



Published  
January 2021

# P1-021: Map creation, monitoring and maintenance for automated driving – Literature Review

*This research is funded by the Department of Transport and Main Roads, RACQ, Queensland University of Technology and iMOVE CRC and supported by the Cooperative Research Centres program, an Australian Government initiative.*

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## Study Partners



# 1 Abstract

Automated vehicles (AVs) are an emerging new technology which promises to remove some, or all, driving tasks from human control. In recent years technological advances have made automated vehicles increasingly viable, with low levels of automation already in market-ready vehicles. Transitioning from semi-autonomous to fully-autonomous widespread operation is the current problem facing most key AV developers. Challenges include developing reliable autonomous driving solutions for operation in conditions such as heavy traffic, snow, rain, and that reliably detect and interact with vulnerable road users like pedestrians and cyclists. As of writing, only a small number of automated vehicle developers are running trials without any safety driver in the car, and still rely on remote supervision in these cases or a vigilant backup driver in the case of Teslas.

Some of the aforementioned difficulties can be alleviated by providing automated vehicles with a prior high definition (HD) map. Prior maps encode road-level features such as the position of street signs and lane markings, with up-to centimetre accuracy. This allows for the vehicle to verify the data received by its sensors against the prior map, and to even “fill in the gaps” where the incoming sensor data is limited due to difficulties such as rain or occlusions. Such findings were confirmed by a prior iMOVE Australia, TMR and QUT project titled *P1-007: How Automated Vehicles Will Interact with Road Infrastructure Now and in the Future*.<sup>1</sup>

The objective of this project, a partnership between iMOVE, TMR, RACQ and QUT, is to conduct a comprehensive literature review into the use of prior maps in automated vehicles, with a particular focus on the potential role for government in developing, monitoring and maintaining these maps. Reliably maintaining these prior maps in a manner that is sufficiently responsive to enable the ongoing and safe operation of AVs is a challenge that will likely require some form of collaboration between car manufacturers, map makers and Governments, with agreements concerning geospatial data storage and sharing critical to the future success of automated vehicles.

In this report, we discuss the key issues concerning the use of prior maps for automated vehicles. The report contains a detailed review of the technology behind high definition (HD) prior maps for automated vehicles, along with many discussion points based on our literature search, encompassing data from both private companies and overseas Governments. The discussion considers what overseas Governments have done to assist the development and deployment of HD prior maps, what data needs to be shared between Government and private enterprises, and a set of recommendations that would potentially suit the Australian context, considering a range of adoption and partnership strategies going forwards. We hope that this report aids in the development of future projects and policies in Queensland that help facilitate the introduction of sustainably deployable automated vehicles.

1: <https://imoveaustralia.com/news-articles/intelligent-transport-systems/autonomous-vehicles-australian-roads/>

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### 3 Glossary of Terminology and Abbreviations

- **Absolute Accuracy** - A term using in spatial maps to define the proximity of a measured map feature to the true position (in global coordinates) of that map feature (the difference between a map and the real world).
- **ADAS** - Advanced Driver Assistance Systems. Defines automation systems that assist the human driver in performing the dynamic driving task.
- **AEB** - Automated Emergency Braking.
- **AV** - An acronym for Automated Vehicle. A vehicle which may perform all of its actions autonomously. An automated vehicle is capable of performing the entire dynamic driving task without human input, either with human supervision (SAE level 3 autonomy), without human supervision but limited ODD (SAE level 4 autonomy), or under all possible conditions (SAE level 5 autonomy).
- **CAM** - Connected and Automated Mobility. Refers to vehicles that are both connected by communication systems and automated.
- **CAM** – CAM can also refer to the data format called Cooperative Awareness Message. This is a V2X data format defined by ETSI (similar to DENM). The purpose of a CAM is to communicate and share the location of vehicles, vulnerable road users and roadside infrastructure to each other.
- **Connected Vehicle** - A vehicle which has built-in real-time communications with the world outside the vehicle. This could include internet access, communications with other vehicles and communications with roadside infrastructure.
- **Datex II** – A data exchange standard used to transfer traffic management data between traffic management centres in the EU. It is heavily supported by private companies in the EU.
- **DENM** – Decentralized Environmental Notification Message. Is a data format used for ITS communications, particularly for V2X communications, as defined by ETSI. Its primary purpose is to communicate abnormal events (accidents, road works, abnormal traffic conditions) to vehicles.
- **DSRC** - Dedicated Short-range Communications.
- **Dynamic Driving Task** - Refers to all the functions required to operate a vehicle safely in on-road traffic. Includes steering, acceleration, braking, hazard detection and path planning.
- **ETSI** – European Telecommunications Standards Institute. Is an organisation whose objective is to produce information and communications technology standards to fulfil the needs of the EU.
- **FCD** - Floating Car Data. Is timestamped geo-localisation and speed data directly collected by moving vehicles. At present, this data is typically collected using mobile phones in cars.
- **GIS** - Geographic Information System.

- **GLOSA** – Green Light Optimal Speed Advice.
- **GNSS** - Global Navigation Satellite System.
- **HAD** - Highly Automated Driving.
- **ICP** - Iterative Closest Point. An algorithm that attempts to align two point clouds by iteratively estimating a geometric transformation between the two point clouds and removing outlying points.
- **ISO 26262** - Standard titled “Road vehicles - Functional safety”, published by the International Organisation for Standardization.
- **ITS** – Intelligent Transportation System.
- **LiDAR** - Light Detection and Ranging. A sensor that uses low energy laser light to record distances to objects in the environment.
- **ODD** - Operational Design Domain. Defines the parameters in which the automated vehicle is allowed to operate.
- **Point Cloud** – is a collection of points in a 3D space. Each point has its own x, y and z coordinates and typically is very dense (i.e. a very large number of points in a given area).
- **Relative Accuracy** – is the positional accuracy of a point on a map, when compared to other points on the map. In other words, a high relative accuracy means that the distance between two points on the map is equivalent to the true distance between those two points if they are measured in the real world.
- **VANET** - Vehicular Ad Hoc network. A term defining groups of stationary and/or mobile vehicles connected by a wireless network.
- **V2V** - Vehicle to Vehicle. A term defining communications between vehicles.
- **V2X** - Vehicle to Environment. A term defining communications between a vehicle and the surrounding environment.
- **VRU** – Vulnerable Road User. A term defining a pedestrian, or cyclist who is either on the road, or in close vicinity of the road.
- **Voxel** – a voxel is analogous to the 3D version of a pixel; it is a cube within a 3D model and may be either an occupancy voxel (binary, denoting the presence or lack of a solid object) or colour voxel.
- **XFCD** - Extended Floating Car Data. Defines additional floating car data beyond position and velocity. This can include rain sensors, hazard warning flashers and advanced driver assistance systems.

## 4 Introduction

This report, titled P1-021: Map creation, monitoring and maintenance for automated driving, provides a holistic literature review of the creation, use and maintenance of prior maps for automated vehicles. Specifically, this report focuses on automated road transport vehicles and a spectrum of maps ranging from enhanced digital maps to high definition maps. **Section 6** begins by describing the technology underpinning high definition maps and the use-cases of these maps. Data formats for storing HD maps and formats for transmitting data to enable real-time map updates are discussed in **Sections 6.5** and **6.6** respectively. **Section 7** provides an overview of the entire prior map space, discussing how automated vehicles can benefit from standard digital maps, enhanced digital maps but most of all, high definition maps. **Section 8** dives deeper into high definition maps, discussing individual map solutions provided by map makers and automated vehicle companies, to the extent to which was possible given significant commercial pressures around privacy in the sector. **Section 9** provides critical information on the progress international governments have made in this space, including what they have done to create, assist, maintain or consume prior maps for automated vehicles. **Sections 9.6** and **9.7** summarize current progress on collaboration between infrastructure managers and private map providers, to move towards the goal of real-time accurate high definition maps. Finally, **Sections 10** and **11** provide discussion on recommendations and avenues for future work; what are the possibilities moving forwards, considering the position of Australia with respect to adopting these new technologies.

The content of this report was guided by the following project scope:

- What is being done globally to investigate the use of prior maps in automated driving?
- What are the EU, US and other governments assuming?
- What are the likely industry models, considering the following specifications of:
  - Type of content
  - Extent
  - File formats
  - Initial acquisition approaches
  - Maintenance requirements
  - Limitations
  - Commercial models
- What models are being implemented or considered for the government’s role in prior maps, which could include being the creator, curator or consumer of maps.
- What is being assumed of the government?

The authors would like to conclude this section by acknowledging and thanking the valuable input and discussion from all parties involved including but not limited to: TomTom, Atlatec, AustriaTech, Austrian Institute of Technology, and the Centre for Accident Research and Road Safety – Queensland.



## 5 Methodology

In this section we discuss the data sources used to compile this report. The primary data sources used to date are listed below:

- Web-page searching using a search engine (Google)
- QUT Library search
- British Standards Online database searching
- Hyper-links within documents found via web-page searches
- Conference proceedings
- Networking - discussions with industry
- Searches within Government databases, for example U.S. Government Accountability Office

A sample of the search terms used is provided below:

- “US DOT HD maps for automated vehicles”
- “automated vehicle maps”
- “connected and automated mobility”
- “difference between NDS and ADASIS”
- “national mapping agency Ordnance Survey”
- “intelligent transport systems”

As part of this project, we completed the following interviews and email conversations:

- Interview with HERE Technologies representative on 20/08/2020.
- Interview with TomTom representatives on 24/08/2020.
- Email correspondence with Atlatec representative.
- Email correspondence with representative from AustriaTech.
- Email correspondence with Research Scientist at Austrian Institute of Technology.
- Email correspondence with Centre for Accident Research and Road Safety – Qld.

## 6 Overview of Mapping

Maps are navigational tools used by humans for thousands of years, which in modern times have evolved into highly detailed meter-accuracy maps enabled by technology advances including satellites. The first use of maps in vehicles stems back to the 1930s, with a paper-reel system and crude dead reckoning used to create a basic navigation system for a human driver [1]. The advent of GPS revolutionised the concept of in-vehicle navigation; however, for Advanced Driver Assistance Systems (ADAS) and Automated vehicles, more detailed maps are required.

In *High Definition Map for Automated Driving: Overview and Analysis* by Lui et.al., three map types are defined: digital maps, enhanced digital maps and high definition (HD) maps. Digital maps are the traditional modern street maps, such as Google Maps and OpenStreetMap. Enhanced digital maps include additional data such as road geometry, signage, lane design and speed limits [2]. The enhanced digital map originated from the NextMAP project [3] in the EU, beginning in the year 2000. Finally, HD maps include all the features of the previous categories, plus a 3D representation of the world surrounding the vehicle. The concept of a HD map was developed in 2010 at a Mercedes-Benz research planning workshop [4]. A HD map can be considered as an additional “sensor”, one that is immune to environmental occlusions (if the map is kept accurate and is used appropriately, with an understanding of its own limitations). Maps can be owned and maintained by different stakeholders, from Government to Private Enterprises, and collaboration between both parties is likely to be essential for achieving sufficiently reliable maps for autonomous driving. In the following subsections, the technology behind map usage by automated vehicles is discussed in more detail.

### 6.1 Technology – Usages of Maps in Automated Vehicles

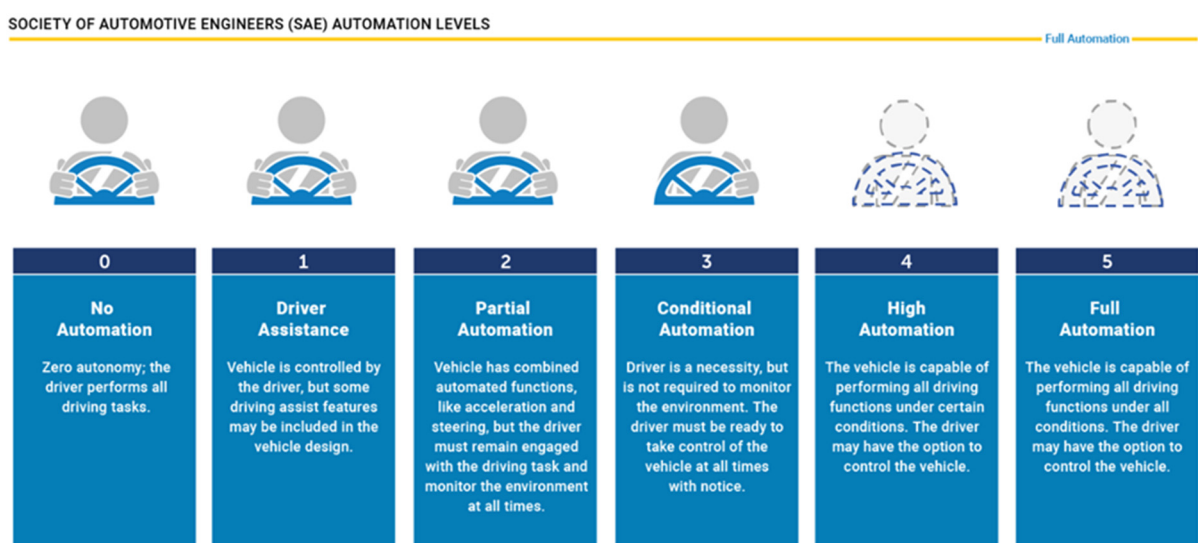


Figure 1: The Society of Automotive Engineers has defined five levels of AV autonomy [5].

We provide Figure 1 from [5] above, to inform the reader of the different levels of autonomy in driver-less vehicles. Maps are useful for all levels of autonomy, but become increasingly critical as the level of automation is increased (Tesla is a key current example of a provider of medium level autonomy in on-road vehicles without the use of maps, but full Level 4-5 mapless autonomous driving has not yet been demonstrated reliably, despite repeated claims).

Why are prior maps critical for autonomous driving? Lyft's self-driving division wrote an article which provides justifications for using high quality prior generated maps on AVs [6].

These benefits are listed and summarised below:

**Mapping as pre-computation:**

If the map is updated regularly and reliably, parts of the autonomy problem can be solved in advanced in an offline manner, using advanced computation equipment that would be impractical to contain on-board the vehicle.

**Mapping to improve safety:**

HD maps can encode speed information but also track speed profiles derived from actual human drivers (e.g. what is the safe speed to turn around a curve).

**Mapping as a unique sensor:**

Maps have no range limitation, and are immune to run-time occlusion from dynamic objects. This is also termed Electronic Horizon Predictive Awareness.

**Map as a global shared state:**

Map data is shared and updated by multiple AVs, allowing for real-time map updates and improved confidence in the accuracy of the map.

The value of a prior map to an automated vehicle is dependent on both the amount of useful information in the map and the frequency of updates. Update frequency is not an absolute as it depends on the dynamism of the environment - with highly dynamic environments generally requiring more frequent map updates. The amount of information present in a map representation can be loosely categorized into one of three categories: digital maps, enhanced digital maps and high definition maps.

## 6.2 Technology – Types of Maps

### 6.2.1 Digital Maps

A standard digital map is the traditional electronic street map in regular use by humans, as provided by numerous map creators including Google Maps, Garmin, OpenStreetMap and Apple Maps. These are *topometric* maps, encoding street structure, names and approximate distances. It's important to note that an automated vehicle can still gain benefit from access to these prior maps, but these maps alone are unlikely to be a key enabler of full autonomous operation (as opposed to HD maps).

These types of maps are now almost universally built-in to brand new vehicles. Unfortunately, these in-built maps typically have no connectivity to external devices and are only updated when the vehicle is returned to a dealership for a service. As a result, update frequencies are annually or bi-annually at most.

Such a low update frequency means these maps have very limited utility for automated vehicles. The utility can be increased if the update frequency is increased, such that the map reflects both an accurate road network and traffic condition updates (e.g. accidents). As an example of this, recently Ford integrated Waze (a crowd-sourced real-time updated map) into their in-vehicle navigation system [7]. However even with an up-to-date map, the lack of positionally accurate and identifiable environment details (e.g. the position of a stop sign) limits the degree to which it can aid an automated vehicle, except in high level navigation tasks like planning the fastest route from A to B.

### 6.2.2 Enhanced Digital Maps

An enhanced digital map can be defined as a standard digital map that has had some additional data types included, that is beneficial to both Advanced Driver Assistance Systems (ADAS) and fully automated vehicles. Additions include road speed limits, road curvature, lane structure and road signs (e.g. stop signs). These additions are described in more detail in the list below. The list was compiled using features provided by TomTom's ADAS map solution [8].

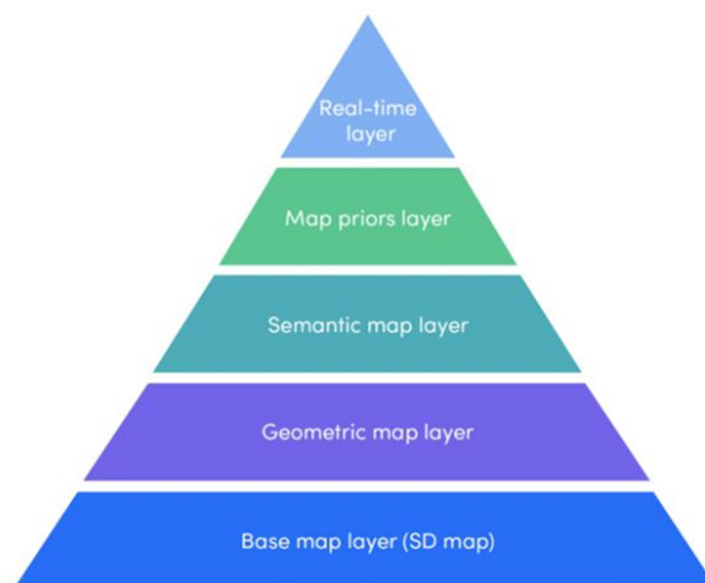
- **Road Curvature** - an enhanced map typically includes the curvature, in degrees, of curves in the road. Usually this includes a recommended safe speed to navigate the curve and could also include multiple speed options depending on the weather conditions.
- **Gradient** - the ADAS map will include the gradient (slope) of the road. Such details are very important for autonomous trucks, where inappropriate gear selection can cause excessive wear on their brakes.
- **Curvature at junction** - essentially describes the "sharpness" of a junction. Advanced knowledge of this attribute enables an automated vehicle to accelerate at the correct

speed to handle the curve into the junction, to manage both passenger comfort and vehicle safety.

- **Lane at Junction** - informs either the driver or automated vehicle of lane markings and possible manoeuvre options for the junction.
- **Traffic signs** - provides prior information concerning the presence of important signage to either the driver or automated vehicle.
- **Speed restrictions** - enhances the functionality of adaptive cruise control.

In the literature, there is no clear division between an enhanced digital map and a high definition map; some providers market quite basic maps (with minimal additional features) as a “HD map”, at odds with the more common definitions of a HD map comprising a dense 3D world representation. In this report, we make the divide clear by categorising any map product which stores a 3D world representation as a HD map, and any remaining maps are defined as enhanced digital maps. **Standardization of terminology will likely be key** to further progress in the commercial and government provision and usage of these maps.

### 6.2.3 High Definition Maps



*Figure 2: Lyft's HD map pyramid structure [6].*

A High Definition (HD) map extends upon an enhanced digital map by recording a 3D representation of the world around the vehicle. This representation can be generated using a variety of sensors including LiDAR, radar and cameras. It is worth repeating that the definition of what constitutes a “HD map” varies by provider - there are no strict guidelines as to what constitutes a HD map. However, the key agreement between all providers is that the HD map must have a high positional accuracy, in the order of approximately 10cm [9], [10]. Higher accuracy is always better, although technological limitations restrict the maximum possible accuracy of map features (please refer to Section 6.4 for a further



discussion on map accuracy). At the basic end of the HD mapping spectrum, a HD map can simply be a collection of accurate positioning of road signs, lane markings and guardrails in the environment. At the advanced end, a HD map is a dense LiDAR point cloud, storing the distance to every obstacle around the vehicle. A HD map will typically be broken down into multiple layers, where each layer will include different types of information - as an example of Lyft's HD map layers, see Figure 2.

