabet Inc.):

Waymo, a subsidiary of Alphabet Inc. (Google's parent company), has developed its own HD maps to support its autonomous vehicle technology. These maps play a crucial role in Waymo's self-driving capabilities [WAYMO20].

- I**n-House Developed HD Maps:** Waymo develops its own HD maps tailored to its autonomous driving technology, ensuring a close integration between perception and mapping.
- **Localization and Decision-Making:** The maps play a critical role in localization and decision-making, contributing to the overall safety and reliability of Waymo's autonomous vehicles.
- **Integration:** Waymo's HD maps are tightly integrated into its autonomous driving technology stack.

4. Mobileye (Intel):

Mobileye, an Intel company, focuses on developing advanced driver-assistance systems and autonomous driving solutions. They work on Road Experience Management (REM) technology [MOBILE24], which uses crowdsourced data to create and update HD maps.

- **Road Experience Management (REM) Technology:** Mobileye's REM technology relies on crowdsourced data for map creation and continuous updates, providing a dynamic and accurate representation of the environment.
- **Detailed Mapping:** The maps created by Mobileye focus on detailed information to support advanced driver-assistance systems.
- **Real-Time Data Collection:** The emphasis is on real-time data collection to capture changes and events as they occur on the road.

5. NVIDIA:

NVIDIA is known for its work in artificial intelligence and autonomous driving technology. In 2021 with the acquisition of DeepMap they entered the development of mapping solutions for autonomous vehicles [NVIDIA24], leveraging their expertise in AI and computing.

- **AI and Computing Integration:** NVIDIA leverages its expertise in artificial intelligence and computing to provide mapping solutions tailored for autonomous vehicles.
- **Integration with Autonomous Driving Platform:** The maps are designed to seamlessly integrate with NVIDIA's autonomous driving platform, enhancing perception capabilities.
- **High-Definition Mapping and Localization Solutions:** providing high-definition mapping and localization solutions for autonomous vehicles.
- **Real-Time Updates and Maintenance:** The emphasis is on real-time updates and maintenance to ensure the accuracy of the maps in dynamic environments.

6. Civil Maps (Velodyne Lidar):

Civil Maps, now part of Velodyne Lidar, has been involved in providing HD mapping solutions for autonomous vehicles [CIVIL24]. Their technology includes semantic mapping to enhance understanding of the environment.

 S**emantic Mapping:** Civil Maps emphasizes semantic mapping, providing additional context for understanding the environment.

 Integration with Velodyne Lidar: The maps integrate with Velodyne Lidar technology, enhancing the accuracy and richness of the 3D point cloud data.

 Real-Time Mapping: Civil Maps' technology includes real-time mapping capabilities for immediate updates.

7. Ushr (TomTom subsidiary):

Ushr, acquired by TomTom, focuses on HD mapping technology for autonomous vehicles. Their maps provide detailed information for precise localization and navigation.

- **Accurate Road and Lane Information:** Ushr's HD maps provide accurate details about road geometry and lane-level specifics.
- **Integration with TomTom:** As a subsidiary of TomTom, Ushr's technology is integrated with TomTom's mapping expertise.
- **Localization Support:** The maps are designed to support precise localization for autonomous vehicles using TomTom's technology.

8. Baidu Apollo:

Baidu's Apollo platform includes HD mapping capabilities for autonomous driving [BAIDU24]. Baidu has been actively working on developing technologies for self-driving vehicles.

- **HD Mapping Capabilities:** Baidu's Apollo platform incorporates HD mapping capabilities tailored for autonomous driving within its ecosystem.

- **Real-Time Updates:** Baidu's emphasis on real-time updates ensures that the maps reflect the latest road conditions.
- **AI Technologies Integration:** Baidu's AI technologies are likely integrated into the mapping solutions for enhanced capabilities.

9. Aurora Innovation:

Aurora is known for its work in autonomous vehicle technology, and they emphasize the importance of HD mapping for their self-driving systems [AURORA]. They work on integrating perception, mapping, and control into a unified platform.

- **Integration of Perception, Mapping, and Control:** Aurora focuses on integrating perception, mapping, and control into a unified platform for autonomous systems.
- **Advanced Mapping Technologies:** The company emphasizes the use of advanced mapping technologies to support precise navigation in self-driving vehicles.
- **Applications in Self-Driving and Logistics:** Aurora's mapping solutions find applications in self-driving vehicles and logistics, contributing to efficient and safe operations.

5 The HD maps of the ULTIMO project partners

5.1 GAMA - Vehicle manufacturer

GAMA (previously Navya), known for its pioneering role in automated vehicle technology, has been at the forefront of developing high-definition (HD) maps to enhance the functionality of its autonomous vehicles. These maps are a cornerstone of GAMA's technology, providing detailed, precise, and accurate representations of the environment. HD maps are essential for autonomous driving systems, offering a level of detail that goes far beyond conventional mapping techniques, ensuring vehicles can navigate safely and efficiently.

The HD maps created by GAMA incorporate several advanced features to support autonomous vehicle scenarios. They offer centimeter-level precision, enabling vehicles to understand their surroundings with high accuracy. This precision is achieved through an AI-assisted processing pipeline and adherence to industry-standard HD map formats. GAMA's maps are specifically designed to support the unique needs of autonomous vehicles, with data updated to reflect the high level of detail required for these applications.