In Lyft's HD map, the five core layers are described as follows [6], [11]:

- **Base map layer** – the entire HD map is layered on-top of a standard street map.
- **Geometric map layer** – in Lyft's maps, the geometric layer contains a 3D representation of the world around the road network. This 3D representation is created using sensors such as LiDAR and cameras, and is represented by a voxel map with voxels of size 5cm x 5cm x 5cm. Voxels are small cubes used to represent 3D spaces – they are a lower-storage alternative to point clouds.
- **Semantic map layer** – the semantic map layer contains all the semantic data, including lane marking positions, direction of travel and position of traffic signs. There are three sub-layers within the semantic layer:
  - **Road graph layer** – the road graph layer within the semantic layer contains all the road segments and interconnections – the number of lanes, direction of travel for each lane, and yield relationships between all lanes across the entire road network. This layer is sometimes referred to as the **logic layer**.
  - **Lane geometry layer** – the lane geometry layer contains centimetre accurate lane geometry. In Lyft's maps, this also includes details such as the type of lane (i.e. is the lane dashed and thus allows for overtaking, or solid?).
  - **Semantic features** – finally, the semantic layer includes all objects relevant to the driving task, such as traffic lights, pedestrian crossings and road signs. The map represents these both as 3D positions in the world, but also temporally dynamic semantic data. For instance, a traffic light contains three states, while a pedestrian crossing may also contain multiple states, such as “a pedestrian on the crossing”, “a pedestrian approaching the crossing” or “empty”.
- **Map priors layer** – this layer supplements the semantic layer by including “learnt” data from experience (crowd-sourced data). For example, the average time taken for a traffic light to change state could be stored for every traffic light, enabling predictive driving behaviours. Another prior is the probability of encountering parked cars on the side of a narrow road, which allows the AV to increase its “caution” while driving, to prepare for manoeuvres that avoid hitting pedestrians that emerge between parked cars, or to enter the opposing lane to navigate around a parked car in a narrow street. These types of behaviours are arguably representative of some of the major challenges for current driverless cars, as they include the social norms that humans have innately adopted while driving, but which are hard to explicitly code in an artificial driving system.

- **Real-time knowledge layer** – the final layer is the only layer designed to be updated in real-time, to reflect changing conditions in the road network. This includes locating and describing incidents like traffic congestion, accidents and road work. In Lyft's proposed map, this layer is updated using crowd-sharing, but this layer could also be updated using data provided from infrastructure providers and managers (Government).

As each HD map solution is different, an alternative description of the content included in a HD map is provided below. The information below is compiled based on a combination of the open-source Apollo software [12] and DeepMap's U.S. patent *High Definition Map and Route Storage Management System for Autonomous vehicles* [13].

- **Lane positions and widths** - An automated vehicle must know the exact position of all lane markings for safe driving. The 2D position of lane markings is stored, along with the lane type (solid line, dashed line etc.). Lane markings also include markings within intersections, markings to denote the road edge, and markings to indicate off ramps. In Queensland, lane markings can also denote a give way or stop condition (transverse lines). Lane markings also include arrows, denoting whether a lane is for turning or travelling straight. In the DeepMap patent, the lane data includes both the position of explicitly marked lane markings, lanes that are implicit (e.g. a country road with no lines but two directions of travel), navigable spaces adjacent to lanes (for reacting in emergencies) and a representation of the lane network structure (lane logic) that enables the vehicle to plan a legal route between its current location and a target destination.
- **Road Sign Positions** - A HD map needs to store the exact 3D position of important road signs relative to the map and vehicle. Road signage includes stop signs, traffic lights, give way signs, one-way road signs, traffic signs and any other signage that might be relevant. This task is especially challenging when signage conventions and road rules varies by country. Typically, the position of a sign is encoded by a *centroid* (an imaginary point in the exact middle of the sign) and a *bounding box* (a set of coordinates defining the size of the sign).
- **Special road features** - this includes pedestrian crossings, school zones, speed bumps, bicycle lanes and bus lanes. Accurately identifying special features requires a labelled map along with image recognition software within the vehicle.
- **Occupancy map** - in the DeepMap patent, the occupancy map is a spatial 3D representation of the road and all physical objects around the road. This representation can be stored as mesh geometry, point cloud or voxels. The 3D model is required to accurately localise the automated vehicle in the map (to centimetre accuracy). A small subset of HD map solutions disregard the 3D occupancy map solution by instead simplifying the map to 2D; for example, TomTom's RoadDNA (see Section 8.1).

One of the challenges in developing HD maps is accounting for the wide variety of road rules between different countries. As an example, California has “Center Left Turn Lanes”, which are a specially designated section of the road denoted by two sets of solid dashed double lines [14]. These lane markings are not present on Australian roads. Even within Australia, lane markings and road signs can vary. For instance, Melbourne features “Hook Turns” (Figure 3) and a corresponding sign, which is a special type of right-hand turn rule that is only present in the state of Victoria [15].



*Figure 3: Melbourne’s infamous “Hook Turns” require the driver to pause in the middle of an intersection (often across tram tracks) and then make a right turn across several lanes of traffic. Source: authors.*

A second challenge is the data storage requirements of HD maps. For example, Google’s Waymo automated vehicle collects approximately 1GB of data every 20 seconds [16]. As discussed in DeepMap’s patent, a country-wide HD map could be in the Petabyte size. As a vehicle has a limited storage space (that won’t be trivially solved by likely hard drive advances for several years), map data will need to be downloaded to the vehicle in a dynamic fashion, refreshing the cached map as the vehicle traverses through the environment. In DeepMaps’s approach, they partition the full HD map into map tiles. Individual map tiles are downloaded to the vehicle based on the map tile the vehicle is currently within [13].

One of the greatest challenges in using a HD map is the localisation component. As more detailed position information is added to the map, it becomes critical to know the exact position of the vehicle within the map. The required accuracy is greater than that provided by GPS, therefore software is required to localise the vehicle within the map by comparing the incoming sensor data with the existing map. This task becomes even more challenging when considering that a roadway typically contains numerous dynamic and temporary objects; the localisation system needs to have some understanding about what objects are temporary to avoid using them as landmarks when localizing.

## 6.3 Localization

It is worth noting that errors in localisation (calculating the position of the vehicle within the map of the environment) can have severe negative impacts on a self-driving system that relies on a HD map - so localisation is a critical enabler of the use of HD maps. An example situation would be an automated vehicle which thinks it is in a different road lane than it actually is, potentially creating a dangerous situation. Localisation becomes challenging when the environment around the vehicle differs from the pre-recorded map. This can occur due to appearance changes (e.g. day to night), dynamic objects (e.g. cars and pedestrians), and changes to the structure of the environment over time (e.g. road works, new buildings). U.S. patents filed by Waymo provide discussion as to how current autonomous driving companies are attempting to solve the localisation challenge. Localisation is also a popular research topic, with numerous academic publications in this field.

### 6.3.1 Known Industry Solutions

As the automated vehicle industry is highly competitive, detailed publicly available localisation algorithms are non-existent, however, high level overviews are available from a variety of sources. For example, in Google's patent US 9387854 B1 (Use of Environmental Information to Aid Image Processing for Autonomous vehicles), the following (simplified) process is used to localise [17]:

- Compare environmental information (a prior map) indicative of the lane of travel to the image data (incoming from vehicle sensors) to determine a portion of the image data that corresponds to the lane of travel.
- The environmental information may include a prior obtained image map that defines boundaries for lanes of travel, plus further information indicating any known structures, signs or other features.
- The comparison is performed by transforming the image data into the coordinate frame of the prior map, using the camera transform and relative location of lanes and boundaries. This projection may be in three dimensions using 3D image data.

As a second example, we discuss TomTom's RoadDNA solution [18] (see Figure 4). Using a mapping vehicle equipped with a suite of sensors including LiDAR and omnidirectional cameras, TomTom creates a dense representation of the road environment, with depth information to all features in the environment. Using this information, they compress this 3D data into a collection of 2D raster images, where the intensity of the image corresponds to the depth to particular parts of the environment. The automated vehicle can also convert incoming sensor data into this 2D depth image; these two depth images can then be compared using pattern matching techniques. Depth images can be more invariant to environmental changes compared to raw camera images, since significant structural changes generally occur less frequently in a road environment than appearance changes. As long as

the map is updated frequently, the RoadDNA solution enables accurate localization, but with significantly reduced data storage requirements (compared to a dense LiDAR point cloud).

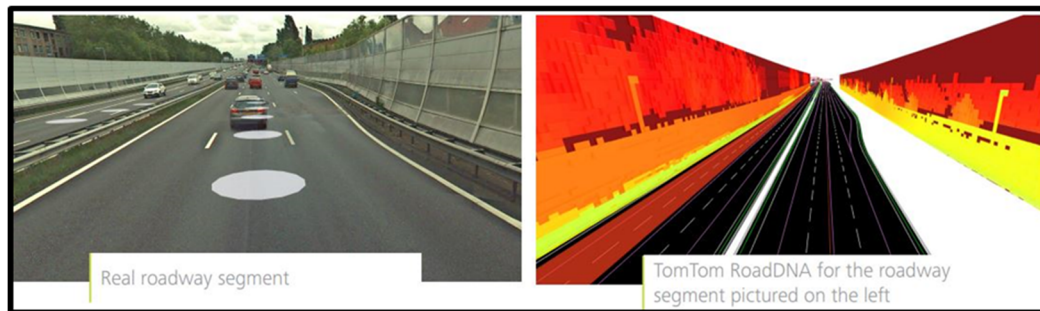


Figure 4: RoadDNA product demo provided in TomTom's RoadDNA product sheet [18].

### 6.3.2 Academic Solutions

In the academic literature, there exists numerous solutions to provide centimetre-accurate localisation. Academic solutions generally lack the extensive real-world verification of patented solutions developed by private companies; however, they do provide a publicly available description of the most recent technology in this field.

A well-known localisation system is *ORB-SLAM* [19]. ORB-SLAM is somewhat unique in that it provides both accurate localisation and tracking capabilities while being able to operate in real-time. It is one of the most industry-ready academic solutions and only requires a camera (no LiDAR or radar). Unfortunately, the ORB-SLAM paper only tested the method on short-routes, with its actual applicability for city-wide vehicle localisation uncertain. It can be assumed that the system would function better for long navigation routes when combined with other sensors (GPS, IMU, LiDAR and radar). ORB-SLAM is also designed for the SLAM (Simultaneously Localisation And Mapping) task, where access to a prior map is not guaranteed. In SLAM, the system must build up a map of the environment whilst simultaneously using that map to keep track of where it is (localise). In most automated vehicle situations, a prior map is available, thus enabling greater localisation robustness.



Figure 5: ORB-SLAM in action, detecting visual features in the left and producing keyframes on the right [20].



The process of fusing data from multiple sensors and localizing to a known prior map is most commonly achieved using traditional (tried and proven) probability-based solutions. In the following paragraphs we discuss further academic solutions, gradually increasing the number of sensors used in each chosen example.

In the paper *Robust Ego-motion Estimation and Map Matching Technique for Autonomous vehicle Localization with High Definition Digital Map* [21], a vehicle is localised to a HD map just using image data. This is achieved by detecting salient visual features with semantic meaning (e.g. road markings) and using a particle filter (along with camera perspective projection) to compare these detected markings to a prior map containing road features such as lane markings. The paper makes the assertion that HD maps that do not contain LiDAR information (i.e. a point cloud) are significantly smaller in storage size.

*Using High definition Maps for Precise Urban Vehicle Localization* [22] uses a particle filter to compare sensory scans against a HD map. They also combine localisation data from both an IMU and GPS receiver. In their results they show that the Root Mean Squared Error (RMSE) in localisation accuracy was 2.8m without a HD map prior, 1.5m with a HD map and odometry (IMU), and 1.2m with a HD map, odometry and GPS. While these accuracies are inferior to commercial solutions (which have much larger engineering teams to perfect the algorithms), the results still clearly demonstrate the importance of prior HD maps for automated vehicle localisation.

When an automated vehicle uses LiDAR as a sensor, often the Iterative Closest Point (ICP) algorithm is used to localise a LiDAR point cloud to a pre-collected set of points in a prior map. The ICP algorithm (which can operate on 3D points) is a least squares optimiser that attempts to iteratively find the best rotation, scale and translation to transform a set of incoming LiDAR points into a database set of points [23], [24]. The paper *Map-Based Localization Method for Autonomous Vehicles Using 3D-LIDAR* [25] discusses the techniques behind aligning LiDAR points using ICP; they also fuse sensor data using a Kalman Filter.

Finally, high accuracy localisation can also be achieved using RTK (Real-time Kinematic) GPS. However, because RTK GPS requires a network of ground stations to work correctly, additional infrastructure will need to be installed in order to successfully have automated vehicles localizing accurately using RTK GPS. GPS is also subject to dropouts, interference and multi-path reflection in densely build urban environments, which, while potentially acceptable when using it for long range navigation planning, is inadequate for second by second local positioning-based control of automated vehicles. Alternatively, a very recent (19<sup>th</sup> November 2020) solution from Hexagon, coined “RTK From the Sky” promises to provide high accuracy GPS localisation without the ground station requirement [26].

## 6.4 Technology – Map Creation

The initial creation of prior maps for automated vehicles is a major challenge in itself, which scales in proportion to the coverage of the map and the level of detail in the map. Maps can

be created with a variety of methods and sensors; for example, survey vehicles can map the road network using GPS, camera and LiDAR. Map creation techniques have implications for who does the map creation - for example, certain mapping techniques may easily map an entire city if a fleet of thousands of vehicles are sharing mapping responsibilities, where a single or small fleet of vehicles may be inadequate. The map creation mechanism has implications for what sort of provider can create (and update) them - small players may be at a fundamental disadvantage compared to large fleet operators. There are many methods of creating maps, with competing companies utilising different techniques. In this section we provide a detailed example of a mapping technique that was patented by DeepMap. The patents filed by DeepMap provide the most comprehensive publicly available, technical description of a proprietary mapping approach, in an industry known for its competitiveness and confidentiality.

DeepMaps patent US 10598489 *Visual Odometry and Pairwise Alignment for High Definition Map Creation* provides a detailed explanation of their map creation process, which we summarise below [27]:

- DeepMap generates a HD map of the environment surrounding the vehicle by capturing both sensor data and the 3D pose of the vehicle. The pose contains 6 degrees of freedom (translation along the x,y and z axis along with roll, pitch and yaw). The pose is necessary to convert the incoming 2D sensor data from cameras and other imaging devices into a 3D representation, in order to create a detailed 3D HD map.
- The sensor data is collected using LiDAR, camera, GPS and IMU sensors. The pose is calculated using a fusion of ICP (iterative closest point) with LiDAR, IMU (inertial measurement unit) pose estimates, and pairwise alignment using a sequence of images. To avoid errors due to dynamic objects, the patent specifies a method of localizing using just a downwards facing view of the roadway.

Further, US Patent US 10545029 *Lane Network Construction Using High Definition Maps for Autonomous vehicles* by DeepMap provides further explanation, specifying individual sub-modules. One such sub-module is their sign identification and mapping system [28]:

- First, the incoming image from the vehicle's vision sensor is passed through an image detection system (which can be a convolutional neural network trained to recognise traffic signs). This image detection system classifies the types of signs in the image, and specifies a polygon with the minimal vertices required to encompass the entirety of the traffic sign (repeated for every sign in the image). Figure 6 shows an example of the vertices defined around traffic signs.
- Second, a depth map, from LiDAR or RADAR, is used to generate an accurate distance to features in the environment, from which a 3D map is generated.
- The bounding box generated in the first step is used to find a 3-point subset of the entire depth map that corresponds to the traffic sign (repeated for each sign). Aligning

the camera image to the 3D map can be performed using a variety of methods, such as provided in the earlier set of dot-points. Other methods are also suggested in the patent, such as utilising the standardisation of traffic sign dimensions (e.g. if the classifier identifies a stop sign, it can be assumed it has an expected set of dimensions). See Figure 7 for an example of the point-subset on a sign.

- The final outcome is a 3D model of every traffic sign observed by the vehicle, which is then inserted into the 3D representation of the environment around the vehicle.
- Another convolutional neural network then receives a segment of the image corresponding only to the identified traffic signs, which is designed to generate the text recognised on the sign. Figure 8 shows the processing pipeline as described in the patent.

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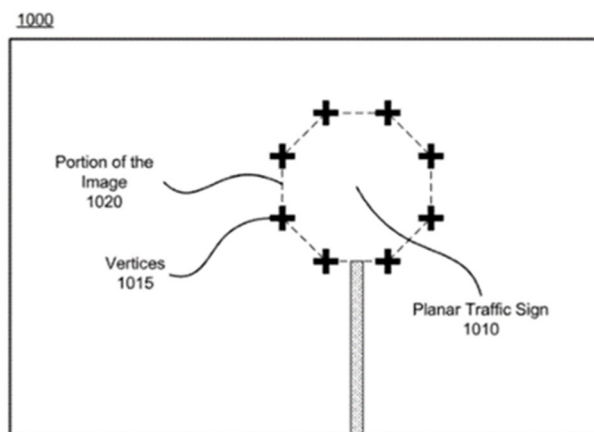


FIG. 10A

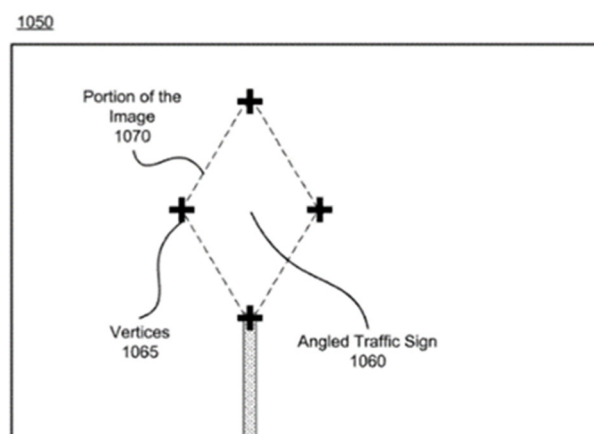


FIG. 10B

Figure 6: A traffic sign bounding box, as defined in DeepMap's patent [28].

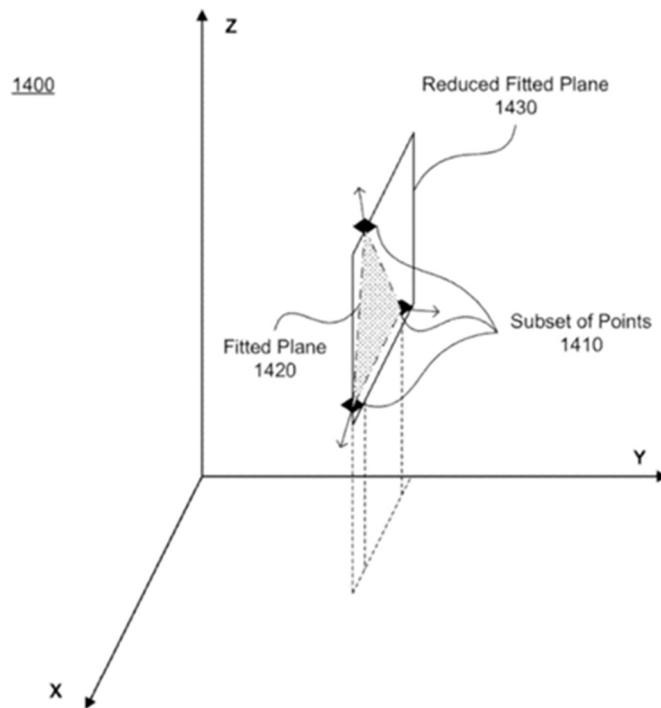


FIG. 14

Figure 7: An example of three 3D points assigned to a traffic sign, as defined by DeepMap's patent [28].

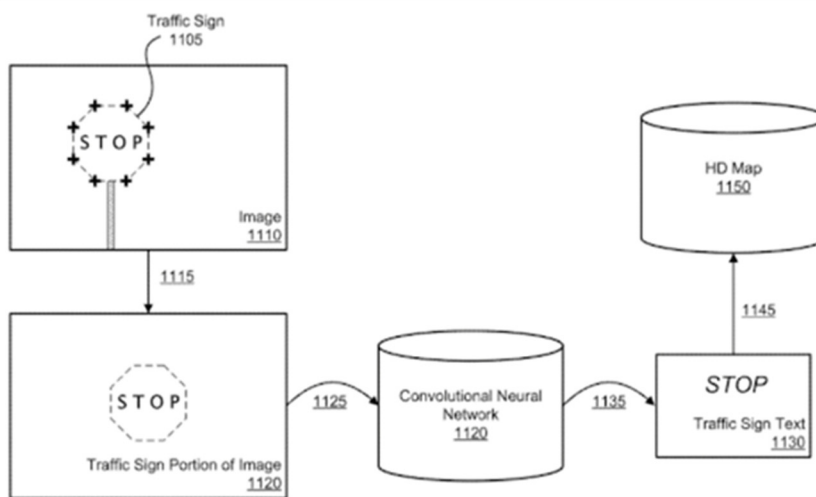


FIG. 11

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Figure 8: DeepMap's patented processing pipeline for recognising and classifying traffic signs [28].

Another sub-module is their lane line identification system [28]:

- DeepMap’s systems begins with a pixel-wise classification neural network, which classifies pixels based on their likelihood of being located along the centre of a lane line. This step returns a 2D probability map.
- The highest probability points are then mapped onto the 3D map.
- Cluster analysis is run on the set of 3D lane line points, to group neighbouring points together to define a solid line. The cluster analysis involves multiple stages; the first stage identifies “skeleton points”, which are then clustered into lane line clusters. The algorithm can automatically map any configuration of lane marking, whether straight or curved, solid or dashed (Figure 9).
- Polylines are then plotted between skeleton points, using the lane line clusters in combination with outlier rejection based on known lane structure assumptions. The patent describes a large sequence of outlier detection systems, since the initial lane detection network can produce outlier points - that is, pixels misclassified as lane centre pixels. This step produces solid lane lines on the 3D map.
- These automatically generated lane representations are finally added to a lane element graph, which represents a full network of lanes in the road environment. Further algorithmic checks are performed to ensure the generated lane structure is coherent. Human verification may also be used, however, human input dramatically increases the creation and maintenance costs of the HD map generation system. DeepMap’s lane element graph also contains features such as traffic signs and speed bumps (see Figure 10).

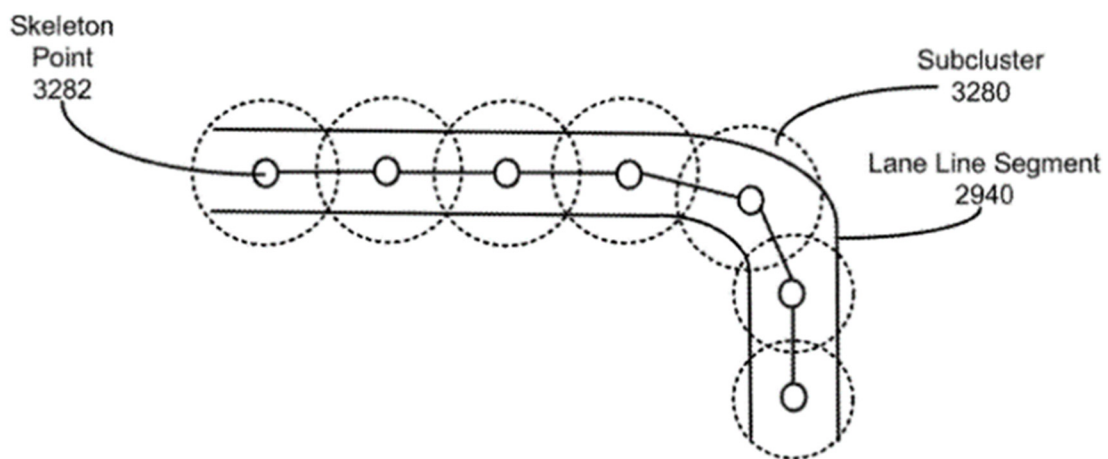


Figure 9: DeepMap's method maps road lane markings by creating lines between clusters of lane candidate points generated by a pixel-wise neural network [28].

In summary, creating high definition maps is a time consuming and difficult task, particularly when high positional accuracy and reliability are paramount to safe operation of automated vehicles. At this stage it is worth clarifying that the accuracy of a HD map is also limited by the sensor technology used. For instance, for a camera system, the positional accuracy of any feature in the image is proportional to both the image resolution (higher resolution increases accuracy) and the distance of said feature from the camera lens (larger distances will lower



the accuracy). While the exact relationships are complex and depend on the technique being used, we can qualitatively characterise it here. If a road sign is observed 100 meters from the vehicle, then the positional accuracy can be calculated based on the pixel resolution of the camera and the number of pixels required to accurately identify that the pixels correspond to a road sign. The accuracy of a HD map may also be intentionally limited by the map producer, in order to reduce both data storage requirements and compute requirements. In an interview with a TomTom representative, it was stated that TomTom selected a map accuracy of approximately 15cm, as a trade-off between storage requirements and application requirements.

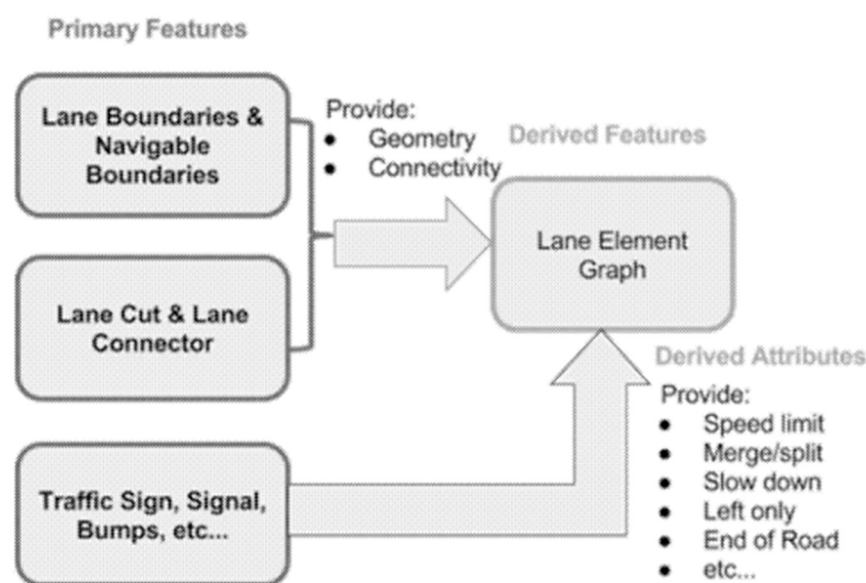


Figure 10: In DeepMap's patent, multiple types of road features are added to the lane element graph description [28].

## 6.5 Technology – Data Formats

This section discusses the data formats used in, and required for, HD maps. Since HD maps are complex combinations of geographic data and software, many data formats are potentially contained within a single HD map. Additionally, a separate set of data formats are required in the communication protocols to interact with the HD map – for instance, data formats are required to enable updating HD maps with real-time traffic and road work information.

A major source of data format information is the report: *Geodata report – analysis and recommendations for self-driving vehicle testing*, as published by Zenzic [29]. We have compiled a list of relevant data formats in Table 1 using data from a similar table in the Zenzic report, along with additions discovered during this literature review. Some of the information presented in the table was sourced from [30].

Table 1: A holistic list of relevant data formats for maps for AVs

Formats	Description
<b>3D data storage formats</b>	
OBJ	Open geometry definition file format. Used to represent a 3D object including coordinates, texture maps and polygonal faces.
LAS	A data format for storing and transmitting LiDAR point cloud data.
LAZ	Compressed LiDAR file format. The compressed version of a LAS file.
E57	A format for storing point clouds, images, and metadata produced by 3D imaging systems.
PLY	The PLY (Polygon File Format) stores 3D data as produced by 3D scanners. It represents 3D objects as a collection of polygons.
DAE (COLLADA)	COLLADA 3D graphic files. These files are used to store digital twin data.
<b>Geographic data and road network storage formats</b>	
CEN/TS 17268	A data standard defined by the European Committee for Standardization, designed to transmit geographic information for updating enhanced digital maps. It is specifically designed for map updates of a more static nature – dynamic data like traffic speed is covered by Datex II.
TN-ITS	The future successor to CEN/TS 17268, and the “brand name” of the data format. It is intended to compliment Datex II, and be the unified and standardised data format for all geospatial data for HD maps and automated vehicles.
ESRI grid	ESRI grid is a proprietary raster GIS file format.
ESRI shapefile	A vector data format for storing the location, shape, and geographic attributes of features, developed by ESRI.
GDF	GDF (Geographic Data Files) is an international standard for modelling road network data. It is split into three levels: basic physical infrastructure, a linked graph connecting lane-level road elements and a final layer that contains a standard digital road map.
GeoJSON	An open JSON formatted file designed to represent geographical features.
GeoTIFF	Open file format and widely used standard, based on the TIFF format. It is used as an interchange format for georeferenced raster imagery.
GML	An XML grammar for expressing geographical features.
SDF	Spatial Data File is a geodatabase file format developed by Autodesk.
OpenCRG	Open file format for the detailed description, creation and evaluation of road surfaces.
OpenDRIVE	Open file format specification to describe a road network’s logic.
OpenSCENARIO	Open file format for the description of dynamic contents in driving simulation applications.
<b>Traffic data communication formats</b>	
Datex II	Datex II defines a set of standards for the communication of dynamic traffic data between traffic management centres in the EU.

<b>DENM</b>	Decentralized Environmental Notification Basic Service. A low-bandwidth communication protocol for transmitting V2V and V2I data.
<b>OpenLR</b>	TomTom’s publicly available data format and standard used in their maps. It is designed to rapidly exchange location-relevant data between independent data providers and could be suitable for handling the communications between Government and independent map providers.
<b>Protobuf</b>	Protobuf (Protocol Buffers) is a data format designed by Google for the serialisation and transfer of data. It is used in the machine learning platform TensorFlow, and is also the file format used by HERE Technologies for their HD maps [31].
<b>SENSORIS</b>	The Sensor Interface Specification (SENSORIS) is a standardised communication format for bi-directional data transfer between vehicles and clouds. Messages are based on the Protobuf format, and the standard was first proposed in 2016.
<b>TPEG</b>	TPEG (Transport Protocol Expert Group) is a data protocol for location referenced traffic and travel data transmission. TPEG is based off the XML data format.
<b>CAM</b>	CAM (Cooperative Awareness Messages) are used in V2X communications to share the location of road users and infrastructure between each other.
<b>XML</b>	Extensible Markup Language data file.
<b>JSON</b>	Standard data interchange format that stores simple data structures and objects.
<b>MAPEM</b>	MAPEM (Map Message) is an I2V data format used to transmit intersection logic data to a connected vehicle.
<b>SPATEM</b>	SPATEM (Signal Phase and Timing) is an I2V data format specifically used to transmit light signalling data to connected vehicles, for GLOSA (Green Light Optimal Speed Advice).

The Zenzic report recommended (updated after a consultation round with industry) four critical data formats for AVs from this list: LAS 1.2 or LAZ (compressed), OBJ, OpenDrive/OpenSCENARIO and GeoJSON/LAZ/E57/GeoPackage (see page 4 of the Zenzic report [29]). In the Zenzic report, they state that there is currently no central source of geospatial data that supports interoperability through the full life cycle of self-driving vehicles. While this is currently true, this report has accumulated evidence that the EU, through the C-Roads platform and the NordicWay project, is currently addressing this issue [32], [33]. This will be achieved by enhancing the existing Datex II standards to better suit connected and automated vehicles. The objective of NordicWay is to establish a solution for cross-border interoperability of C-ITS systems – a goal which requires harmonised communication standards. Their solution involves the establishment of a NordicWay server, which acts as a communications hub that interchanges C-ITS messages between different countries, different OEM clouds (TomTom, HERE) and local traffic management centres. The NordicWay server communicates using the Datex II format, and messages are routed using

AMQP (Advanced Message Queueing Protocol). The *Basic Interface* is the name given to the interchange system that links all of these actors. The basic interface is a harmonised system that has the following consistent features:

- Uses IPv4/IPv6 internet protocol
- Transport Layer Security 1.3
- AMQP according to OASIS specification for version 1.0
- Payload agnostic – can be used to transmit Datex II or DENM messages.

The system is subscriber based; each actor can subscribe using AMQP to the specific messages they want to receive. The interchange is reported to meet the following requirements, as quoted from the report *NordicWay 2 Architecture, Draft*:

1. Interoperable exchange and crowd sourcing of digital traffic information related to traffic safety such as hazards and road works
2. Decoupling of actors
3. Lightweight, primarily provides message routing between actors
4. Geo based filters
5. Standardized interfaces
6. Transport security
7. Possibility to deploy on a PaaS/IaaS/Native implementation.

We include a collection of technical diagrams from the NordicWay report, to aid in future implementations. For further technical details, please refer to the cited documents [32], [33]. C-Roads is also adopting the NordicWay model across Europe as a whole, as detailed by the draft (not public) report *C-ITS IP Based Interface Profile*.

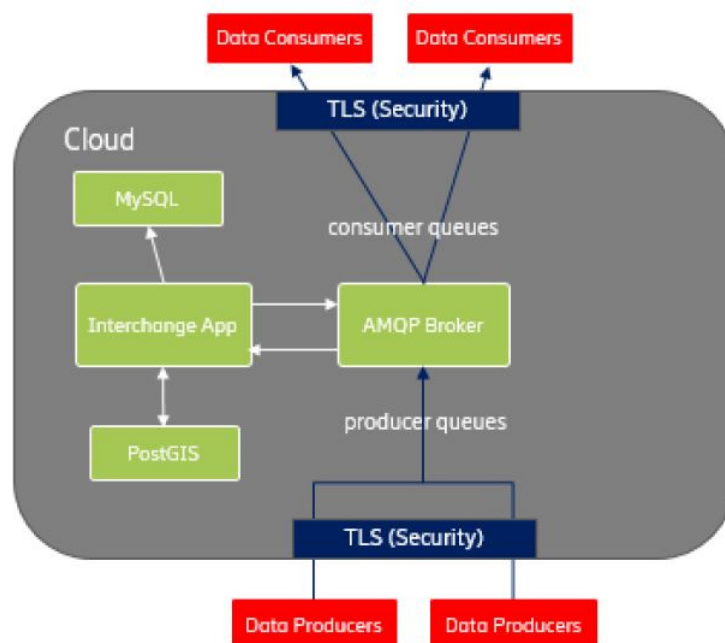


Figure 11: NordicWay interchange network architecture [32].

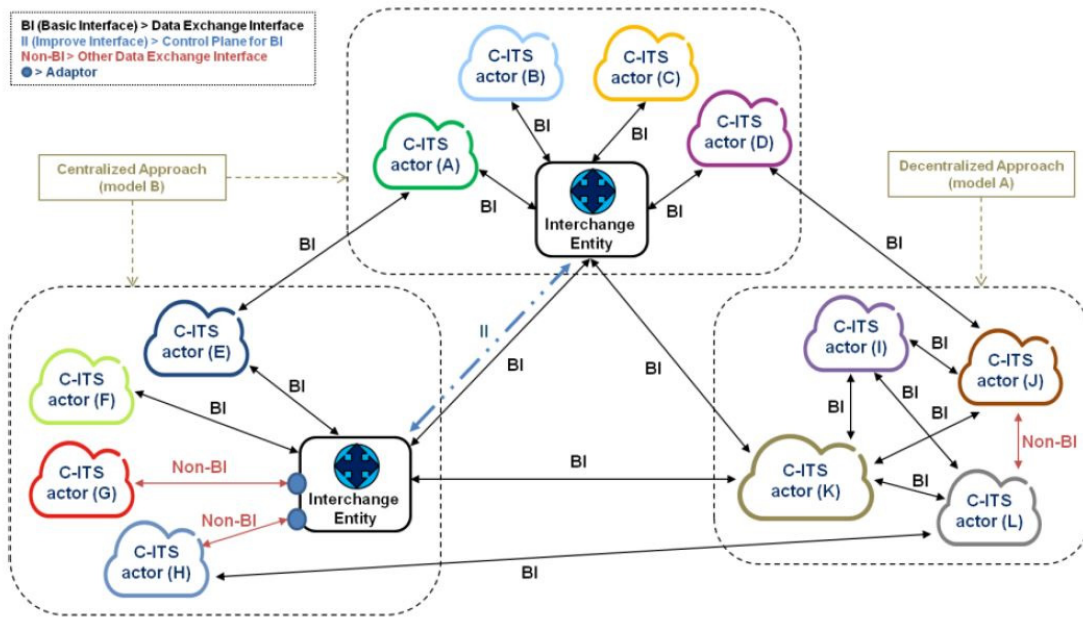


Figure 12: C-Roads interchange deployment models – centralized and decentralized [33].

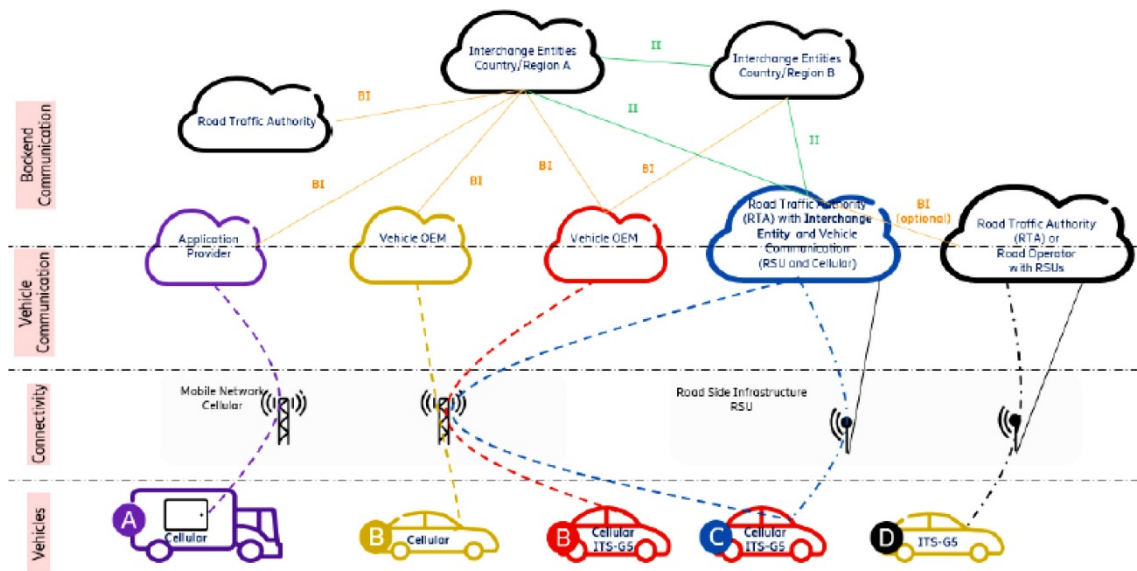


Figure 13: NordicWay implementation example [32].

In Figure 13, the dashed lines will typically be communicating using the DENM protocol, and the solid lines will be communicating using the Datex II protocol. The DENM and Datex II standards will be discussed further in Section 6.6. NordicWay and C-Roads is also discussed further in Section 9.3.

There is also a second project in the EU that is attempting to standardise geospatial data for connected and automated vehicles, called *TN-ITS*. While the NordicWay project is focusing on harmonisation and sharing of rapidly changing data (e.g. vehicle probe data, roadworks, accidents), the *TN-ITS* project is concerned with the exchange of information on changes in static (not-changing) road attributes. As mentioned on the About Us page of the *TN-ITS*

website [34], there currently are many different data storage formats for GIS data (as was identified by the Zenzic report) and it is difficult to convert between them. The objective of TN-ITS is to create a common exchange format, “enabling creation of plugins to existing (legacy) systems for extraction of information on changes in road attributes”. These legacy systems are typically the digital systems of the road authorities. This will enable immediate updates for HD map providers, when road authorities make changes to the road network, such as adding a new traffic light, or a new give-way sign. Further technical discussion of TN-ITS will be covered in Section 6.6.3. Given government’s likely role in, or at least awareness of many types of longer term change, this project is particularly relevant when considering the potential role of government in HD maps for automated vehicles.

It is worth concluding this section with a note of caution. While the TN-ITS and Datex II standardisation will go a long way to providing the data required for real-time HD maps, neither standard addresses the need for centimetre accurate localisation data, either through LiDAR point-clouds or camera images; further work is still required.

### 6.5.1 Road Elements

In this sub-section, the individual components of a HD map are described. We provide Table 2, which lists each of the components and a description. Because there is no standard format for current HD maps, each HD map provider adds a different feature set to their maps; for this table we include all components that are common to the majority of publicly distributed HD maps. The data provided in the Table was sourced from both product sheets and [2]. Furthermore, using a HD map demo recently released by Atlatec, we include Figure 14 and Figure 15 which show a real HD map for automated vehicles using the OpenDRIVE format.

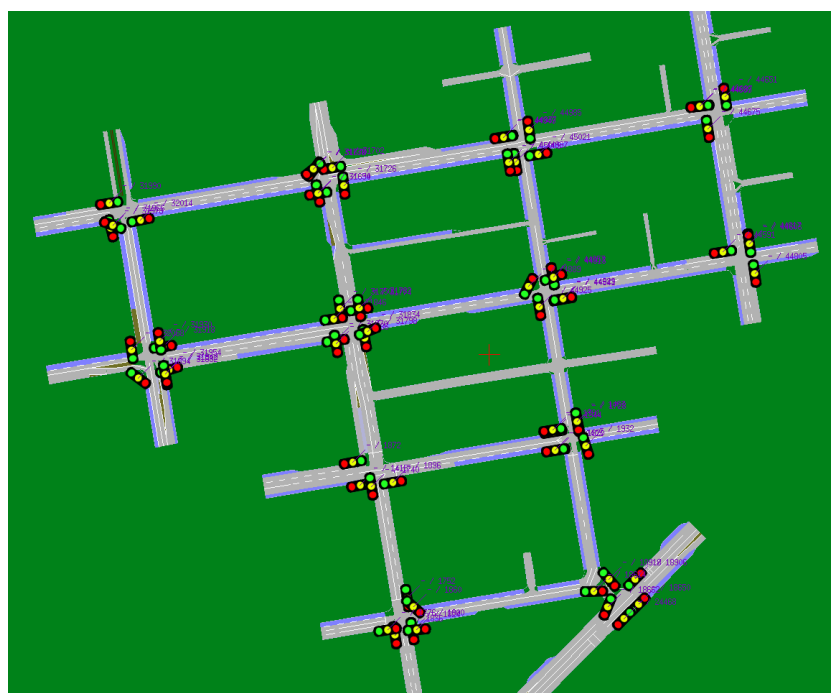


Figure 14: OpenDRIVE HD map of San Francisco, as released publicly by Atlatec [35].