In the realm of autonomous driving, HD maps extend the vehicle's sensor field of view and refine the localization of the vehicle to a precise location. This is crucial for path planning and improving sensor perception, where vision sensors alone may not detect objects beyond a certain range. By integrating detailed information about lane geometries, borders, traffic signs, and other road furniture, HD maps provide a more comprehensive understanding of the road, enhancing the vehicle's decision-making capabilities.

However, creating and maintaining these HD maps comes with its challenges, such as real-time data streaming issues and the high costs associated with autonomous vehicle HD mapping. Speed and accuracy are critical, as the maps need to reflect dynamic road changes quickly to maintain safety. The adoption of 5G technology is expected to alleviate some of these challenges by providing the necessary speed and latency for over-the-air updates. Another significant issue is the lack of common standards in HD mapping, which complicates the integration and interoperability of maps from different providers. To overcome this, efforts are being made towards standardization, with initiatives like the Navigation Data Standards (NDS) Association working to create a global standard for in-vehicle navigation and HD maps.

For GAMA and other players in the autonomous vehicle industry, HD maps are not just a tool for navigation but a critical component of the broader ecosystem required for the safe and effective operation of self-driving cars. The development and refinement of HD maps continue to be a key area of focus, with advancements in technology and collaboration among industry stakeholders paving the way for the future of autonomous driving.

5.1.1 Overview of GAMA HD Maps

GAMA's HD maps are intricately designed to provide a comprehensive virtual representation of the environment, tailored specifically for the unique demands of autonomous vehicles. These maps merge detailed 3D data, semantic information, and vehicle-specific behaviors to enhance navigation capabilities, ensuring a seamless integration with the autonomous driving systems. Below is an expanded adaptation of the components and functionalities of GAMA's HD Maps, drawing from the latest advancements and practices in the field of autonomous driving technologies.

5.1.1.1 Components of GAMA HD Maps

5.1.1.1.1 Sensor Map

Acquisition:

GAMA leverages a cutting-edge Mobile Mapping System (MMS) that comprises a sensor box integrated with a specialized software on a tablet, facilitating mobility across various vehicles. This box includes a Lidar system for detailed point cloud generation, an Inertial Navigation System (INS) to track movement accurately, and a GNSS antenna for precise geolocation, capturing comprehensive data on roads, lanes, traffic signs, and barriers. The tablet acts as the operational core, allowing mapping personnel to oversee the data collection effectively, highlighting the system's flexibility and real-time monitoring capabilities.

Figure 10 : Example of NAVYA point-cloud

Post-Processing:

The raw data undergoes rigorous offline processing, including:

1. **Filtering**: Discarding imprecise scans to maintain data relevance, ensuring the high quality of the final map.
2. **Map Construction:** Integrating scans with essential attributes like GNSS quality and vehicle speed, creating a unified and detailed map that serves as the backbone for further analysis and application.
3. **Semantic Segmentation**: Employing either manual annotation or advanced machine learning techniques (based on our own datasets) to classify and label each environmental element captured in the point clouds. This segmentation is enhanced by a robust dataset, encompassing a diverse range of environments and conditions, underpinning the system's adaptability and accuracy [ALMIN23].
4. **Format Optimization**: Tailoring the Sensor Map's format to meet the specific needs of autonomous driving algorithms, facilitating efficient data retrieval and processing.