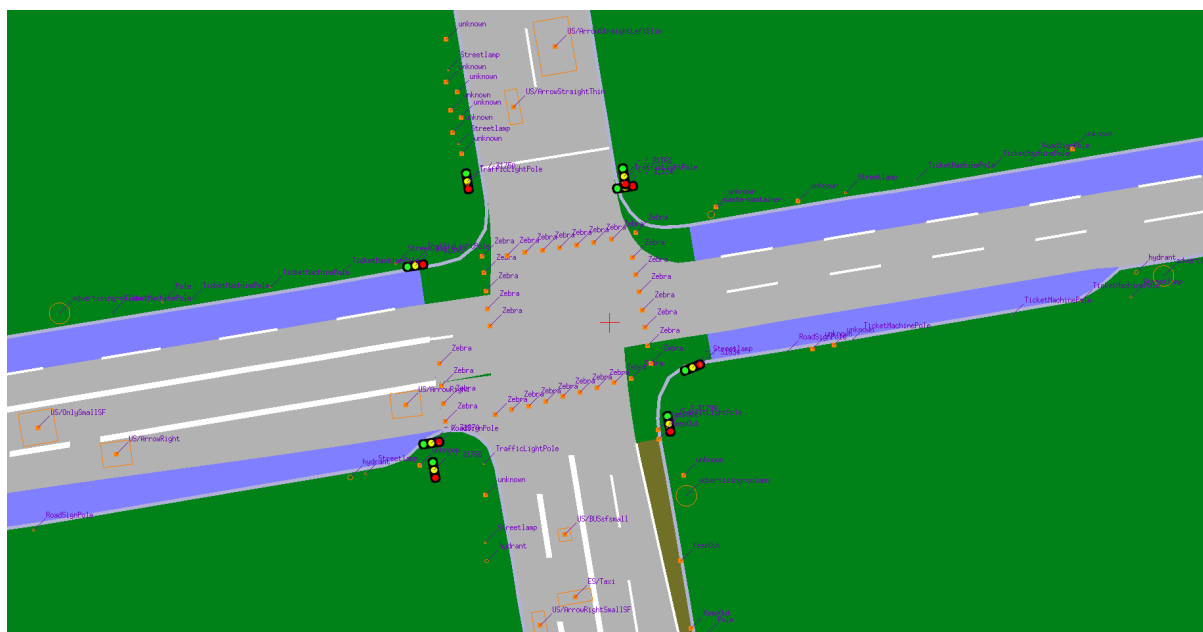


Figure 15: OpenDRIVE HD map of San Francisco, as released publicly by Atltec. This is a zoomed-in view, showing additional map features [35].

Table 2: Common Map Elements

Element Name	Description
Speed Limit Signs	HD maps include both the designated speed limit for each section of road along with the expected 3D position and sign text of all speed limit signs.
Electronic speed signs	A sub-set of speed signs that are electronic and can be dynamically modified by road transport departments. In Australia these signs have been noted as causing major recognition difficulties for existing traffic sign recognition systems, as discussed in length in the report <i>Guidance and Readability Criteria for Traffic Sign Recognition Systems Reading Electronic Signs</i> [36].
Road warning signs	As defined on the website of the Queensland Government, road warning signs include those indicating stop and giveway instructions, changes to the road’s surface or condition, and merging and added lanes (and more). The position and semantic meaning of all these types of signs must be encoded in any HD map. For a full list of these signs please refer to: <a href="https://www.qld.gov.au/transport/safety/signs/warning">https://www.qld.gov.au/transport/safety/signs/warning</a>
Lane structure	HD maps include detailed data concerning the number of lanes and exact positions of all lane markings.
Traffic lights	The location of traffic lights in the network is stored in the map, both as an approximate position (i.e. which intersections have lights) and exact 3D position. Traffic lights also need to encode the design of the light - i.e. whether the light is a single column of red, yellow, green or has turning arrows as well.



<b>Road edges</b>	While this may seem like a trivial element, to account for all possible situations, a prior HD map needs to encode the exact position of the road edges. This can be considered as a form of geo-fencing, which helps guarantee that the automated vehicle never drives off the road, risking the safety of off-road vulnerable road users.
<b>Pedestrian crossings</b>	Crossings, along with other high-risk areas like school zones and shared zones, need to be encoded in a HD map.
<b>Environment appearance</b>	By encoding a representation of the world around the road, an automated vehicle can localise with respect to the map. Some HD map providers and autonomous car companies use a LiDAR point cloud (e.g. Waymo), some use a depth image (e.g. TomTom), and some use the position of road features to localise (HERE). Some map providers do not provide this feature at all (Mapbox), although all such maps have been classified as “Enhanced Digital Maps” in this report, rather than HD maps.
<b>Road slope</b>	The slope of the road. This data can improve the performance of an automated gearbox and throttle, especially for heavy vehicles.
<b>Road surface</b>	Whether the road is bitumen, gravel or dirt. May also include a measure of whether the road is in good or poor maintenance condition.

## 6.6 Technology – Map Updating

Why do maps need updating? The reality is that the world is constantly changing, whether that be the construction of new road lanes, or the change of a traditional speed sign to an electronic sign. As discussed in the IEEE International Conference on Robotics and Automation (ICRA) paper *How to Keep HD Maps for Automated Driving Up To Date* by BMW group [37], three types of deviations between a map and the real world are major concerns for automated vehicles:

- Changes due to construction sites
- Changes without a designated construction site (missing street signs, etc.)
- Mapping errors

A HD map, which stores the exact position of each relevant object in the environment, needs to be updated regularly in order to maintain high accuracy – and therefore be reliable for an automated vehicle. A typical AV implementation makes critical decisions based partly on information provided by the map, so there’s unlikely to be a halfway point – *a poor quality, out-of-date map may do more damage than good*. Regular map updates could potentially be achieved in part via Government collaboration, from prior traverses of specialised mapping vehicles, crowdsourcing and aerial imagery, as well as through direct notifications of planned changes. More specifically, the update process can occur in at least four ways:

1. The infrastructure provider (Government) sends an over-air update directly to the automated vehicles, indicating a known change (i.e. road-works).
2. The producer of the HD map (usually a private company) collects new data and updates their map. This updated map is then transmitted to the automated vehicles.
3. The infrastructure provider (Government) sends a message to the HD map suppliers, detailing known changes in the environment, which is then used to update the HD map on the cloud before being transmitted to the automated vehicles.
4. A number of AVs in the fleet detect a change in the environment, with respect to the prior map, and communicates this data back to the HD map provider. The HD map provider validates this data, then transmits this updated map to all other AVs in the fleet.

The update process can be further categorised into one of two categories: dynamic data, or static data. Dynamic data represents rapidly changing situations, such as an accident on the road network, a traffic jam, or road works. Static data represents more permanent road changes: the construction of new traffic lights, a new give-way sign, or a new lane on a motorway. To capture this wide range of potential combinations of communications, a variety of data formats currently exist. The communications formats can be summarised by considering the actors in the situation – Government (the transport authority), private HD map providers (and OEMs), and the vehicles themselves. The most prominent formats are summarised in the communications flow diagram shown in Figure 16.

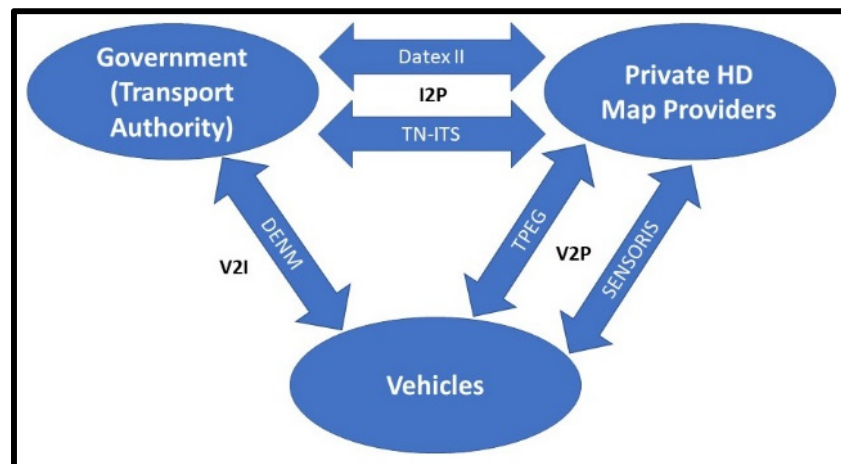


Figure 16: Updating HD maps regularly and reliably requires all three links in this chain of communication formats.

Each of the communication routes, hereby summarised as V2I (Vehicle to Infrastructure), V2P (Vehicle to Private) and I2P (Infrastructure to Private), will be separately discussed in the following sub-sections.

### 6.6.1 V2I – DENM

Standards are required for transmission of data from Government to vehicles, with the DENM (Decentralized Environmental Notification Message) standard being a recent example, as defined by ETSI EN 302 637-3 [38]. The DENM is designed to transmit information related to road hazards or disruptions, along with the type and position of the change. The DENM contains four data containers: a management container, situation container, location container and “A la carte” container. The management container includes information such as the time the change was detected and the position of the change. The situation container describes the type of change (*eventType*), of which there are 24 high-level event types and multiple sub-categorises within each high-level event type. For example, the high-level category Roadworks contains the sub-causes: unavailable, major roadworks, road marking work, slow moving road maintenance, short-term stationary roadworks, street cleaning and winter service. The location container contains *traces*, which are a list of waypoints that form an itinerary approaching and leaving the event position, to describe the length of the roadworks. The final container includes miscellaneous additional data, such as *lanePosition* and *externalTemperature*. For DENM to be used to update HD maps, first the *lanePosition* data is essential, and second, the reliability of the lane position data needs to be very high. It is worth noting that DENM was designed for driver assistance and not automated driving, nor for updating HD maps. Its primary purpose is for the rapid transmission of ITS data to a fleet of connected vehicles.

### 6.6.2 V2P – TPEG and SENSORIS

To transmit data from private HD map supplies to vehicles, the TPEG (Transport Protocol Expert Group) protocol is (currently) commonly used. TPEG is designed to transmit geographically referenced data between vehicles and the cloud, bi-directionally. The geographic referencing can be either as a point, a line, or as a 2D area. Rather than using TPEG’s in-built geographic referencing, TPEG can also use OpenLR instead. In terms of the information transferred, TPEG can transmit traffic event information, parking information, traffic flow data, weather data, fuel price information and other proprietary CA (Conditional Access) data.

SENSORIS (Sensor Interface Specification) is both a recent data format and organisation, founded in 2016. The objective of SENSORIS is to create a global standardised interface for the exchange of sensor data between vehicles and clouds [39]. It is specifically designed to interface with *low-level* AV hardware, with encoders and decoders for data type transmission between differently compiled software systems. For example, SENSORIS is specifically designed to convert C++ data (most automated vehicles are programmed in either C or C++) into cloud programming languages like Java. The Protobuf format, provided by Google, is used to serialize the data for transmission, either by wire or wirelessly. SENSORIS has in-built support for geographic referenced data and is designed to handle both a wide variety and size of data. It is currently the communications format used by HERE for their transmission of HD

map data for connected and automated vehicles [40]. SENSORIS is arguably superior to TPEG, as it is able to transmit detailed sensor data (images, LiDAR scans), unlike TPEG, which has no apparent capability for transmitting raw sensor data.

### 6.6.3 I2P – Datex II and TN-ITS

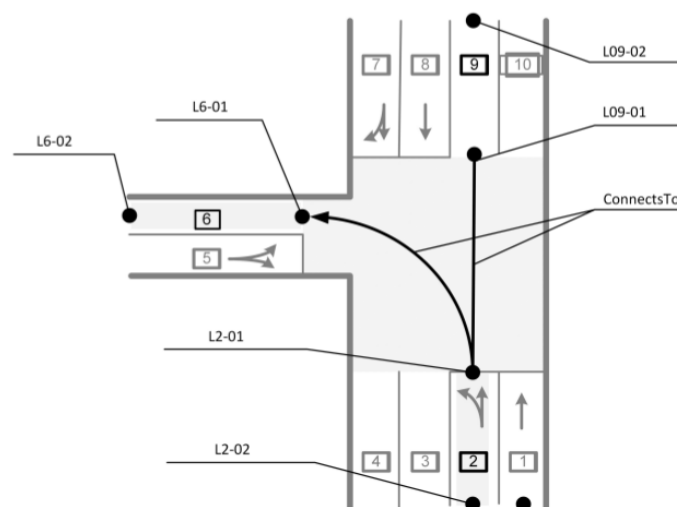
In this final sub-section, Datex II and TN-ITS will be discussed, arguably the most important data standards due to their critical role for both inter-infrastructure digital communications and transmission of real-time data to HD map providers.

Datex II is the standard for transmitting traffic data between traffic management centres in the EU. Additionally, HD mapping companies in the EU (TomTom, HERE) have developed software to interface with Datex II [41], [42]. Datex II is an electronic language for the exchange of location referenced traffic information, with the technical specifications for this framework given in the CEN/TS 16157 standard. A key advantage of the Datex II system is that the data is communicated using the well-known XML data format, and in addition, an extension for Datex II exists which directly adds OpenLR into the Datex format. Datex II is the data format being used to send data to automated vehicles in the NordicWay2 project in the EU. For this project, Datex II is used to transmit weather and road condition data, the location of slow and stationary vehicles, obstacles on the road, lane closures, and more. Datex II is designed for communicating rapidly changing data from the road network; a near-full list of the types of data Datex II can transmit is included below:

- Traffic Signal Management (see CEN/TS 16157-9:2020)
  - Intersection State and Timings
  - Advisory Speed (GLOSA)
  - Pedestrian/Bicycle Detection Boolean
  - Intersection Geometry and Lane Logic (see Figure 17)
    - Lane attributes – barrier, bicycle, parking, pedestrian crossing and more
    - Lane direction
    - Lane width
    - All lane data can be linearly referencing using either GML, TPEG, package “LinearReferencing” (EN ISO 19148) or OpenLR
- Location referenced alerts (see CEN/TS 16157-2:2019)
  - Can be either area, linear or point locations
  - Again, location referencing can be in either GML, TPEG, package “LinearReferencing” (EN ISO 19148) or OpenLR
- The Situation model (see CEN/TS 16157-3:2018)
  - Is structured in a hierarchical format, with the SituationRecord package at the top.
  - Consists of the packages SituationRecord, Impact, ServiceInformation, TrafficElement, Conditions, Accident, Obstruction, Activity, OperatorAction,

Roadworks, NetworkManagement and GenericSituationElement. Some of these will be discussed further here.

- ServiceInformation is used to transmit general road service messages, such as disruption to normal services on a road or roadside (e.g. the unavailability of parking spots). ServiceInformation is a sub-class of the SituationRecord package.
- TrafficElement includes the data: Accident (accident cause, type, number of vehicles involved in the accident), Abnormal traffic (queue length, relative traffic flow, traffic trend), Obstructions, Driving Conditions (road surface conditions, weather conditions). The accident, obstruction and conditions packages are sub-packages of the TrafficElement package. TrafficElement is a sub-class of the SituationRecord package.
- The OperatorAction package includes all data related to activities initiated by the transport authority, such as roadworks. The roadworks package includes data such as: whether the road is open to traffic, the number of maintenance vehicles being used, and type of road maintenance being performed.
- Variable Message Sign Data (CEN/TS 16157-4:2014)
- Parking data (availability and location of parking spaces) (CEN/TS 16157-6:2015)



Key	
L6-01	first node - egress lane
L6-02	last node - egress lane
L2-01	first node - stop bar - ingress lane
L2-02	last node - ingress lane
L09-01	first node - egress lane
L09-02	last node - egress lane

Figure 17: Example of the intersection logic and geometric supported by Datex II (also supported by MAPEM) [43].

This report notes that the road work details included in Datex II lack sufficient detail for automated vehicles. For instance, for optimal enhancement of automated vehicles, it's likely that the roadworks package will need to include details of which lanes are open/closed, the

new speed limits through the work zone, and any detour route guidance. Additionally, if the road works impinge on the lane widths, this too needs to be communicated to the automated vehicle. In light of the fact that the authorship team received email correspondence suggesting that the EU will use Datex II for HD map data communications (for event-based data), we speculate that there is some probability that the EU will enhance the Datex II standard in the near future to address this limitation.

The second digital infrastructure communications standard in the EU is called TN-ITS, as defined by PD CEN/TS 17268:2018 *Intelligent transport systems – ITS spatial data – data exchange on changes in road attributes*. The purpose of TN-ITS is to ensure that digital maps for intelligent transport systems are kept up to date, by transferring change data from road authorities to relevant third parties. More specifically, in contrast to Datex II which is designed to transmit event-based data, TN-ITS is designed to communicate changes to static road attributes. Below we summarise the content of PD CEN/TS 17268:2018, describing the data that can be transmitted using TN-ITS:

- Road Feature
  - A road feature represents static road data like traffic signs and is geo-referenced with a linear location reference. Like Datex II, TN-ITS is compatible with a variety of location referencing methods such as OpenLR and AGORA-C (ISO 17572-3). It is worth noting that OpenLR location referencing is in 2D and can be stored as either a point along a line (line being the road), a length along a road, or a latitude and longitude coordinate.
  - Additional data can also be stored within a road feature object, such as validity duration (e.g. if the feature is temporary) and other restrictions (time-of-day, lane, road category, vehicle type, etc.).
- The road feature types include the following:
  - Pedestrian crossing
  - Restriction for vehicles
  - Speed limit
  - Start of speed limit
  - End of speed limit
  - Prohibition of overtaking
  - Start of motorway
  - Closed to all vehicles in both directions
  - Road sign (which has its own set of sub-classes)
- For a full specification of all data that can be stored in TN-ITS, please refer to <http://spec.tn-its.eu/codelists>
- Finally, whether Queensland directly adopts TN-ITS or not, either way, the XML data within the above link could be relatively easily incorporated in any future ITS data standards developed for Queensland, with edits to the road sign XML schema

<http://spec.tn-its.eu/codelists/RoadSignTypeCode.xml> to reflect Queensland road signs.

Unfortunately, TN-ITS (and OpenLR) possesses a critical flaw: the location referencing of road features is in 2D not 3D – there is no height component. For automated vehicle traffic sign recognition systems, the 3D position of the road sign ideally should also be known.

## 6.7 Technology – Specific Use-Cases of Prior HD Maps for Automated Vehicles

The table below contains a comprehensive list of cases when prior high definition maps are required, along with a criticality rating. It is worth noting that all automated vehicles will require a standard definition map as a minimum requirement; without it, the vehicle has no way of computing the route to take (on the road network) to reach the destination.

*Table 3: Situations where prior maps are required, along with criticality ratings for automated vehicles.*

Task	Why?	Criticality
Recognising traffic signs	When the environmental conditions deteriorate (rain, night-time, etc.) existing traffic sign detectors experience reduced detection rates. However, if an accurate and up-to-date prior map and accurate localisation is available, when the traffic sign detector fails the prior map can be used as a safety critical fallback system.	High
Validating lane markings	While automated vehicles have in-build lane detection systems, these can be tricked into falsely identifying a lane marking if accidental or malicious changes are made to a road. A prior lane map allows the vehicle to validate the markings detected by the system and disregard any erroneous markings.	High
Localisation	To recap, localisation is knowing the position of the automated vehicle in the world. For safe autonomous driving, localisation needs to be in the centimetre accuracy range. This is because the validation of traffic signs and lane markings, from a prior map, is reliant on first knowing the position of the vehicle. However, since GPS is not that accurate, highly accurate localisation can only occur by comparing the incoming sensor data to a prior map. Unlike the detection of traffic signs or lane markings, the temporary loss of localisation is not necessarily a catastrophic failure <b>as long as the vehicle can self-diagnose that its localisation system is not functioning</b> . If failure detection works, the vehicle can still recognise signs and lane markings and execute basic manoeuvres.	High



	However, the vehicle has no way to confirm the accuracy of its predictions (by comparing against a prior map). Self-diagnosis of localisation failure is an unsolved problem and a work-in-progress in the research community.	
<b>Logic Information</b>	A key requirement of a prior map for an automated vehicle is lane logic details. This is because lane logic describes the direction of travel of a lane, or whether a lane is going straight ahead or is a turning lane only. Such data can be provided by lane markings, however, if errors are present in either the real-world markings, or the markings in the map representations, the consequences would potentially be severe.	High
<b>Geofence boundaries</b>	Due to limitations in the technology, automated vehicles may (especially early on) be limited to specific regions in a city or country. While geofence boundaries can be enforced using GPS, any GPS drop-outs could cause the vehicle to venture outside the geofenced region. A prior map can have this geofence encoded in the data, thus ensuring that the automated vehicle stays in its designation area.	Med
<b>"Electronic Horizon"</b>	The "Electronic Horizon" is the term given to the ability to pseudo-perceive future road conditions based on a near real-time prior map. For instance, if an accident occurs 2km ahead, this data can be transmitted to the vehicle's HD map and the software can compute a detour trajectory that avoids the accident.	Med
<b>Optimal route calculations</b>	Additional map data can further enhance the route calculations of an automated vehicle. This could include only plotting routes on good quality roads (i.e. avoiding pot-holes) or avoiding roads with traffic lights, as examples.	Low
<b>Smart gear changing</b>	Most HD maps include road gradients, which can be used to inform an automatic gearbox as to the ideal time to change gears to maximise fuel efficiency and reduce wear on mechanical systems.	Low

## 6.8 Cybersecurity

With all the data communications discussed in prior sections, cybersecurity is naturally an important topic of discussion, but a detailed treatment is beyond the scope of this report beyond stating its obvious importance. An example of a cybersecurity system designed for C-ITS is called the Security Credential Management System (SCMS). SCMS is a security infrastructure that issues and manages certificates specifically for V2V and V2I communications. Notably, SCMS is currently being used to secure the communications of the

Ipswich Connected Vehicle Pilot [44]. Overseas, the US DOT has initiated a national SCMS development project to develop a national SCMS standard in the US [45].

## 6.9 Summary

A large selection of technology and engineering capabilities is required to create, maintain and use maps for automated vehicles in a safe and reliable manner. Rather than being easily separated into discrete classes, maps for automated vehicles exist across a spectrum ranging from basic digital maps to advanced high definition point cloud maps. As a rule of thumb, more advanced and detailed maps provide the greatest improvement to the function of a highly automated vehicle, but require the largest investment in map creation and maintenance.

## 7 Providers and Users of Maps for Automated vehicles

In this section, the companies and government bodies providing and utilizing prior maps in the context of automated vehicles are discussed. Situations where both governments and private corporations are working together to provide a mapping service are especially noted, given the report's focus on government's potential role in maps for automated vehicles.

Our initial literature search has identified the following private corporations as providing or using some form of map for automated vehicles:

- TomTom
- Google
- Bosch
- Nvidia
- HERE
- Sanborn
- DeepMap
- Apollo
- Waze
- Lyft
- NavInfo
- Elektrobit
- Nutonomy (from Aptiv)
- Denso
- AutoX
- Atlatec
- Zoox
- Mapbox
- Uber
- Mobileye

This is not an exhaustive list, with many other start-ups operating in this space. A subset of the companies in this list are discussed in more detail in the following sections.

### 7.1 Standard Digital Maps

A standard digital map is the traditional type of “street map” humans use regularly, as provided by numerous map creators including Google Maps, Garmin, OpenStreetMap and Apple Maps. These basic street maps are considered topometric maps, encoding street structure, names and approximate distances.

AV solutions have been proposed which solely use these topometric maps. *MapLite* from MIT [46] (as shown at the 2020 IEEE International Conference on Robotics and Automation) demonstrated successful autonomous navigation using OpenStreetMap as a prior map, for a 15km test route. As mentioned in the paper, a topometric map is significantly less demanding with respect to the required storage space. A detailed map used to localise over 20,000 miles of roads requires 200GB, while a similar topometric map could be stored using approximately only 3.5GB of storage [46]. However, while this example highlights the storage differences when using non-HD maps for enhancing AVs, it's not likely to prove their viability given its small size and the lack of distracting actors in the test environment.

Street maps for AVs become more useful as both the update frequency and semantic content increases. For instance, Waze (<https://www.waze.com/>) combines a traditional street map with crowdsourcing. Users of Waze can report road works, traffic jams and accidents (and, controversially, police cameras) to the website which then become available to other Waze users (and also introduce new issues of verification of crowd-sourced data). Such approaches would allow an AV to become more adaptable to changes in driving conditions, with maps continually updated in real-time by any cars using Waze [47].

Alternatively, general location-inspecific learning-based approaches have been suggested as an alternative to storing HD maps. As discussed in the Scaled Machine Learning Conference by Andrej Karpathy (Sr. Director of Artificial Intelligence at Tesla) Tesla is avoiding the use of HD maps, claiming that the creation and maintenance of HD maps is expensive and not scalable [48]. Further, the disadvantage of HD mapping for AVs is that every road requires a unique HD representation to be stored. Tesla is instead leveraging deep learning to mitigate the need for maps; by learning general representations, their objective is to have a scalable automated vehicle that can drive on unfamiliar roads [49]. However, the efficacy of this approach is still in question, given some recent high profile accidents involving Tesla vehicles operating in Auto Pilot mode [50] and an absence of convincing widespread demonstration of Level 4 and above Tesla operation. While Tesla is avoiding the use of HD maps, a recent tweet from Elon Musk hinted that Tesla may use a HD “micro-map” in the future [51]. These maps would be created from the Tesla vehicles themselves and possibly used to identify and avoid potholes, which appears to be a very specific use-case scenario.

## 7.2 Enhanced Digital Maps

An enhanced digital map can be defined as a standard map with additional data types included, that is beneficial to both Advanced Driver Assistance Systems (ADAS) and fully automated vehicles. One of the earliest examples was the NextMap project in Europe beginning in 2000, which included additions such as 4m absolute and 1m relative positional accuracy (see Glossary), road curvature, speed limits and lane information [3]. The NextMap project was a collaboration between ERTICO, Tele Atlas (now TomTom) and several car manufacturers including BMW Group and Daimler. A few years later a similar project was completed in the U.S., called the Enhanced Digital Mapping Project [52].

In recent years, a number of standards have emerged for the design of these enhanced maps for autonomous driving. The Navigation Data Standard (NDS) is a standardized data storage format for maps, which is shared amongst all member corporations of the NDS association (founded in 2008). It is continuously being evolved to meet the map requirements for cars manufactured by member corporations. Currently NDS maps include lane level data, localisation data, obstacle data and road topology [53]. A detailed visual overview of NDS features can be seen in Figure 18 [54], and an open source version is publicly available, called the NDS Open Lane Model (<https://www.openlanemodel.org/>).

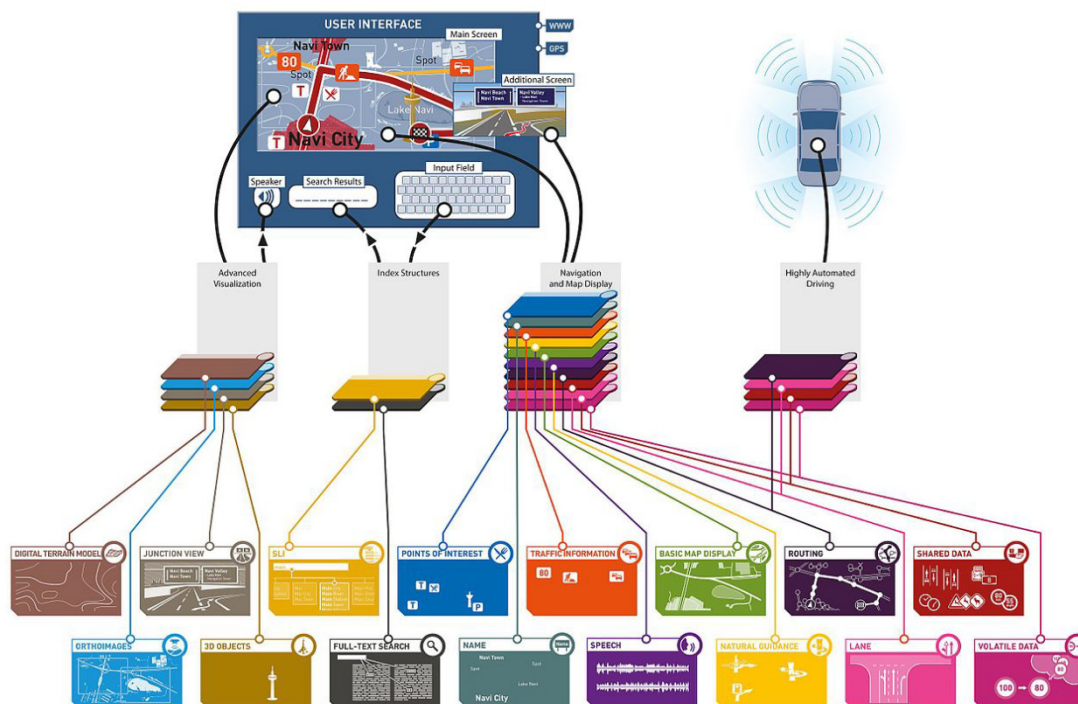


Figure 18: A graphic detailing the large variety of map features supported by the NDS standard [54].

At a similar time to the development of NDS, SAFESPOT developed the LDM (Local Dynamic Map). The SAFESPOT project was an EU initiative (which ended in 2010) with the aim of creating dynamic cooperative networks where vehicles and road infrastructure communicate to share information (collected both in vehicle and at the roadside) in order to enhance the driver's perception of the vehicle's surroundings [55]. The LDM is also defined by the 2011 technical report ETSI TR 102 863: *Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Local Dynamic Map (LDM); Rationale for and guidance on standardization*. The primary difference between NDS and LDM is that NDS was funded by a private consortium, while LDM (through SAFESPOT) was publicly funded. NDS has also continued to be updated, while LDM appears to be discontinued as of 2020 (although its concept has likely inspired current solutions). Both NDS and LDM contain a variety of road features, except LDM is separated into four different layers, which are: Highly dynamic data, Transient dynamic data, Transient static data and Permanent static data (see Figure 19) [56]–[58]. The multi-layer formulation of the LDM makes it an effective enhanced digital map; in fact, Japan has used the LDM as the basis of their latest DynamicMap 2.0, which is a full HD map. Data can be communicated to and from the LDM using either Co-operative Awareness Messages (CAMs), Decentralized Environmental Notification Messages (DENMs), or TPEG (Transport Protocol Expert Group) messages. It is worth noting that the LDM contains almost all the features needed for a HD map, missing only the high centimetre positional accuracy of features (i.e. road-signs) and localisation data (i.e. 3D point clouds). Key advantages of the LDM include the large number of categories for traffic-affecting hazard causes (see page 28

of ETSI TR 102 863). Given the topic of this report, the LDM is also particularly interesting as an example of a Government creating and maintaining an enhanced map system.

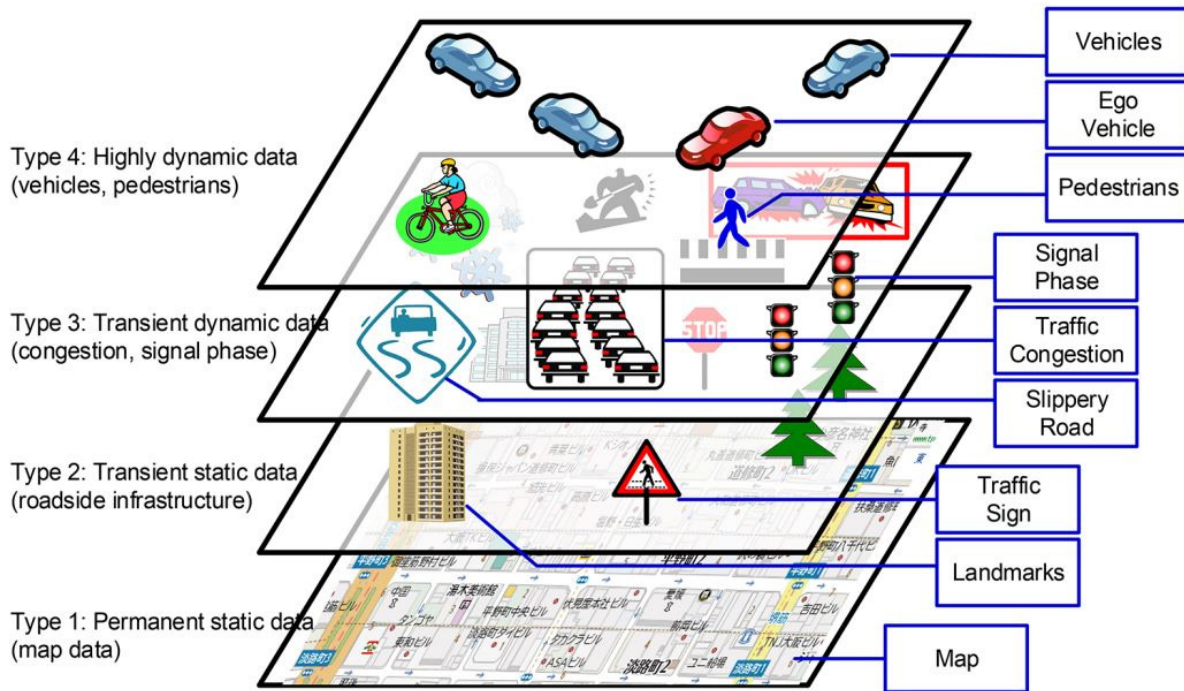


Figure 19: The features and layers of the LDM (Local Dynamic Map) [56].

A second relevant standard is called ADASIS (Advanced Driver Assistance Systems Interface Specifications), founded by the public-private partnership ERTICO in 2002. ADASIS provides the interface between map data, stored in formats such as the NDS standard, and the Electronic Control Unit of the vehicle. Figure 20 provides a visual overview of the function of the ADASIS standard with respect to the NDS standard.

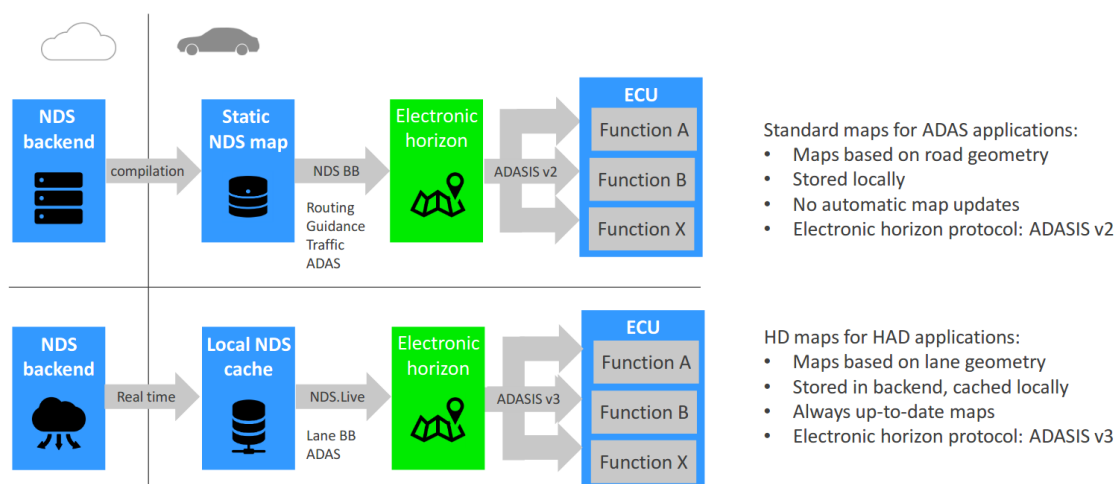


Figure 20: As discussed in the 1st NDS public conference on June 13, 2019, both NDS and ADASIS are design to work together [54].



Currently two versions of the ADASIS standard exist: version two and version three. Key attributes of these two standards are listed below [59].

**ADASIS v2:**

- Road-level data for advanced driver assistance applications.
- Designed for the in-vehicle CAN bus communications network.
- Road data stored as a single line with attributes provided at a meter accuracy level.

**ADASIS v3 – extends ADASIS v2 with the following additions:**

- Lane-level data at the centimetre accuracy.
- Stored road geometry (gradient, curvature).
- Requires Ethernet connection within the vehicle.

At this point map standards and in-vehicle communication standards have been discussed. However, a final component is the standards for communication between vehicles and both the cloud and infrastructure. The European Union and HERE are jointly working on an initiative called SENSORIS (Sensor Interface Specification), which is leading the development of vehicle to cloud communication standards. SENSORIS can be summarised as an innovation platform of private and public partners which is defining a global standardised interface between cloud-based information and vehicles, coordinated by ERTICO [39] (for further details please refer to Section 6.6.2).

A number of companies provide commercial map solutions which meet the standards outlined above. TomTom, a global navigation software and map provider, released the TomTom ADAS map in 2012 (and which has continued to be updated since then). The TomTom ADAS map solution complies with both the NDS and ADASIS v2 standards and provides features such as road gradients, road curvature, lane count and traffic signs [8], [59]. TomTom also provides more advanced HD map solutions which are discussed in Sections 6.3.1 and 8.1. TomTom has also created OpenLR, an open-source standard for the transmission of linear referenced data, irrespective of the map formats used [60]. OpenLR can be used to transmit map data between two maps, even if the maps are in different formats. This means that OpenLR is well suited to handling the task of transferring map updates between different vendors, or between Government and industry (refer to Section 6.6.3 for further details concerning OpenLR).

The company HERE is another major producer of maps, with backing from major automobile companies including Audi, BMW and Daimler [61]. They provide a wide range of different modular products, each adding additional features to their maps. For example, one product is called HERE Road Signs. HERE Road Signs automatically collects and records road signs from connected vehicles (via installed cameras) then uploads this data to the cloud, where, after data validation, the map details are updated to all other vehicle subscribers [62]. However, this product is currently only available in Europe and North America. They also engage in



public-private partnerships, which enable further improvements to map data through collaboration with Governments. For example, the city of Copenhagen, HERE and BMW have collaborated on the SOCRATES (System of Coordinated Roadside and Automotive Services for Traffic Efficiency and Safety) 2.0 project. The SOCRATES project was an interactive traffic management project in the cities of Amsterdam, Antwerp, Copenhagen and Munich [63]. The maps provided by HERE are currently being used in DRIVE PILOT, an upcoming Level 3 automated vehicle being developed by Daimler through its Mercedes-Benz range [64]. DRIVE PILOT will use HERE's range of HD maps, which is discussed further in Section 8.2.

Mapbox (<https://www.mapbox.com/navigation/>) is another provider of Enhanced Digital Maps. This location data platform for mobile and web applications produces and maintains maps for these applications [65]. Mapbox maps are updated using crowdsourcing, from mobile devices which have Mapbox software installed on the device – they currently receive data from approximately 600 million mobile devices. The large number of real-time sensors enable them to provide up-to-date maps. Mapbox provides an automotive product offering, which overlays real-time traffic data on a high-resolution standard digital map. They also claim to include AI-powered object detection in this product, although this data appears to be used “in the moment” and not stored in a HD map. They appear to be leveraging their product as a “base map” that is powered by the extensive crowdsourcing capabilities of Mapbox, from which automotive manufacturers can then build additional capabilities on-top of the map. In addition to the publicly available product described in this paragraph, Mapbox is also developing a HD map data storage and transmission system called Vector Tile 3 [66]. Mapbox are working with Mobileye to develop the full HD map solution called RoadBook [67].

Finally, one known challenge in using prior maps with AVs is the temporary changes to map data which occur when road works are being performed. As identified in the 2018 US Department of Transport report *Preparing for the Future of Transportation: Automated Vehicles 3.0* [68], while infrastructure operators maintain data on road work activities, a common specification for this data does not currently exist (in the U.S.). Therefore, it is currently difficult for vehicle manufacturers and navigation software developers to access and use road work data in real-time across different jurisdictions.

### 7.3 Aerial Maps

The increased practicality and availability of aerial environmental scanning from aircraft has led to an abundance of aerial mapping providers, including Australian companies Nearmap and Aerometrex. Aerial imagery generally comprises high resolution imagery of the environment as well as altitude data obtained through range-sensor-based scanning of the environment. Its widespread coverage offers the potential for integration into mapping systems for automated vehicles, although aerial imagery alone is unlikely to be entirely sufficient for AV HD mapping purposes, given much of the environment is not observable from the air due to obscuration factors.

Toyota Research Institute-Advanced Development (TRI-AD) is developing high definition map building for surface roads using satellite imagery provided by Maxar Technologies [69]. As discussed in Denzo's report (translated to English), *Autonomous vehicle using digital map as a soft infrastructure*, a high-precision digital map is defined as being indispensable for the automatic driving system [70]. Digital maps can be considered as soft infrastructure. In conjunction with Toyota's work, Denzo are also focusing on developing HD maps using aerial or satellite imagery as an orthogonal image. The idea is to avoid creating HD maps using specialised survey vehicles – that way the cost of producing HD maps is substantially reduced. The problem of obscuration factors has been partially addressed using post-processing techniques, with a final HD map accuracy of 25cm [71].