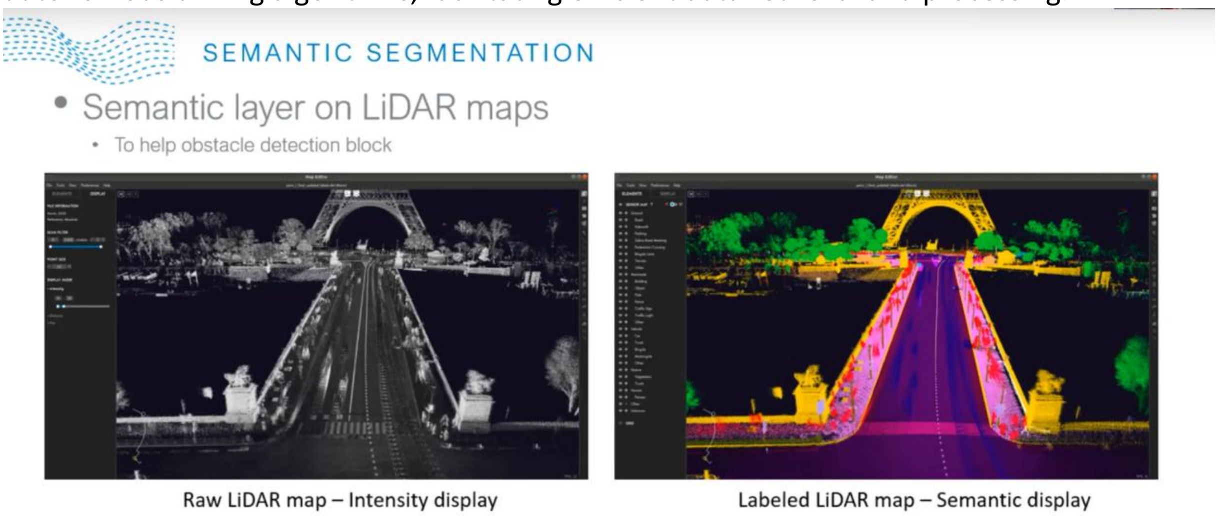

Figure 11 Semantic Segmentation of LIDAR map

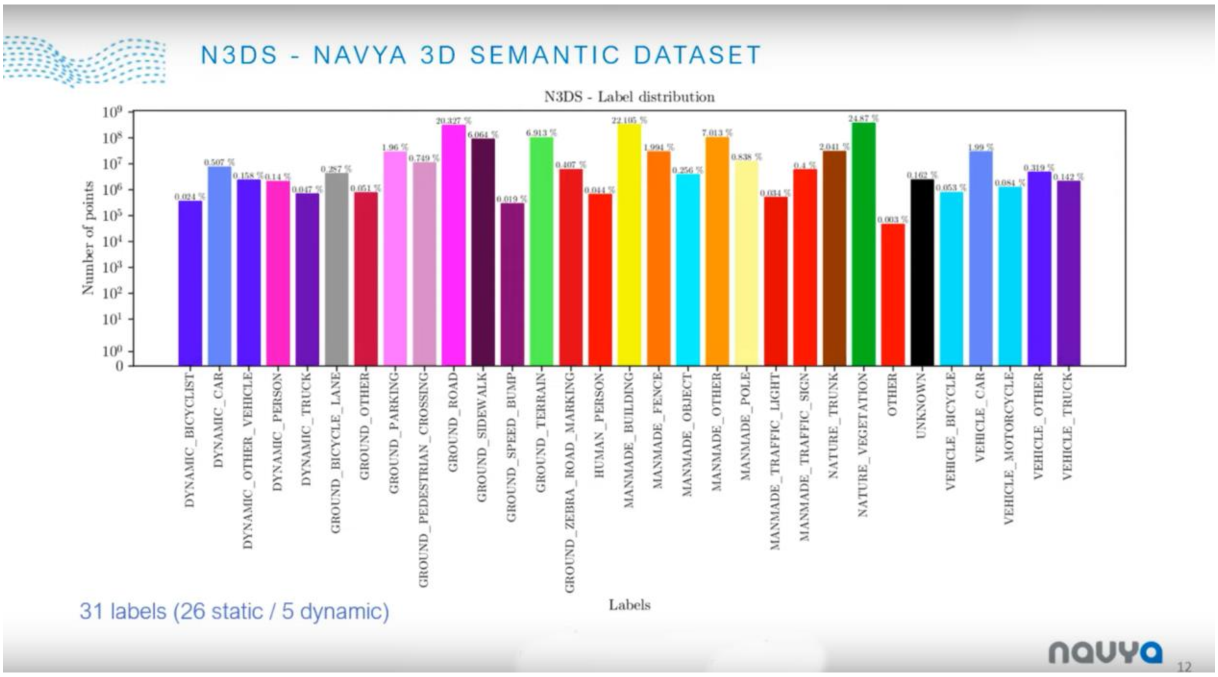

Figure 12 NAVYA 3D semantic dataset

Use:

The Sensor Map is instrumental for several autonomous vehicle functionalities:

1. **Localization**: Enhancing map matching capabilities through varied data points like intensity and color.
2. **Obstacle Detection**: Identifying zones requiring heightened perception system engagement for obstacle tracking. Moreover, it serves as a foundational layer for road creation and is optimized for virtual environment visualization and editing, emphasizing its role in dynamic loading and object identification.

5.1.1.1.2 Road Map

Content:

The Road Map, derived from the Sensor Map, encompasses several layers:

1. **Physical Items**: Detailed visualization of roads, lanes, markings, and roadside elements, all characterized by precise attributes to replicate the physical world accurately.
2. **Road Safety Rules**: A comprehensive set of regulations guiding road use, ensuring safety and orderliness in vehicular movement.
3. **Vehicle-Specific Behaviors**: Customized instructions that adapt vehicle operations to the prevailing road conditions and rules, enhancing safety and efficiency.
4. **Algorithm-Specific Features**: Tailored indications for AD systems, reflecting the evolving nature of autonomous driving technologies and their requirements.

Creation:

This map is crafted through a mix of automated processes, capitalizing on semantic segmentation for accurate physical feature depiction, and manual inputs for non-physical attributes and corrections. GAMA's proprietary Map Editor software facilitates the meticulous creation of each element, evidencing the customizability and depth of the Road Map.

Use:

Serving as the AD system's reference point, the Road Map supports various applications:

1. **Visualization**: Offering passengers and supervisors a detailed overview of the journey.
2. **Mission Management**: Assisting in journey planning by defining routes and key waypoints.
3. **Driving Planning & Control**: Aiding in trajectory optimization for comfort and efficiency, based on lane-keeping strategies and future road event anticipation.
4. **Perception**: Enhancing localization and object tracking capabilities through detailed road mark analysis.

The Road Map's lighter format compared to the Sensor Map underscores its efficiency and practicality in computational processing, reflecting its optimized design for real-time autonomous vehicle operations.

In summary, GAMA's HD maps embody a fusion of sophisticated data acquisition, processing techniques, and detailed environmental modelling. This comprehensive approach ensures autonomous vehicles are equipped with the necessary information to navigate complex environments safely and efficiently, marking a significant milestone in the journey towards fully autonomous driving.

6 Fleet orchestrator maps – relation with HD maps

Fleet orchestrators are using city maps for the organization and management of the AV fleets. The maps used by fleet orchestrators for autonomous vehicles vary depending on the orchestrator's technology stack, partnerships, and the preferences of the autonomous vehicle (AV) companies using their services. The types of maps fleet orchestrators may use come from various sources, of which we provide an overview of the most important.

1. **Commercial HD Maps:**
   - Fleet orchestrators may leverage commercially available High-Definition (HD) maps, such as those provided by companies like Here Technologies, TomTom, or other mapping service providers. These maps offer detailed information about road networks, lane markings, traffic signs, and other essential features.
2. **Customized Maps:**
   - Some fleet orchestrators may develop or customize their own maps tailored to the specific operational areas of their autonomous vehicle fleets. These customized maps could include additional information relevant to their use cases.

3. **Real-Time Traffic and Dynamic Data:**
   - Fleet orchestrators often integrate real-time traffic data and dynamic information into their mapping systems. This allows for more adaptive route planning and dispatching based on the current traffic conditions and events.
4. **Geospatial Data Platforms:**
   - Fleet orchestrators may use geospatial data platforms that offer comprehensive mapping solutions. These platforms can provide various layers of information, including terrain data, building footprints, and other geospatial details.
5. **OpenStreetMap (OSM):**
   - OSM is a collaborative mapping project that provides free and editable map data. Some fleet orchestrators may utilize OSM data, possibly in combination with other sources, to build their mapping solutions.
6. **Sensor Fusion Maps:**
   - Fleet orchestrators may integrate data from various sensors on autonomous vehicles, such as LiDAR and cameras, to create sensor fusion maps. These maps enhance localization and provide additional context about the environment.
7. **Collaboration with HD Map Providers:**
   - Fleet orchestrators may collaborate with HD map providers to ensure compatibility with their systems. This collaboration could involve incorporating HD map data into the orchestrator's platform for more accurate route planning and navigation.

The ULTIMO project incorporates three major fleet orchestrators: ZF, Padam and Trapeze/Voyagerr, each making use of specific maps with specific features. We provide in the following an overview of the maps used by project fleet orchestrators.

6.1 ZF-CV

ZF's fleet orchestration platform strategically utilizes standard-definition (SD) maps to facilitate map-related tasks essential for orchestration, such as routing, navigation, and map matching. These SD maps typically model the drivable street network through a graph, employing edges to depict road segments and nodes to symbolize intersections. This structural approach is vital for detailed and efficient route planning in the context of fleet management and autonomous vehicle navigation.

6.1.1 Key Characteristics of SD Maps in Fleet Orchestration:

1. **Graph Representation**: The road network is abstracted as a graph, where edges denote road segments and nodes represent intersections, providing a clear structure for routing and navigation.
2. **Lane Representation**: Lanes within the edges are detailed as line strings, marked by geographic coordinates that pinpoint the center of the lane, aiding in precise lane-level navigation.
3. **Attribute Enrichment**: Edges are enhanced with attributes critical for driving decisions, such as speed limits, weight restrictions, and more. These attributes influence routing

decisions, ensuring compliance with road regulations and optimizing routes for specific vehicle characteristics.

4. **Linear Referencing**: Changes within an edge, like attribute modifications, are efficiently encoded using linear referencing. This method allows for dynamic updates and accurate representation of road conditions.
5. **Node Information**: Nodes incorporate data on driving continuation possibilities, encompassing turn restrictions, traffic lights, and precedence rules. This information is crucial for understanding intersection dynamics and making informed driving decisions.

6.1.2 Variability and Supplier Diversity:

SD maps' data formats and specifics can vary significantly depending on the provider. This diversity ranges from commercial entities like TomTom or HERE, offering extensive coverage and detailed attributes, to community-driven projects like OpenStreetMap, known for its open and collaborative mapping efforts. Additionally, autonomous vehicle (AV) manufacturers may develop proprietary SD maps tailored to their operational design domains (ODD), including unique elements such as specific turns, charging stations, or detailed segmentation for movement authority management.

6.1.3 The Evolution of AV Maps:

While today's AV deployments often necessitate custom mapping solutions to accommodate specific operational needs, the distinction between AV maps and general-purpose maps is expected to blur as AV technology matures. This evolution will likely result in more standardized mapping approaches, integrating unique AV requirements into broader mapping frameworks and making advanced navigation features more widely accessible.

The dynamic nature of SD maps, combined with the varied landscape of map suppliers, underscores the importance of adaptable and sophisticated mapping solutions in the realm of fleet orchestration and autonomous vehicle navigation. As the technology and applications of AVs continue to evolve, so too will the complexity and capability of the underlying mapping systems, promising enhanced efficiency, safety, and adaptability for future mobility solutions.