Another approach involves collecting aerial images using drones, rather than satellites. Drones have the advantage of being lower to the ground, enabling greater visibility of road features and less visibility obstruction issues. For example, Hyundai MNSOFT (<http://www.hyundai-mnsoft.com/EN/aboutus/company.mms>) is using a combination of ground (survey) mapping vehicles, aerial mapping vehicles and the live automated vehicles themselves all as sources of data to feed into the creation of a HD map for autonomous driving.

While not directly related to automated driving, Queensland Department of Transport and Main Roads has collected ground and aerial LiDAR data for over 6000 km of state-controlled roads in Queensland [72]. This data has, so far, been used for oversize and over-mass transport calculations, as well as asset management, but could be further utilised as a data source for a future HD map.

## 7.4 High Definition (HD) Maps - Overview

A HD map extends upon an enhanced digital map by recording a 3D representation of the world around the vehicle. This representation can be generated using a variety of sensors including LiDAR, Radar and Cameras. It is worth noting that the definition of what constitutes a "HD map" varies by provider - there are no strict guidelines as to what constitutes a HD map. However, the key agreement between all providers is that the HD map must have high positional fidelity and accuracy, in the order of approximately 10cm [9], [10]. At the basic end of the HD mapping spectrum, a HD map can simply be an encoding of the accurate positions of road signs, lane markings and guardrails. At the advanced end, a HD map is a dense LiDAR point cloud, storing the distance to every obstacle around the vehicle.

A wide variety of companies generate HD maps for automated vehicles, ranging from small self-driving start-ups to large international map providers. Below we provide a bullet-point list of some of the key, publicly visible providers and their respective solutions, with greater detail provided in Section 8.

- TomTom - HDMap and RoadDNA

- HERE Technologies
- Nvidia - DriveWorks
- DeepMap
- Sanborn
- Waymo
- Nutonomy
- Atlatec
- Apollo
- Mobileye

## 7.5 Updating and Maintaining Maps

As discussed in Apollo’s report *Reliable and Safe maps for Automated Driving* [73], a map used by an AV can become a safety hazard if the map deviates sufficiently from the reality perceived by the vehicle’s sensors. In this regard, the map is particularly critical; unlike a mapless automated vehicle, the vehicle is relying on the map, and hence map errors can be particularly problematic. As identified in Apollo’s report, a map will differ from the real-world in the following cases:

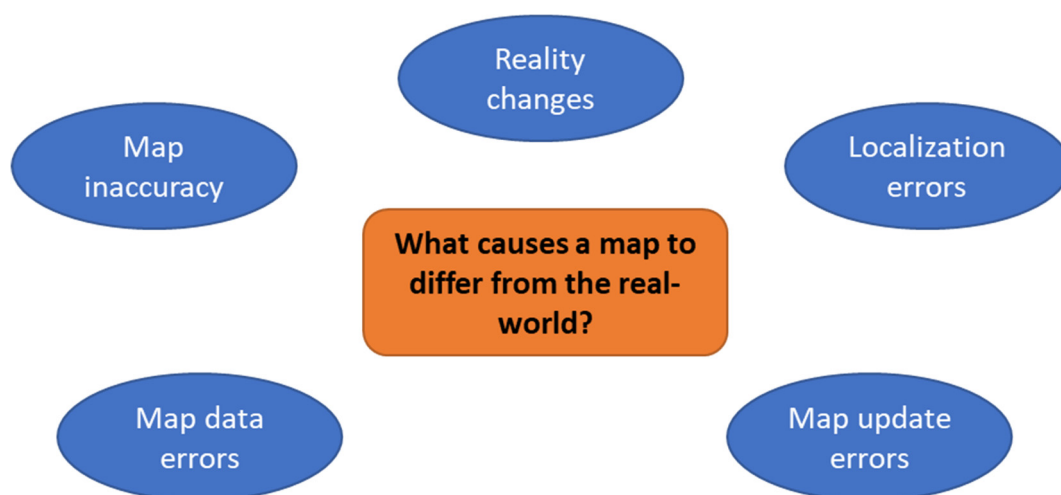


Figure 21: Diagram of the various factors causing a map to differ from reality.

Map accuracy describes the positional accuracy of the map. For example, if the map accuracy is two meters, we can be confident of the road curvature and position of signage to a precision of two meters. This may be sufficient for certain AV navigation tasks, however detecting whether a lane-marking has been tampered with, or whether a stop-sign has been moved, may not be possible. Map data errors reflect the suite of potential failure cases in the map creation process. For instance, a particular road may simply be missing from the map due to human or software error. A full diagram of map data errors as discussed in Apollo’s report is shown in Figure 22.

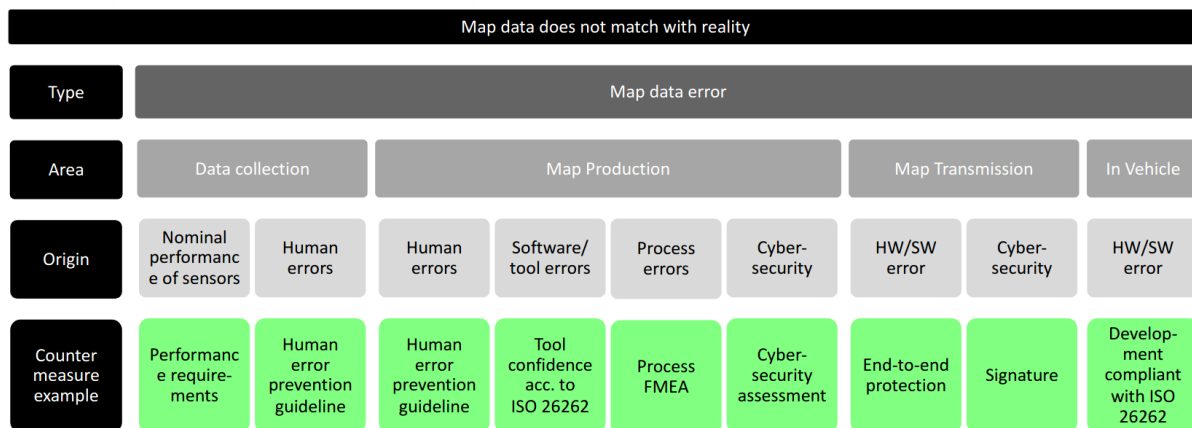


Figure 22: Map data error examples, as suggested by Apollo [73].

Since a map can only be regarded as accurate at the moment it was created (and even then only if the map creation process was faultless), and since the real-world environment is constantly in flux, some level of discrepancy will inevitably exist between a map and the world it is meant to represent. It is important for an AV to detect any relevant differences between a map and the incoming sensor data and react appropriately. Figure 23 provides a visual overview of the types of situations that can arise.

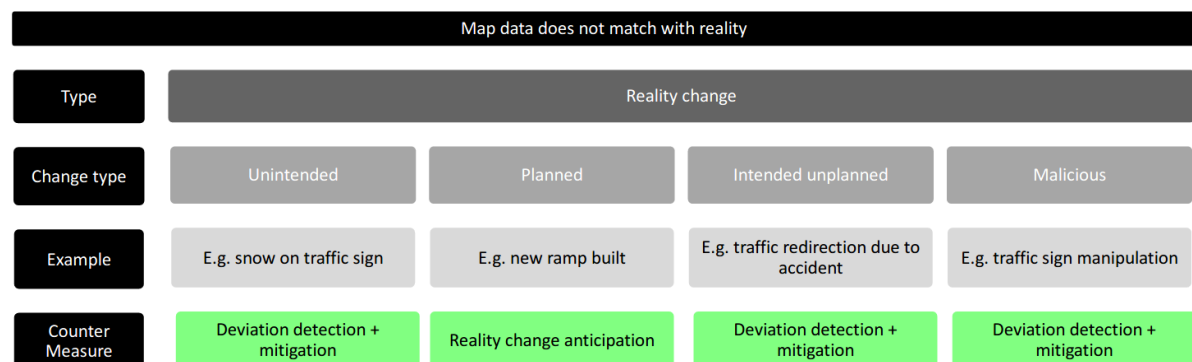


Figure 23: Mapping in a changing world: the flip case, where the world changes but the map doesn't [73].

The process of updating maps is especially challenging when the map is required to have high definition features. A common approach to mapping is to drive the environment using specially designed mapping vehicles with custom sensors. The collected sensor data is then processed offline using a team of map editors, to assemble a complete map. This is an expensive and time-consuming process and therefore limits the update frequency of the map. As detailed in DeepMap's patent, conventional mapping techniques can't sufficiently keep maps up-to-date to enable safe autonomous driving [27].

Crowdsourcing data collection is one potential solution to the map update problem - but the crowd sourcing of data must occur at (or at more than) the fidelity level required for the particular mapping system. In addition, a close connection between Government jurisdictions and map creators would be a second solution to map updates (in particular for changes

relating to road works, which are typically under the purview of various governments or councils). While this appears to be a challenging task, the digitization of road work data is already a solved problem, even in Queensland - the CAVI trial in Ipswich City has enabled the transmission of accurate road work data to digital users of the Queensland Traffic website (<https://qldtraffic.qld.gov.au/>). The challenge will be converting this data into a file format that can be read by the cloud services of a HD map provider. Some discussion on this topic is included in Section 8; discussions with TomTom have shown promise in particular.

## 7.6 Ownership of Data

As identified on page 21 of the United States Government Accountability Office (GAO) report *Automated Vehicles: Comprehensive Plan Could Help DOT Address Challenges* [74], clarification about who owns and has access to map data collected by AVs is required. Additionally, data standards may be required across vehicles, so that map data collected can be easily compared between different types of vehicles. Some of the key considerations include whether governments should request or expect some access or co-ownership of data acquired by companies, how governments who acquire map-related data themselves can share this data with AV operators who operate in their areas, and general considerations around ethical and privacy concerns given the inherently public nature of road-based map datasets.

## 7.7 Summary

The provision of maps for automated vehicles is rapidly becoming an established field, with numerous car manufacturers investing in this field, as well as entire companies focused on the provision of maps as their core business model. An initial literature review discovered many companies providing standard and enhanced digital maps, along with internationally recognised standards to ensure that these maps have sufficient detail to safely be used in advanced driver assistance systems (ADAS). This section also introduced key considerations when developing and utilising maps for AVs, specifically the issues of ownership of data and maintaining maps and validation of crowd-sourced data.

Our review has revealed that the “enhanced digital map”, which can be essentially summarised via the ADASIS v2 standard, is a mature field with numerous competing commercial solutions on the market. These maps are incorporated into existing vehicles on our roads, and used in features such as Adaptive Cruise Control, Lane Keeping Assist and Traffic Jam Assist. The “HD map” field is an emerging market, with large companies like TomTom and HERE competing with smaller start-ups, all positioning themselves to leverage the expected commercialisation of Level 3 and higher automated vehicles. The following section will discuss this field in detail.

## 8 High Definition Maps

This section provides an in-depth analysis of all relevant high definition (HD) mapping approaches for automated vehicles. Each sub-section contains the HD map solution provided by a particular private or public enterprise, including highlights of coordinated public and private efforts. We summarise our findings using the Table below (the table is a quick reference, more information can be found in the respective subsection). We provide TomTom as a flagship study: while many HD map providers are unwilling to share detailed technical information, there are likely to be many commonalities across all approaches.

*Table 4: Summary of HD Map Providers*

Provider	Categories	Description
TomTom	Features	A proprietary HD map solution that can be condensed into a small file size and localised using their RoadDNA solution.
	Supported level of automation	Theoretically up to level 4.
	Government partnerships	Collaboration in Australia through the NTC, collaboration with EU C-ITS C-Roads and other projects.
	Maintenance requirements	Regular map updates, ideally communicated via an XML schema encoded using either the Datex II standard or the OpenLR standard.
	Map update frequency	1-3 minutes, if supported by transport authority communications.
	Demonstrated use cases	ADAS applications in the EU.
HERE	Features	A proprietary HD map solution .
	Supported level of automation	Up to level 3, as demonstrated by implementation in the upcoming Mercedes Drive Pilot. Theoretically up to Level 4.
	Government partnerships	Australia and New Zealand Cooperative Research Centre for Spatial Information (CRCSI). Variety of EU C-ITS projects, including C-Roads and TN-ITS.
	Maintenance requirements	Regular map updates, communicated using Datex II, TN-ITS or SENSORIS specifications.
	Map update frequency	Not publicly disclosed
	Demonstrated use cases	ADAS applications in the EU
Waymo	Features	Arguably the most accurate HD map available due to the use of dense LiDAR

		point clouds. However, the map coverage is very limited.
	Supported level of automation	Up to level 4, as proven by Arizona AV testing.
	Government partnerships	None (to the best of the authors knowledge)
	Maintenance requirements	Not publicly disclosed
	Map update frequency	Not publicly disclosed
	Demonstrated use cases	Autonomous taxi's in Arizona
<b>Atlatec</b>	Features	A light-weight and easy-to-use HD map that can be created using just camera data
	Supported level of automation	Theoretically up to level 4, however lack of real-world use-cases
	Government partnerships	Projects in Germany
	Maintenance requirements	Traffic management employee to manually update the map
	Map update frequency	Manual updates, therefore approximately daily.
	Demonstrated use cases	UNICARagil project in Germany
<b>Nvidia, Sanborn, DeepMap, Nutonomy, Apollo, Mobileye</b>	All these companies are also providers of high definition prior maps for automated vehicles, but limited public information is available.	

## 8.1 TomTom

TomTom is a location technology specialist, who develops and maintains accurate maps and navigation software, along with real-time traffic information services. They are focusing on developing maps and services for the future connected and automated vehicle market, through the provision of a variety of products. As discussed earlier in Section 7.2 (Enhanced Digital Maps), TomTom's "ADAS Map" product provides a collection of road attributes as an addition to a standard digital map. These attributes can then be used by a driver assistance system (Level 1 and 2 automated vehicles). These attributes may also be useful to a human driver too.

TomTom is developing HD maps to suit fully automated vehicles, through two products called HD Map and AutoStream. HD map was first released in 2015, with coverage across Europe, North America and Asia. The features of HD map are summarised below:

1. Lane geometry
2. Lane-level speed limits
3. Lane markings



4. Traffic signs
5. Position of road borders and guardrails
6. Lane connectivity
7. 15-20cm relative accuracy
8. RoadDNA localisation solution

These features comply with the requirements of the ADASIS v3 standard, however the addition of RoadDNA is what makes this product a full HD map solution. RoadDNA converts a 3D depth map (collected using sensors such as LiDAR) into a 2D raster depth image. This approach is different to the normal technique of storing the full 3D point cloud on the vehicle; as discussed in the RoadDNA Product Sheet, a compressed 2D view is easier to use in-vehicle where processing capabilities may be limited. They have also developed algorithms which can localise the position of an automated vehicle with respect to their maps [75]–[77].

While the HD map product contains a significant feature set, it lacks any mechanisms for rapid and regular map updates. This is where TomTom’s second product AutoStream is applicable. Autostream provides on-demand streaming of High Definition (HD) and/or ADAS map data. That way the local copy of the map in the vehicle is always up-to-date with the cloud copy. The cloud map is kept up-to-date via data collected by TomTom; from a discussion with a TomTom representative, ideally the map should be updated every 1-3 minutes. The map update process can be automated using live-streamed data provided directly from crowdsourcing and Government traffic management centres.

TomTom provides a list of some key statistics regarding their mapping efforts to date [76]:

- World-wide, TomTom is actively tracking 48 trillion data points.
- Five Billion pixels of resolution per square kilometre.
- 600 million real-time collection devices on the road for real-time condition updates.
- Three million kilometres mapped in HD annually.

In addition to the above international statistics, TomTom has also mapped 300,000km of Australian roads in high definition. This was achieved using a mapping vehicle equipped with a Velodyne 32 LiDAR, a Ladybug 5 omnidirectional camera, GPS and a 6 DOF (Degree Of Freedom) IMU (inertial measurement unit). Their mapping efforts have currently been focused on the major roads and motorways in urban regions. While this mapping data is available, the HD map product is currently not available in Australia - at present there is a lack of demand from car manufacturers with respect to using these maps in cars sold in Australia. TomTom is only a software provider; to use the HD map the vehicles need specialised hardware, which is paid for by the OEMs (Original Equipment Manufacturers). Successfully deploying HD maps is also a case of “more is better”; the ability to rapidly update the prior map is improved when more connected vehicles are on the roads.

There are some further limitations to utilising current TomTom's HD map offering in Australia. First, pre-trained AI models often experience difficulty on Australian roads. Because the AI is trained on overseas roads, the AI has reduced detection accuracy on Australian roads. From an interview with TomTom representatives, it was stated that TomTom finds that the AI networks that were originally trained on roads in the EU to be the worst, although re-training the neural networks on Australian roads improves the performance. This training phenomenon was also observed in the project *P1-007: How Automated Vehicles Will Interact with Road Infrastructure Now and in the Future*. The second limitation is the challenge of converting the existing communications software (from infrastructure to TomTom cloud) to suit Australia. Currently, since TomTom is headquartered in the EU, the focus has been on developing software in conjunction with existing EU traffic management data formats (such as the Datex II standard). The decision then becomes, does the Government convert its digital infrastructure communication protocol to follow the Datex II standard, or does TomTom develop software that can communicate with Australia's existing traffic management data formats? Further discussion is included in Section 10.

## 8.2 HERE

HERE offers a HD Live Map product, which is a cloud-based mapping product and service. The map has multiple layers - a road model, HD lane model and HD localisation model (see Figure 24). The road model is a standard road map, but also includes the position of the road centreline and road-level attributes (such as speed restrictions and road gradient and curvature). The HD lane model provides lane-level details like lane boundaries and lane marking types. The HD localisation model allows the vehicle to localise itself using the position of road objects such as guard rails, walls, signs and poles. These are mapped using HERE TRUE vehicles with four cameras, a Velodyne LiDAR and an IMU (Inertial Measurement Unit) [78].

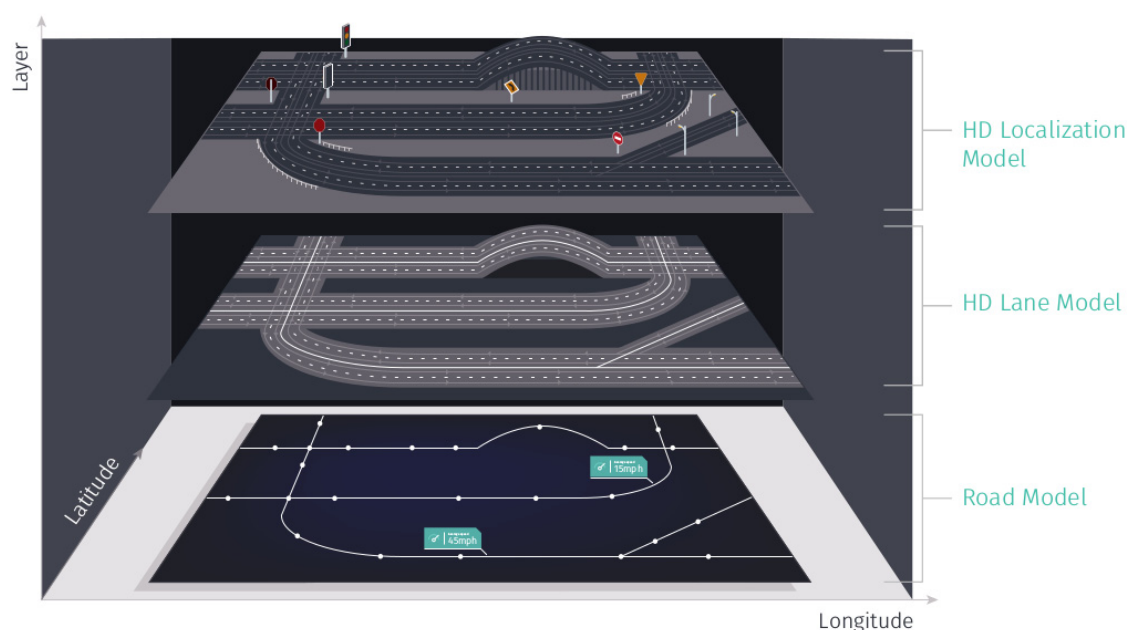


Figure 24: Demonstration of HERE's map layers in their HD Live Map product [78].

HERE places a strong emphasis on building maps, using a wide range of data collection sources. Sensor data is collected using crowdsourcing from both specialised mapping vehicles and existing vehicles equipped with sensors for ADAS features. Their “self-healing map process” is used to update maps based on incoming observations, as outlined by Figure 25. Maps are also updated using traffic data supplied by Government transport departments (using data formats Datex II and TN-ITS), however at this stage this update process is only available in the EU.