6.2 Padam

Padam Mobility stands at the forefront of Demand Responsive Transit (DRT) services, offering innovative solutions to dynamically manage and operate on-demand transportation systems. This flexibility allows for both real-time and scheduled services, necessitating robust and detailed map information to function effectively.

6.2.1 Map Information Needed

To ensure the seamless operation of DRT services, Padam Mobility relies on comprehensive map information:

1. Service Stops: Locations where passengers can board or alight from the service vehicles. These stops are crucial for planning routes and scheduling pickups or drop-offs.

2. Service Parkings: Designated parking areas for service vehicles when not in operation. These locations are vital for efficient fleet management and reducing response times for on-demand services.
3. Travel Time Between Stops: Critical for scheduling and route optimization, these times allow for accurate prediction of service schedules and enhancing passenger satisfaction.

Optional information enhances the service further:

1. Local or Global Travel Time Factors: Adjustments to travel times based on congestion, roadworks, or other factors that can impact the usual travel durations.
2. Streets Not Available for Service Vehicles: Identifying roads that are unsuitable or restricted for service vehicles, ensuring that routing algorithms avoid these areas.

6.2.2 Structuration and Format

Padam Mobility engages directly with clients, including operators and authorities, to gather essential geolocation data for stops and parking, as well as an initial travel time matrix. This collaboration ensures that the service is tailored to the specific needs and conditions of each area:

1. Custom Map Creation: Utilizing the collected data, Padam Mobility crafts a custom map in the OpenStreetMap format, serving as the primary reference for the service. This map is continually refined based on field feedback and data collected throughout the service lifecycle.
2. Real-Time Traffic Data: Incorporating data from real-time traffic providers offers the ability to dynamically adjust routes and schedules, accommodating for unexpected road conditions and ensuring optimal service performance.

6.2.3 Features

The custom map developed by Padam Mobility includes several key features to optimize DRT operations:

1. Road Restrictions for Service Vehicles: The ability to mark specific streets as off-limits for service vehicles, ensuring that routes are safe and efficient.
2. Travel Time Adjustments: Applying factors to travel times, either locally for specific routes or globally across the service, allows for more accurate scheduling and routing in response to varying conditions.
3. Time Slot-Specific Travel Times: Recognizing that travel times can vary significantly throughout the day, this feature allows for the definition of different travel times for specific time slots, enhancing the accuracy of service schedules.

Through these advanced mapping capabilities and features, Padam Mobility provides a robust foundation for DRT services, enabling flexible, efficient, and reliable transportation solutions tailored to the unique demands of each service area.

6.3 Trapeze/Voyagerr

Trapeze/Voyagerr is at the cutting edge of providing on-demand transportation solutions, catering to both private operators and public authorities. The company emphasizes the importance of precise and detailed mapping data to enhance its services, recognizing the critical role of maps in routing, navigation, and map matching..

6.3.1 Mapping sources

Voyagerr relies on a variety of mapping sources to tailor its services to specific areas, understanding that the right map can significantly impact service quality.. Over the years mapping sources has become increasingly better, still it is vital to get the right map for the projected service area, this goes for both the actual network but also for the address points and points of interest. However, commercial maps are expensive, so to the budget conscious client compromises may have to be taken, resulting in perhaps less accuracy in distance, travel time or pickup/drop-off locations.

To this end a number of format can be accepted as source for the mapping service :

- Commercially Available Maps: Such as TomTom, Google, and Here, known for their comprehensive coverage and detailed attributes, essential for accurate distance, travel time, and pickup/drop-off locations.
- Publicly Available Map: OpenStreetMap offers a collaborative platform that allows for up-to-date and versatile mapping data, beneficial for budget-conscious clients.
- State Subsidized and ESRI Based Maps: Provide additional options, offering detailed geolocation and travel time data essential for route planning (Statens kartverk, Adresspoints : DAV, ESRI based maps)

Typically, if there is a need to embed the map into the solution, they are delivered in MIF or ESRI format for further processing.

6.3.2 Preparing the map

Some of the map providers have online services that can be used by the optimization directly in terms of calculating distance and travel times. Obviously, the preparation and updates are handled by the map provider in those circumstances.

However, depending on the client's service area, number of vehicles / clusters / runs, number of trips relying on an online map may be too slow to get the right quality in optimization. Once the numbers add up the complexity and permutations to investigate multiply exponentially.

To that end, the network is loaded into an embedded network engine, which eliminates all the overhead and computes distances and travel times in parallel threads, allowing for deeper and faster optimization.

Initially, if embedded, the map will be loaded with arc-based speed profiles either prepared by the map vendor or based upon the clients' observations. If applicable speed profiles for different vehicle types can be added.

6.3.3 Updating the map from usage

Adress points : Typically, new address points are made during usage, i.e. at a hospital there may be several entrances for different purposes, fine tuning and reusing these address points makes the map usage more efficient. At some PU/DO locations the load/unload time may also differ from standards, and including these will also increase accuracy.

Observations : Observations of speed, distance and travel time is being gathered from the vehicle device or the vehicle itself. Depending on the frequency of receiving signals these observations are used to finetune the speed profiles based on certain criteria.

*Frequent travels :*On-demand travelers tend to travel the same routes. This is used to maintain a cache of often travelled routes. This speeds up calculating travel times immensely and can be used both for the online and the embedded version of the network engine.

Inaccessible If the provided address points and/or the network proves to have points that are inaccessible for i.e. wheelchair users, or certain alleys where vehicles of a certain type cannot access, this is added to the map continuously.

6.3.4 Scheduled updates of the map

With a subscription from a map provider, an update is received regularly, typically every quarter of a year. Due to faring, updates are normally scheduled such that clients can expect the same fare for a trip for a specified time, normally once every year. An update to the map may alter the distance for a trip, and sites will rather live with the inaccuracy, than deal with unhappy clients where the fare has been changed unexpectedly. If needed a special map for faring can also be embedded.

Roadwork : Planned roadwork can be added to the map with a layer that prohibits or slow down speed on the specific segments of the network.

6.3.5 Non - Scheduled updates of the map

Accidents : Monitoring the execution of the scheduled PU/DO will disclose if main streets have been blocked by an accident. The delays will start to get bigger, and the procedures for dealing with this will kick in. Depending on the signals from the vehicle device a predictable delay module can be activated to allow for earlier detection of problems in the network.

Commercial real time traffic monitoring services can also be used for earlier detection of delays, and activation of mitigation procedures.

Snowfall : In case of heavy snowfall a polygon based reduction of speed can be imposed on the map, where the polygons can be “lifted” as the roads are getting cleared of snow.

6.3.6 Relation and needs with AV HD maps

In order to achieve a high-quality service and deployment of AVs, the HD maps used by the Automated vehicles and the maps used by the fleet orchestrators must be highly synchronized and compatible, based on close integration and collaboration. HD maps for AVs provide the detailed information needed for precise vehicle operations, while fleet orchestrators leverage this information to optimize the routing, dispatching, and overall management of the entire fleet, whether it includes autonomous or human-driven vehicles.

Needs :

- synchronised updates (technical details : xml files etc
- temporary roads info
- Speed info

Due to the way public transportation is organised in the Nordic countries, synchronizing maps in the vehicles that operate the different public transportation services is not feasible task. The PTA will be administrating the routes and doing the scheduling / optimization, and will put out route packages for tender, that the PTO will bid for to win. The PTA does not have any jurisdiction to impose their maps on the PTO fleet of vehicles and the PTO may also use their vehicles for other purposes with different mapping configurations.

The same goes for vehicles used for on demand services. The PTA will optimise in real time the on-demand bookings into routes that are assigned to the operators. The operator will have won a contract delivering x number of vehicles with a specified capacity and in a defined timeframe. It is then up to the operator to assign the vehicle most suited in his operation to execute the task.

Unsynchronised travel times between fleet orchestrator and vehicle is almost a given, since it will always be an approximation. Having the same type of vehicle doing the same route, will in most cases result in different travel times, due to traffic conditions. This means that the orchestration of the fleet of vehicles will have to adapt to an imperfect world in terms of calculation ETA and travel times. Instead it falls on the fleet orchestrator to handle this by continuously recalculate the ETA based upon GPS location signals of the vehicle that is assigned to the route, or if possible call for an ETA estimate from the services that the PTO makes available. This will enable the fleet orchestrator to reschedule, add or alter routes based upon observations made in real time traffic. In this respect there is no difference between operating non-AV and AV vehicles.

Obviously, if roads are closed etc. It makes sense for both the PTA and the PTO to incorporate that into their systems, but it will not be by imposing a synchronised map onto the fleet of vehicles from the different PTO that are operating for the PTA... at least in the nordic way of organising on-demand services.

Conclusion:

There are requirements that the routing maps are in sync across all stakeholders. The (data) standards and APIs required to exchange this data should be defined within the project Ultimo.

- Reason why to be detailed, eg. Road closures, accidents, traffic jams, etc.
- Validation of 3rd party data? Data accuracy needs to be considered to ensure it's from a trusted source and is up to date.

6.4 Conclusions

The creation of HD maps for Automated Driving Systems (ADS) is a complex process requiring several phases and integrating an important number in information layers. Some of the phases and layers of HD maps might be able to be shared and reused by the different ADS manufacturers, like the raw data of LIDAR and images, or the user annotations, while for others this can be from complicated to practically impossible, as is the case of the map generation phase.

As we said the raw data might be easily reused. However they will need to be stored, requiring for a medium size city several thousands of TBs. One issue that needs to be investigated is whether a given resolution and density of the LIDAR would be sufficient for the different ADSs.

From the phase of data processing, the part of cleaning the data is common to all ADSs. However each ADS provider will use its own datasets to segment and identify elements. Therefore we might consider a global common datasets that can be used by all ADS providers. A common dataset would have the advantage to provide a common identification of elements, possibly improving the overall efficiency. We will need however to investigate if the datasets and segmentation techniques are linked to the specific ADS algorithms. Furthermore, a richer dataset can also be a commercial advantage for an ADS provider, as it would be able to classify secondary elements, that might lead to ADS performance improvement.

In the third phase of an HD map creation, the fusion of data, it is not, at this stage, clear how the data fusion is related to the specifics of the ADS. We will investigate the methods used by the different ADS manufactures to identify common parts and differences.