Map data is transferred to vehicles using a map tile system - the connected vehicle only receives the section (or “tile”) of the map that the vehicle is currently located in (using Mapbox’s Vector Tile 3 [66]). This limits the data transfer requirements. The HD map data is transferred using either the Protocol Buffer (Google’s Protobuf) or NDS format. Map data from HERE can be requested using either a REST API or a Javascript API and further technical details can be found at this website:

[https://developer.here.com/documentation/traffic-data-service/dev\\_guide/topics/apply-functional-road-class-filter.html](https://developer.here.com/documentation/traffic-data-service/dev_guide/topics/apply-functional-road-class-filter.html)

Additionally, HERE has the ability to ingest Datex II formatted messages encoding traffic data, through their Traffic Data Service:

[https://developer.here.com/documentation/traffic-data-service/dev\\_guide/topics/concept-datex.html](https://developer.here.com/documentation/traffic-data-service/dev_guide/topics/concept-datex.html)

Finally, important vehicle to cloud communications can also be achieved using SENSORIS, which is a public-private partnership between HERE and Ertico (see Section 6.6.2). SENSORIS can transmit data on weather, road infrastructure and traffic events to the vehicles, and also transmit vehicle status information from the vehicles back to the cloud.

HERE Technologies has also completed a small amount of HD mapping in Australia. In partnership with the Australia and New Zealand Cooperative Research Centre for Spatial Information (CRCSI), HERE trialled the creation of a HD map to support Highly Automated Driving in Victoria [79]. The project also trialled the utilisation of an upcoming Satellite-Based Augmentation System, which promises an improved version of GPS with 10cm accuracy [80]–[82]. While HERE is a major contributor to the development and deployment of HD maps overseas, this report found no evidence of any further collaboration nor or plans to support automated vehicles in Australia.

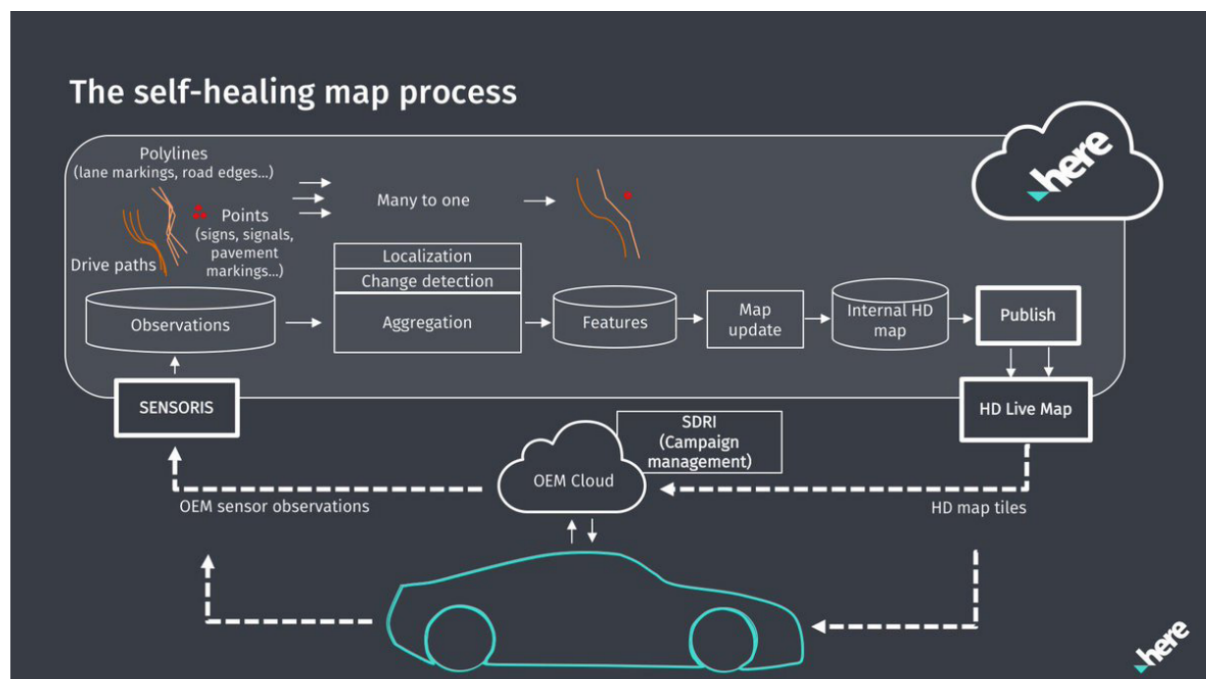


Figure 25: HERE's trademarked self-healing map process [78].

### 8.3 Waymo

Waymo, a subsidiary of Alphabet (commonly known as Google), is a major innovator (and one of the first) in the automated vehicle industry and is currently considered one of the leading AV developers, if not the leader. Waymo automated vehicles have driven over 20 million miles on real-world roads since 2009 [83]. Waymo vehicles operate at Level 4 autonomy and use a vast sensor suite to do so. Specifically, Waymo vehicles have 360-degree field-of-view LiDAR, vision (camera) and radar sensors [84]. The data from these sensors are used to create highly detailed 3D maps of the environment. Waymo vehicles strictly operate only within fully pre-mapped environments. Waymo has also recently open-sourced a demonstration dataset (<https://github.com/waymo-research/waymo-open-dataset>), with detailed road data collected from their sensors [85]. This dataset provides a snapshot of the types of data and their format used by Waymo (note that for this dataset the LiDAR range data was truncated from 300 meters range to 75 meters range [86]). Figure 26, Figure 27, Figure 28 and Figure 29 show examples of the sensor data that is collected by their vehicles.



Figure 26: An example set of images recorded by the camera on a Waymo vehicle, as provided by the Waymo Open Dataset [86].

Figure 26 shows a set of images recorded by a Waymo vehicle, showing the differently orientated camera fields-of-view around the vehicle. To generate this figure, images were extracted from the dataset using a Linux machine running the Waymo Open Dataset Github repository and Tensorflow. Note the bounding boxes on certain objects in the image, which are detections of relevant objects as calculated using Waymo’s software.

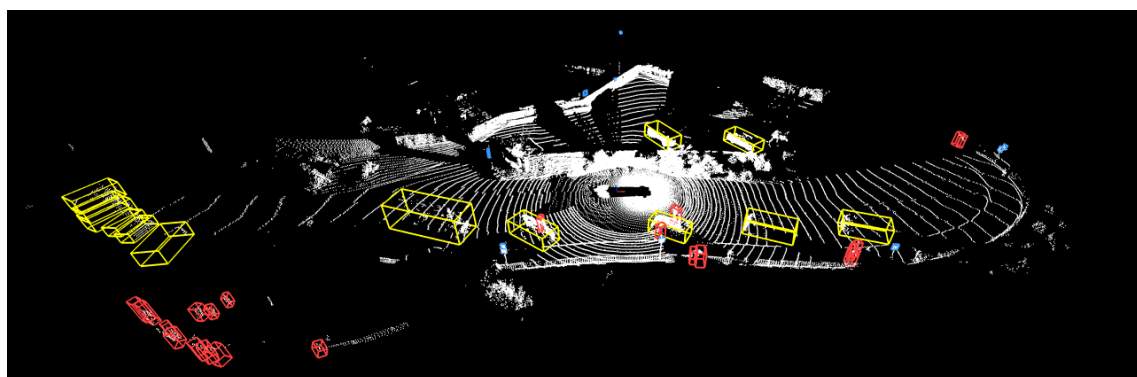


Figure 27: An example of a LiDAR point cloud generated by Waymo’s automated vehicle software [86].

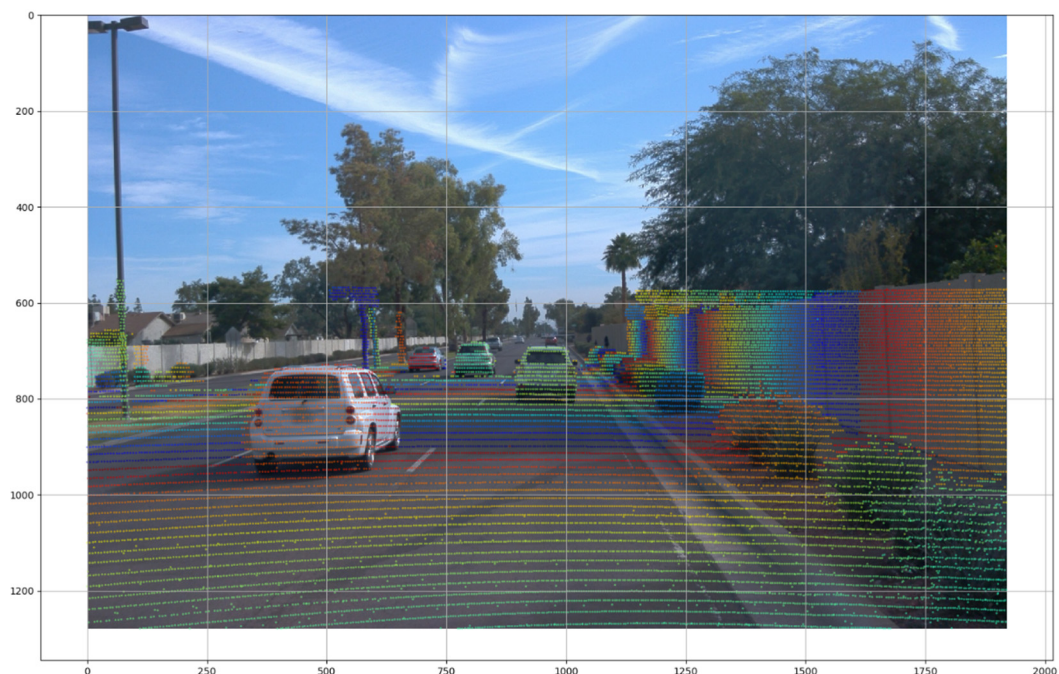


Figure 28: An example LiDAR return image, from the same real-world location as the previous figure. The return image contains six different channels [86].



Figure 28 shows a LiDAR sensor image across six channels. The six channels are, from top to bottom: range (first strongest laser return), LiDAR intensity, LiDAR elongation, range (second strongest laser return), then intensity and elongation again for the second strongest return. While this representation has some value, LiDAR is particularly powerful when used to generate a 3D representation of the world around a vehicle. These are typically called LiDAR point clouds. LiDAR point clouds are one of the standard methods of representing an environment in high definition across automated vehicles and robots, but have high data storage requirements (see Figure 27).

Finally, LiDAR can be simultaneously synchronised with image data, as Figure 29 shows. The colours denote different distances to parts of the image. Combining both LiDAR and vision enables improved classification of objects in the environment by combining geometrical and appearance information.



*Figure 29: LiDAR can be synchronised with images, as this visualisation shows (image generated using the Waymo Open Dataset) [86].*

In summary, using the combination of multiple sensors and object detection algorithms, Waymo is able to generate HD maps of the road networks for their driverless cars. It is worth noting that Waymo is a purely in-house system – their HD maps are solely used by their vehicles, with no public data indicating any intention of selling their HD maps. While this makes Waymo somewhat irrelevant at least in the short term to the objective of HD mapping Australian roads for automated vehicles, it is worth discussing Waymo due to their technological maturity in this space, as a best practice case study, and for the scenario in which they become one of the first entrants into the Australian market.

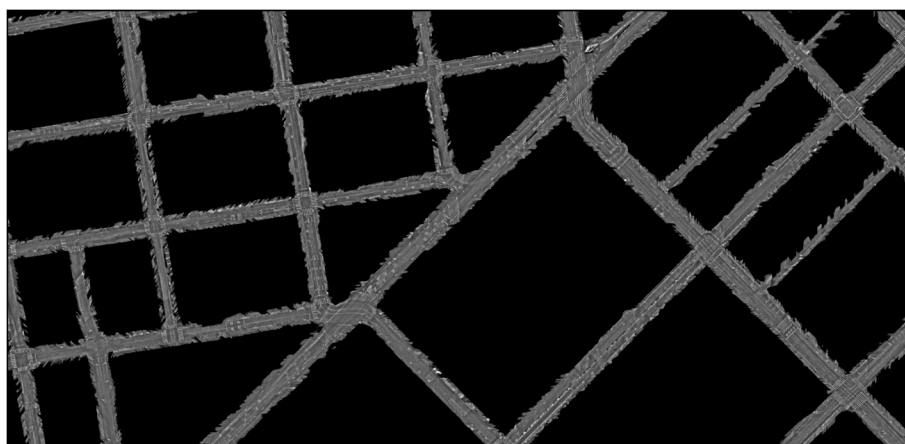
## 8.4 Atlatec

Atlatec<sup>1</sup> is a company producing high definition maps for autonomous driving. The key point of difference between Atlatec and competitors like HERE and TomTom is that they develop their maps using just vision (camera sensors). Rather than requiring specialized mapping vehicles, they have developed a custom roof-mounted sensor box which can be attached to any standard vehicle – see Figure 30. Their solution views the environment around the vehicle using a stereo set of forward-facing cameras. Atlatec then produces HD maps using the collected data, categorising features (such as lane-markings) observed in the image stream. Even though Atlatec’s solution does not use advanced sensors like LiDAR, as can be observed in Figure 31 and in Figure 14 and Figure 15, they can still produce high quality maps. Their ability to easily move into new markets, using a very portable mapping platform, potentially differentiates them from other mapping options in terms of developing HD maps in Australia.



*Figure 30: Atlatec's data collection platform is simply two cameras mounted on top of a vehicle (source: e-mail correspondence with Atlatec).*

1: All information in this section was sourced by email correspondence with Atlatec representatives.



*Figure 31: An example of Atlatec's mapping capabilities on a set of roads in San Francisco (source: e-mail correspondence with Atlatec).*



From discussions with a representative from Atlatec, Atlatec has been working with Governments through Government-Industry partnerships, both as a consortium partner and as suppliers to various consortiums. Examples include the *Test Area Autonomous Driving Baden-Wurttemberg*, the *Test Bed Lower Saxony for automated and connected mobility* and the UNICARagil project (<https://www.unicaragil.de/en/>), which aims to “rethink automated vehicles and their architecture”. Collaboration in Australia is also a possibility for Atlatec in the future.



Figure 32: Atlatec provides an easy-to-use user-interface for updating their maps (source: private correspondence).

To conclude this section, Atlatec has provided some details concerning their map updating process. Unlike TomTom, Atlatec is not implementing automated map updating. Instead, they are developing a user-interface for rapid manual map updates. An example is shown in Figure 32. The map can be updated by either the client directly, or by Atlatec on behalf of a client. The updates are categorized as Semantics-only Updates, or Geometric and Semantic Updates. The Semantics-only Update is where a part of a road is marked as being out of action, or hazardous, say due to road works. A geometric update is a permanent change to road layout, such as new lanes or new highway exits. Geometric updates require a re-mapping of the affected route parts. While this system won't have the 1-3 minute update frequency that TomTom is aiming for, the barrier to adopting these HD maps is much lower, since specialized software to communicate between public and private digital infrastructure is not required.

## 8.5 Nvidia

Nvidia Drive is an open source software stack and library of modules which enables automated vehicles to function. It is not a ready-for-deployment product, but a software tool which can be built-upon to quickly establish a working automated vehicle [87]. The Nvidia Drive Mapping sub-component enables an AV to localise with respect to a HD map, update a cloud-based HD map and directly create HD maps from an AV [88], [89].

The authorship team contacted Nvidia for further details, but they did not reply.

## 8.6 Sanborn

Sanborn has collected aerial and street-level data in parts of California, which is accurate to a 7-10cm range. Their maps include LiDAR data, comply with the ADASIS v3 standard and all relevant street signage [90].

The authorship team contacted Sanborn for further details, but they did not reply.

## 8.7 DeepMap

DeepMap, a Silicon Valley start-up founded in 2016 (<https://www.deepmap.ai/company/>) is focusing their efforts on the creation of HD maps at centimetre level precision, with the ethos that “maps should be made by self-driving vehicles and for self-driving vehicles”. DeepMap have several active U.S. patents, which provides a high-level overview of their patented mapping technology. The details of these patents can be found in Section 6.

The authorship team contacted DeepMap for further details, but they did not reply.

## 8.8 Nutonomy (Aptiv)

Nutonomy, formerly a startup and now a subsidiary of Aptiv, also focuses on using HD maps for autonomous driving. As discussed in the white paper published by Aptiv: *Safety First for Automated Driving* [91], a HD map is necessary as it contains carefully processing of a-priori information to find environment features that are not easily detectable by on-board sensors. If a discrepancy exists between the world and the map, the HD map can be utilized as a reliable redundant source of information (assuming the map is maintained regularly).

The whitepaper introduces the concept of “Reliable Map Attributes” (RMA’s). In the aforementioned white paper, we direct the reader to page 49. While a HD map can be a very dense information representation, up to and including a full 3D model of the environment, a subset of the information in a HD-map is particularly critical to the safety of the AV. Such information includes road speeds, lane markings and stop-signs. Deviations between map and the world are particularly severe (RMA failure as defined in the Aptiv white paper) but can be caused by changes as common as road works and collision damage (e.g. a stop-sign that has been displaced after an accident). These findings against suggest that an almost-real-time map update process is necessary for the safe implementation of AVs. In a quote from the Aptiv white paper: “failures relating to planned road changes can be avoided by incorporating road change plans from a road authority into the map updating process” [91]. This flags a specific example where the role of government is particularly likely in HD mapping for automated vehicles.

Nutonomy has demonstrated evidence of collaborating with road authorities – for example, Nutonomy is testing automated vehicles in Boston and in their Q1 2020 report to the Boston

city government, they recommended that the Boston city council increase the number of designation drop-off zones in the city. Since their driver-less vehicles are programmed to follow the law, the lack of legal pick-up zones is inhibiting the ability for driver-less taxis to operate [92].

## 8.9 Apollo

Apollo, a subsidiary of Baidu in China, is a major developer of future automated vehicle software. Apollo is also the one of the few autonomous driving companies to release open source code [12]. The open source code they provide is a comprehensive package, including perception, simulation, HD mapping, localization, path planning and control systems. Apollo is also one of the few companies in China allowed to perform on-road testing of a Level 4 automated vehicle [93]. Apollo's HD map is based on the OpenDRIVE format and includes roads, lane geometry and labels [94], [95]. It is a light-weight map that is designed to be cheap to create and maintain, however, it has no obvious support for precise positions of traffic signs.

## 8.10 Mobileye

Mobileye is an automated vehicle company utilising only cameras and HD maps to navigate, with a HD map solution called RoadBook. Roadbook includes road geometry (lanes, drivable paths), static objects (traffic signs), lane markings and speed information [67]. Mobileye's HD map creation system is called Road Experience Management (REM). It is a fully crowd-sourcing system, which gathers data for its map using existing consumer vehicles that are installed with Mobileye ADAS systems (from a sensor perspective, the data is collected just using cameras). A key feature is the significant data compression – the data transmitted from the vehicle to the cloud is just 10 kilobytes per kilometre driven [96]. This data compression is achieved by running computations (including AI algorithms) on-board the vehicle. They believe that as the number of concurrent connected vehicles on the road increases, crowdsourcing will be able to satisfy the real-time mapping component of HD maps.

## 8.11 General Limitations of Existing Models

While a wide variety of HD map solutions exist, some general limitations prevalent to all models are still present, with some of these limitations particularly notable when taken in the context of operating in Australia. First and foremost, crowdsourcing is generally assumed to be sufficient for providing near real-time HD map updates. While this may generally be true for countries with very high population densities (e.g. the Netherlands) and high autonomous (or at least cloud-connected instrumented) vehicle market penetration, in Australia many major highways linking our sparsely populated country receive very low traffic levels, meaning crowdsourcing will not result in particularly responsive maps. Exacerbating this sparseness issue is that crowdsourcing is typically based on a voting model over multiple automated vehicles (which will delay map updates even further), to prevent false sensor readings from disrupting the stored map. Second, some of the HD map solutions such as Atlatic and Apollo

(which are based off the OpenDRIVE format) are limited to 2D data storage. This lacks the dimension of height. Arguably, height also needs to be stored in the HD map as height enables improvements to traffic sign recognition systems. It is worth noting that in the previous iMOVE project P1-007 (How Automated Vehicles will Interact with Road Infrastructure Now and in the Future), prior maps was found to significantly improve traffic sign detection performance; however, these improvements were using a 3D prior map representation, not 2D [97]. Finally, it is hypothesised that it is likely (given the reliance on crowd-sourcing) that existing HD map solutions products lack a sufficiently accurate real-time update process for expected (road works) and unexpected (accidents) road impacts, and it's likely that government, given its oversight of road works, could play a key role here.

## 8.12 Usages of HD Maps Beyond Automated vehicles

While this report is predominately focused on the applications of HD maps for connected and automated vehicles, detailed mapping solutions have value in other transport authority situations. For example, detailed 3D models can improve infrastructure design and maintenance, transport modelling and heavy vehicle management.