The final stage of an HD map creation for ADS is its optimisation for the specific Autonomous Driving System. This optimisation is specific for the each ADS, and by cannot be standardised, as this would means that the different ADSs will have to “behave” similarly to each other, since this is what makes the different (and is the commercial advantage) of each ADS manufacturer.

From the above, it is clear that a common HD map, able to be used *as-is* by different ADSs will not be possible. Even is the result of the third phase of the data fusion provides a common model, the optimisation will aways be specific to the ADS.

In the next phase of the project we will define which parts of the resulting map creation phases can be reused as-is, which will need some automated conversion processing and which would be proprietary, tightly linked to the specific ADS.

Another option which we will investigate, will be whether systems for automatic, on the fly HD map generation can be an economic option in a multi-vendor environment. In this model the map generation is no longer an issue, as it vehicle creates its map on-the-fly. The key issue will be how the generated on-the-fly maps and updates are propagated to the fleet, which is composed of vehicles from different vendors, and thus the HD maps are optimised for the specific ADS.
In preparation of the PTO/PTAs for the future of the HD maps, we provide 2 recommendations:

Recommendation 1 – Integration of Operator Maps : incorporate in the project their relevant services that handle the current maps used for their traditional services, so that they can identify how the new types of maps can be effectively integrated to their existing operations.
Recommendation 2 – **Life cycle needs** : identify and classify, based on historical data, the cases and their frequency and duration, that will trigger a map update, identifying the possible sources from which the information can be obtained in advance (ex. road works preparation)

7 Maps for Highway (from MODI)

7.1 Requirements of Highway Logistics Maps

The MODI project concerns logistics on the transport corridor from Rotterdam to Oslo, primarily consisting of highways and logistics hubs. The requirements on HD Maps for heavy logistics trucks on highways differ from those for passenger vehicles in an urban environment due to differences in vehicle type, operation type, speed, and the complexity of the physical environment. However, the vehicles must also operate in city-like environments near the transport hubs, where the requirements are similar to those for passenger vehicles in the urban environment.

Highways offer a relatively static and predictable environment compared to urban areas, as they lack the complexity of pedestrians and other road users, traffic lights, and complex intersections. Once the vehicle has entered a highway, the driving task is relatively stable and fit for automation.

Core elements like lane markings, road signs, exit locations, and basic navigation restrictions remain essential for automated driving on highways, like for urban areas. Heavy vehicles also need access to additional annotations specific to their operation, such as weight limits, bridge and tunnel heights and widths, designated truck lanes, and rest areas. Information about the location and whereabouts of safe harbours where vehicles can perform minimum-risk manoeuvres is a particularly critical component for highway operation.

Finally, as vehicles on highways operate at high speed, the knowledge of what lies ahead must extend further than what is needed in an urban environment with low speed. Heavy vehicles at high speed require a long distance to stop or perform other critical manoeuvres. Therefore, the criticality of dynamic information covering the road ahead is particularly high, and the area of interest will be more extensive.

7.2 Existing HD maps

Currently, existing HD maps have not been developed specifically for the requirements of highway operations. The findings from the MODI project show that existing HD maps from commercial actors suffer from the same challenges as described in this report: vendor-specific construction and the lack of standardization.

Each vendor employs its methods for constructing and maintaining HD maps. This can lead to variations in content, accuracy, and update frequency, making it difficult to assess the overall quality and reliability of the available options.

The absence of standardized specifications creates a fragmented landscape. Different vendors utilize their proprietary formats and structures, hindering interoperability and data exchange. This inconsistency presents a significant challenge for fleet operators needing to integrate data from multiple sources.

7.3 Open issues

Several open issues concerning HD maps for heavy logistics vehicles on highways need to be addressed.

- **Incomplete Coverage**: Creating and maintaining HD maps across extensive highway networks is resource-intensive. Achieving complete coverage can be challenging, leaving certain areas unmapped or inadequately detailed. This can limit the applicability of HD maps for long-haul operations.
- **Data Cost and Updates**: Collecting data and updating HD maps is costly and time-consuming, which can potentially hinder widespread adoption.
- **Standardization Needs**: Establishing standardized formats, content specifications, and update protocols is crucial for ensuring interoperability, data quality, and broader ecosystem integration.
- **Collaboration Gaps**: Bridging the collaboration gaps between mapping authorities, HD map producers, and logistics companies is essential. Sharing data and expertise can accelerate progress in achieving comprehensive, cost-effective, and standardized HD maps tailored to the specific needs of highway logistics.

In conclusion, HD maps present a significant potential for enhanced efficiency and safety in highway logistics. Addressing the current limitations through standardization, collaboration, and innovation will be crucial for unlocking their full potential and facilitating the smooth transition towards automated transportation in this critical sector.

7.4 Relation with the ULTIMO project

The MODI project targets long range logistics, traversing highways and having as arrival point logistics' hubs, that are found in the city or at sub-urban industrial sectors. On the other hand the starting urban logistics' service of the ULTIMO project is the last mile distribution with a starting point the urban or sub-urban logistics' hubs. That is, the two projects cover the complete logistics chain, with a common point the logistics hubs.

The key HD maps that are addressed by the MODI project are high-ways' HD maps. However, the MODI automated vehicles will also drive in urban environments to reach the logistics hubs. As a result HD-maps of the urban roads will be also required by the MODI vehicles.

In the ULTIMO project the main deployment area is the urban environment, and this constitutes the main interest for the HD maps. However, in our site at Oslo the ULTIMO AVs will need to use the high-way connecting the different deployment regions. Therefor, HD maps of the highways will be also required for ULTIMO.

Considering the different needs of HD maps by the different types of vehicles of the two projects (heavy tracks and light shuttles) it is important to identify how and if the needs for HD maps can be aligned and if a consolidated model is possible.

The collaboration work between the two projects will investigate the differences and common parts in the needs of HD maps and propose possible solutions and approaches for the creation of reusable HD maps or portions of them.

8 Alternatives for pre-scanned HD maps

Dynamic map creation techniques, which craft maps in real-time by integrating LiDAR and camera data and leveraging AI to identify road elements, are increasingly utilized by numerous firms. This innovative approach negates the necessity for pre-scanning the terrain, thereby slashing costs and enabling functionality in previously unmapped areas. While this methodology harbors significant potential for Level 5 autonomous driving, its alignment with specific project goals, needs, and use cases might be less than ideal.

For public transportation, the operation area is usually predefined and limited, requiring consistent city information usage across the entire vehicle fleet. Dynamic map creation, tailored more towards private vehicles, lacks the central coordination essential for managing public transport fleets.

Furthermore, public transport systems are governed by strict rules and regulations, dictating permissible stop locations, bypass routes, speed limits, and more. These critical directives must be annotated on the maps before deployment. With dynamic mapping, incorporating another layer for these annotations becomes necessary, albeit in a different format that needs dynamic superposition onto the scanned areas.

The ideal scenario would entail a hybrid model combining pre-scanned maps with real-time updates, enabling vehicles to detect changes in their environment and adjust their operations accordingly. Moreover, a comprehensive logistics system is crucial to disseminate new data across all fleet vehicles efficiently. This integrated approach ensures that vehicles are not only aware of their immediate surroundings but also adhere to predefined operational guidelines, enhancing both efficiency and safety in public transport systems.

By adopting a system that marries the benefits of static pre-scanned maps with the adaptability of dynamic updates, public transportation can achieve a higher level of service reliability and responsiveness to changes in the road environment. This blend of technologies allows for the meticulous planning and coordination required in public transit operations while maintaining the flexibility to navigate unforeseen obstacles and alterations in the urban landscape.

9 Conclusion

An important element of the ULTIMO project to provide an economic model for the creation and maintenance of HD maps that are needed by the AVs. The PTOs of the project will need to map a large area for the mobility services. The model that is used today is a clear customer locking model, where the vehicle manufacturer includes in its deployment set-up services the mapping of the deployment area and includes this in the total price of the vehicle licenses or services, thus increasing the overall cost for the PTO. As ULTIMO targets in reducing the deployment costs of AV based mobility services, and since we expect a multi-vendor fleet, the PTOs cannot logically pay the costs of mapping for each different vehicle type. Although one can consider the creation of the HD map as an investment of the PTO, this is not valid, since the HD map is linked to the specific vehicle manufacturer and, today, cannot be reused or valorized for any other vehicle. For each new vehicle manufacturer the process must start from zero.

Our target is to reuse the largest possible number of elements composing the HD maps. As we have presented the key layers of an HD map are topology layer, geometry layer and semantic layer, followed by format optimisation processing for the specific ADS of the vehicle. It is clear that the topology layer can be reused, as it is based on standard maps available in the market.

From the different elements composing the HD map, the project will identify which elements and layers can be reused or can be easily and automatically converted between the different types of HD maps the vehicle manufactures are using. It is clear, for example, that the topology layer can be reused (and also shared by the fleet orchestrators), as it is based on standard maps available in the market, while the geometry layer depends on the specific scan capabilities of the vehicle and cannot be reused or converted easily. Similarly the semantic layer, with all the PTO annotations and road elements classification can be partly reused.

Implementing conversion algorithms between the different types of HD maps created and used by the different vehicle manufacturers, will be a major challenge as each manufacturer does not provide any information on the models, methodology and algorithms it is using, as each is optimised for the ADS of the manufacturer and any information provided can be reversed engineered and possibly provide information on the ADS algorithms (as this was explained to us by vehicle manufacturers).

Nevertheless, PTOs can specify in the terms of any procurement, that the new vehicle manufacture should take up the existing information of some of the HD map layers and incorporated it to its own HD map at no cost to the PTO. This will eventually force the vehicle manufacturers to adopt a common standard for the specific layers.

At the same time, and since our target is the creation of an overall commercial viable service, we will also look to new technologies and models that some vehicle manufactures are proposing with on-the fly map creation and automated propagation of modifications to the complete fleet[1]. This type of technology, if it performs as it promises, will solve the complete problem of HD mapping costs and life cycle, as the HD map is created by the vehicle itself.

[1] We cannot at this stage provide more information, as this information is confidential.

However, the semantic annotations will still require to be introduced in some way, and thus a standardisation of the semantic information will be once more required.

For the next project period, we will work towards the detailed definition of the HD components and layers, identifying in detail the models and structures used and identify how and at what cost they can be harmonised and eventually stanardised.

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