Certain companies have a business model concerning HD maps designed for these different use-cases. For example, the Australian company Aerometrex produces detailed and accurate 3D maps on a per-contract basis, using aerial images and LiDAR data [98]. These maps then can be used to detect road defects, aid in the design of infrastructure, and locate and measure assets on bridges, roads and tunnels. Nearmaps is another Australian company that provides high definition aerial images which can aid infrastructure construction and maintenance, and urban planning [99]. Neither of these companies are publicly pursuing HD maps for automated vehicles, although these aerial images can be used for maps for aerial autonomous vehicles. The company Wing, a graduate of the Google-X program, has recently begun autonomous delivery trials in Queensland. In addition to GPS, they also use downward facing aerial cameras for backup localisation purposes [100]. Their cameras capture low resolution grayscale images, and it can be assumed that the captured images are compared against a database of pre-collected aerial or satellite images.

Major HD map suppliers like HERE and TomTom do not offer any maps designed for infrastructure inspection or design; their maps are created specifically for mobility solutions rather than static infrastructure. We note that the current development of HD maps is approached by application - there is little evidence of dual-purpose maps that can be used for both automated vehicles and static infrastructure design and maintenance.

Overseas however, the company AND (Automotive Navigation Data) based in the Netherlands, provides maps for both infrastructure design and automated vehicles [101]. Unlike larger companies like HERE and TomTom, they focus on providing specific map solutions to the European and US markets. Their specific solutions enable them to provide

the map features that are required for the customer applications; however, this also means that they are unlikely to provide maps with global coverage.

### 8.13 Summary

A wide variety of different HD map solutions are currently available or being developed, ranging from lightweight HD map solutions that primarily store lane markings and lane logic (Atlatec, Apollo), to more detailed maps that also encode road signs (TomTom, HERE), and finally maps that include full 3D point cloud representations (Waymo). Unfortunately, while the most comprehensive maps with full 3D representations provide the greatest guarantee of safety, these maps are expensive to produce and maintain and require vast quantities of data. Quite possibly the ideal solution may be a tiered (layered) approach, whereby detailed 3D data is updated at a lower frequency and a lower-memory 2D representation of the road network is updated much more frequently. Known existing solutions that are taking this pathway include HERE and Lyft (discussed back in Section 6.2.3), although given the secrecy surrounding these new technologies there are likely other HD maps currently being developed with similar characteristics. It is worth drawing the parallel between these recent tiered approaches and the original idea of a layered map, which originated from the concept of the Local Dynamic Map (LDM, from the SAFESPOT project). The difference between the LDM and existing layered approaches relates dynamism of the map – while the LDM stored highly transient data such as pedestrian and vehicle movements in their map (refer back to Section 7.2), current layered solutions like HERE no longer consider such dynamic data (based on sources such as [78]). This is likely to be the case because the map update frequency is not sufficient for tracking pedestrians. If only this low update rate is available, the task of pedestrian warnings for vehicles may need to be covered using V2I technologies, communications like DENM [38] and VAM [102], as well as last ditch on-board based solutions including radar-based collision avoidance systems. VAM (Vulnerable Road User Awareness Message) is used to communicate the location of vulnerable road users (VRUs) to nearby vehicles on the road network. VAM messages can be generated by roadside ITS stations, the vehicles themselves, or personal ITS stations. In the case of roadside and vehicle sources, VRUs are detected using cameras and software. In the case of personal ITS stations, the VRUs themselves generate the message, using devices such as smartphones or smart watches.

## 9 Government Responses to and Expectations of Automated vehicles and Usage of Prior Maps

### 9.1 United States

The United States Government (both Federally and in some States) have begun responding to the emerging technology of automated vehicles. As described by the US National Highway Traffic Safety Administration, automated vehicles provide four key benefits: safety, economic, convenience and mobility [103]. In terms of safety, because 94% of serious accidents are due to human error [103], automated vehicles can potentially prevent many of these accidents from occurring. Preventing accidents also has economic benefits, by preventing economic losses from lost workplace productivity and from disabilities. Automated vehicles also offer the potential to reduce traffic congestion, especially in ride-share transport models, since automated vehicles can travel faster and with reduced distances between vehicles due to their (potential) superior capabilities compared to human drivers. This offers both economic benefits and convenience benefits, by reducing commute times. Finally, automated vehicles (if not requiring supervision) would enable people who are unable to drive for health reasons to be able to travel around with much greater mobility. The above advantages of automated vehicles are some of the reasons that the US Government is supporting this technology. Additionally, a large number of self-driving companies are headquartered in the U.S.; there are approximately 163 companies involved in automated vehicles with their headquarters in the U.S. [104]. The Government response to supporting this technology can occur at two levels: federally, and at a state level. Initially this section will discuss the federal response, as related to prior maps for automated vehicles.

At the federal level, a key stakeholder in the U.S. Government is the Department of Transportation (DOT). In a quote from the U.S. Government Accountability Office report *Automated Vehicles Comprehensive Plan Could Help DOT Address Challenges*: “According to DOT officials, DOT is first seeking to identify or determine best practices for automated vehicles as an incremental step to avoid issuing regulations prematurely that are unable to keep pace with rapidly advancing technologies” [74]. This statement indicates that DOT’s approach is to allow the private enterprises pioneering this technology to develop the most effective technology with some freedom and add the necessary infrastructure in response to the most promising solutions to the challenge of automated vehicles.

In saying this, the U.S. DOT and U.S. Federal Highway Administration (FHWA) are funding a wide range of AV related projects, although there appears to be a relative lack of funding for prior maps for autonomous driving. Pages 16 and 17 of the report *Ensuring American Leadership in Automated Vehicle Technologies* (Automated Vehicles 4.0) provides a holistic overview of funded projects in relation to AV technological implementations [5]. To summarise, a key focus is the development of cooperative automated driving systems, using



V2V and V2I communication networks (refer to Figure 33 for a visual example of such networks). One noteworthy project is called CARMA, created by the U.S. Federal Highway Administration (FHWA) to encourage collaboration and to improve transport safety, efficiency and mobility [105].



Figure 33: Artist render of what a V2V and V2I connected communications network might look like [106].

The CARMA Platform (<https://highways.dot.gov/research/operations/CARMA-Platform>) is an automated driving system that allows AVs to interact and cooperate with infrastructure (e.g. stop lights) and other vehicles via communication. The platform is publicly available on Github: <https://github.com/usdot-fhwa-stol>. The CARMA project can be summarised as a Government led initiative to promote standardization of V2V and V2I communications. In terms of connected vehicle trials on American roads, three examples are the New York City DOT Pilot ([https://www.its.dot.gov/pilots/pilots\\_nycdot.htm](https://www.its.dot.gov/pilots/pilots_nycdot.htm)), Wyoming DOT Pilot ([https://www.its.dot.gov/pilots/pilots\\_wydot.htm](https://www.its.dot.gov/pilots/pilots_wydot.htm)) and the Tampa (THEA) Pilot ([https://www.its.dot.gov/pilots/pilots\\_thea.htm](https://www.its.dot.gov/pilots/pilots_thea.htm)). All three projects involve the establishment of V2V and V2I infrastructure and communication systems.

A major component of the U.S. government national discussion is the establishment of future (electromagnetic) spectrum reservations for V2V and V2I communications (please refer to page 26 of the Automated Vehicles 4.0 report). Spectrum reservation for future AV communications networks is also an important discussion to have concerning AVs, although beyond the scope of this report. Another valid concern raised in the report concerns cybersecurity systems in relation to automated vehicles, with heavy investment from the U.S. Government in this space across the Department of Energy, Department of Homeland



Security, Department of Justice, Department of Transportation, National Institute of Standards and Technology and the National Security Council. A Norton Rose Fulbright report titled *Autonomous vehicles: The legal landscape in the US* [107] raises the valid point that there are several legal issues and risks with this emerging technology, particularly in relation to cybersecurity, privacy and accident litigation. There is uncertainty concerning whether prior images captured by the vehicle (for prior maps) could pose privacy issues; at this stage there has been no U.S. response to this issue, but future regulatory action may occur in the U.S. to resolve these concerns.

Specifically concerning prior maps for automated vehicles, in 2019 the Pittsburgh Department of Transportation received more than 8 million dollars (from the federal DOT) to research the integration of high definition mapping with rapid updates of road-work situations [106]. As stated by Eric Donnell from the Pennsylvania Transportation Institute: “Penn State scientists will deploy a high definition van to collect data and map work zone configurations. These maps and data will then be used to simulate how connected and automated vehicles impact traffic flow and safety across a variety of operational scenarios” [108]. This grant was part of a larger \$60 million investment package from the U.S. DOT, spread across many different automated driving projects in the U.S. Furthermore, the Penn DOT has produced an automated vehicle strategic plan [109]. While the plan does not discuss prior HD maps, it does propose many V2I, V2V initiatives and pilot programs such as road work warnings, low speed automated shuttle pilots and curve speed warning systems. The report also provides 45 key objectives for the future. Of these 45 objectives, #5, “establish a traffic data management program for CAV” (see page 30), would be the objective that would have the greatest benefit to future HD maps in the state of Pennsylvania.

California is another state that is moving ahead with connected and automated Government responses to the new technology. This is driven in part by the large number of automated driving companies in Silicon Valley. Below is a list of all the companies that are licensed (as of 2018) to test AVs on California’s roads [110]:

Almotive	Continental	NIO	Renovo.auto	Uber
Apex.AI	Automotive Systems	Nissan	Roadstar.AI	Udacity
Apple	CYNGN	Nullmax	SAIC Innovation Center	Valeo North America
Aurora Innovation	Delphi Automotive	Nuro	Samsung Electronics	Volkswagen
AutoX Technologies	Drive.ai	NVIDIA	SF Motors Inc.	Voyage
Baidu	Ford	Phantom AI	Subaru	Waymo
Bauer’s Intelligent Transportation	GM Cruise	PlusAi	Telenav	Zoox
BMW	Jingchi CorpLyft	Pony.AI	Tesla Motors	

Bosch	Mercedes Benz	Qualcomm Technologies	Toyota Research Institute	
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The *Autonomous Vehicles Perspective Paper* [110] mentions the need for industry-wide data sharing protocols, to provide real-time information to connected and automated vehicles. As discussed in the report, standardized data sharing can benefit both AV developers and Government, with data collected on infrastructure (road network, traffic light positions) and road works (and possible road rerouting as a result), using 3D maps generated from LiDAR, radar and cameras. In the Appendix of this report, in the list of suggested future strategies, one of the suggestions is to: “support the development of industry-wide data sharing protocols, defining data needs with appropriate privacy principles to provide real-time infrastructure, congestion, and pricing data to connected vehicles”. To summarise, it appears that the Californian Government is only just beginning to consider the need for prior HD maps and data sharing. Future pilot programs, like this report, are likely to occur in the future in California.

The authors of this report conclude that, compared to the EU, the U.S. Government is further behind in terms of a Government response, particularly in the specific field of prior maps. Ultimately, the root problem may be systematic deficiencies and a lack of investment in the U.S. infrastructure network as a whole, as outlined by the recent article *Reimagining infrastructure in the United States: How to build better* [111]. In saying that, as the majority of automated vehicle companies are based in the U.S., there are many prior maps already being created for U.S. roads (but only accessible to individual companies).

## 9.2 Japan and China

In China and Japan, the Government response has generally been more restrictive regarding this new technology than in the U.S. At present, Japanese law generally does not allow for automated vehicles to operate on public roads [112]. However, in recent months special permissions have been granted for small-scale automated vehicle testing. This testing has been focused on showcasing automated vehicle technology during the now delayed Tokyo Olympics. Before COVID-19, the Japan Strategic Innovation Promotion Program (SIP) planned to deploy approximately 80 self-driving vehicles to drive the route from Haneda Airport, Tokyo, to the Tokyo Olympic village [113]. All these vehicles still required back-up safety drivers. In terms of HD mapping, a few companies are leading the advancements in this space in Japan. Nissan’s ProPilot 2.0 autonomous driving system, which is in development, utilises a 3D high-precision map with data including road curvature, road slope and lane positions [114]. A specific HD mapping company called Dynamic Maps is also spearheading the efforts to create a detailed HD map of Japanese roads, with 29,205 km of roads in Japan fully mapped [115]. Dynamic Maps are supported by both many Japanese car manufacturers, along with the Japanese Government. In terms of the Government response, autonomous driving is a component of their “Society 5.0” vision, and the HD maps created by Dynamic Maps are a component within that vision. Dynamic Maps website (translated to English) states that they

are the only company in Japan that provides continuously updated high-precision 3D maps [116]. However, based on the data on their website, the ability to update their maps based on road changes is still a work in progress. The following paragraphs will outline their work in this space, based on data collected in this literature study.

Dynamic Maps is following the crowd-sourcing map updating approach, using either vehicle probe data or camera image data. Vehicle probe data refers to the vehicle’s position, speed and heading recorded over time. It’s particularly interesting to note because approaches to utilizing it attempt to *indirectly infer* the properties of the road network through these monitored parameters. In this first approach, probe data was entered into a change detection algorithm, which attempts to find a consistent change in driving style across a fleet of connected vehicles, in a particular location. For example, if road works causes all vehicles to reduce speed below the nominal speed of that road, then the location of the speed reduction can be attributed to be the start of the road works. However, the Dynamic Map report [117] (titled: *SIP-adus Update of High-precision Three-dimensional Map with Vehicle Probe Data Progress Report*) identified that this technique is prone to “noise” in the data, due to inconsistent driving behaviours from the crowd-sourced drivers, particularly on ordinary roads (i.e. not motorways). Figure 34 shows an example of their technique.

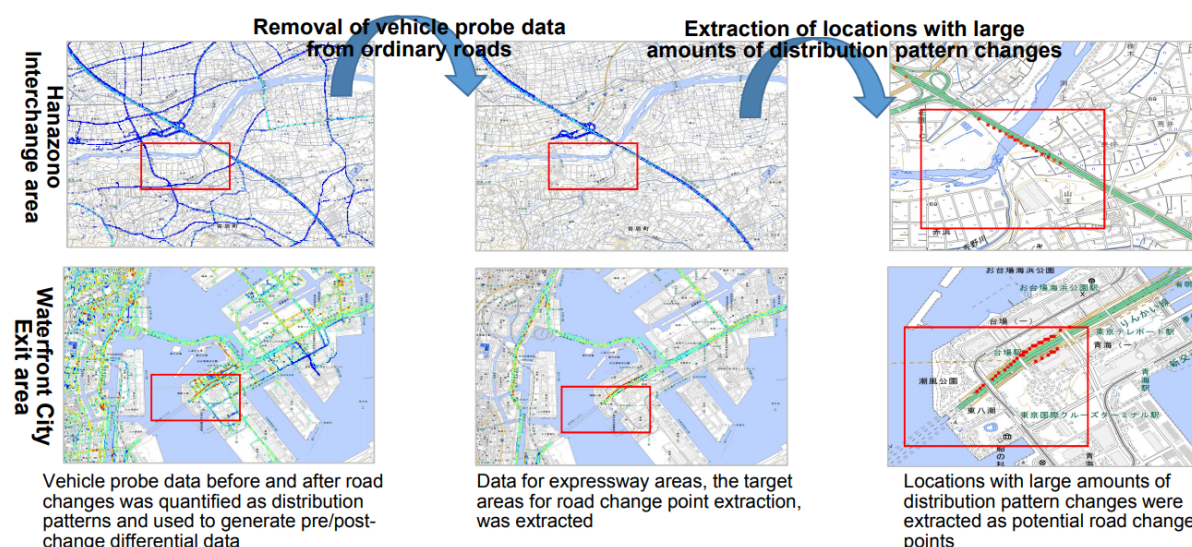


Figure 34: A figure from the Dynamic Map report, showing case examples where they successfully isolate roads which have experienced structural changes, using vehicle probe data [118].

In the second trial which was run by Dynamic Maps, they instead used camera data (from sensors attached to crowd-sourcing vehicles) to directly detect changes in the environment. Changes were detected in planimetric features within the camera image data and compared directly to the 3D data stored in the prior HD map. The trial used three state-of-the-art proprietary change detection techniques, but found that none of these systems could appropriately detect changes with enough accuracy for a production-ready system. The Dynamic Maps report [117] notes that both techniques, probe and camera, are required as

each detects different types of changes – vehicle probe data can detect changes to lane structures or speeds, while camera data is necessary to detect changes to road signs.

To conclude the discussion on Japan's efforts in the space of automated vehicles and prior maps, it is worth noting that several other reports of note have been distributed through SIP-adus: *Cross-ministerial Strategic Innovation Promotion Program – Automated Driving for Universal Services* (SIP-Adus). In the SIP R&D Plan (July 11, 2019) [119], updating high-precision 3D maps using vehicle probe data is listed as one of their R&D goals. Another noteworthy goal is their plan to begin the operation of a service platform (a “portal site”) for the distribution of map data – this would assist in the ability for public and private entities to share data for connected and automated vehicles. The report reveals two additional private companies are also assisting in the production of HD maps in Japan: Mitsubishi Electric Corporation, and Toyota Mapmaster Incorporated.

This section concludes with a brief discussion on automated vehicles and HD maps in China. China also poses certain restrictions on automated vehicles, with the creation of HD maps restricted by licensing requirements [120]. However, the Chinese government is actively supporting the technology [121]. In 2017 the Chinese Ministry of Industry and Information Technology, China Automotive Engineering Institute and the China Association of Automobile Manufacturers established the China Industry Innovation Alliance for the Intelligent and Connected Vehicles (CAICV) [122]. They have published standards including a *Cooperative Intelligent Transportation System Vehicle Communication System Application Layer and Application Data Interaction Standard* (translated from Chinese to English), which includes provisions for enhanced digital maps (please note that a publicly available English translation of this document does not exist). Several Chinese companies are endeavouring to produce HD maps for autonomous driving in China, including NavInfo, Baidu and Momenta.

### 9.3 Europe

In Europe, or more specifically the EU, the development of connected and automated vehicle technologies has been a major policy item for many years, with the organisation ERTICO – ITS Europe founded in 1991. ERTICO is a collaborative organisation between industry leaders and the European Commission, with a vision of improving mobility for environmental sustainability, efficiency (reduced traffic) and safety (zero accidents) [123]. ERTICO is the founding organisation responsible for many EU initiatives including ADASIS, SENSORIS, TISA, TN-ITS and more (these initiatives are discussed in Sections 6.2.2 and 7.2). In the EU, the primary driver for the deployment of connected and automated technology is the goal of improving road safety – a major EU policy is an objective called “Vision Zero”, which is the EU objective to reduce road fatalities to almost zero by 2050 [124].

In 2014 the European Commission created the C-ITS (Cooperative Intelligent Transport Systems) Deployment Platform, with the goal of allowing road users and traffic managers to share information and coordinate actions [125]. Unlike ERTICO, the C-ITS Deployment

Platform is directly managed by the European Commission, in order to have a more prominent role in the deployment of connected driving [125]. In the initial iteration of the platform, as summarised in a report written in 2016 [126], the primary objectives were to address the main technical (spectral reservations, cyber-security and in-vehicle communications) and legal issues (liability, data protection and privacy).

It is not until the updated report in 2017 (representing phase two of the project) that prior maps for automated vehicles become a focus. In this report the term “Digital Infrastructure” is introduced, and the importance of keeping HD maps up-to-date is highlighted [127]. Key components of digital infrastructure from this report are outlined below (non-exhaustive list):

- Two-way communication of traffic safety warnings between vehicles and infrastructure (e.g. accidents, traffic jam, dangerous weather).
- Infrastructure-based sensors to detect road participants, with particular emphasis on pedestrians and cyclists.
- Standardised transmission of short-term road construction or accident situations.
- Transmission of traffic light status.
- Transmission of dynamic speed limits.
- Transmission of position and direction of emergency vehicles.

These features would then modify the in-vehicle HD map in real-time to reflect changes in the environment. In 2017, an automated shuttle trial in Belgium was conducted but without any interaction (communication) with traffic lights, road markings or road signs [128]. The following link contains a list of all automated driving projects in the EU: <https://knowledge-base.connectedautomateddriving.eu/projects/findproject/>. Within the set of projects, a relevant current project is called *data for road safety*. The objective of this project is to develop a proof of concept of a system to share data generated by vehicles and infrastructure, and support both different manufacturers and countries [129]. See: <https://www.dataforroadsafety.eu/contact>.

### 9.3.1 C-Roads

A subset of the C-ITS organisation is called C-Roads. C-Roads is designed to develop and share technical specifications (for connected and automated vehicles) and verify technology through interoperability testing. The C-Roads group is structured into a list of working groups, each with separate milestones, as detailed below [130].

- Working Group C-ITS Organisation (WG1) - their main role is to consolidate the perspective of public actors (Road operators and authorities) and the private sector, enabling the sharing of data between public and private sectors. Tasks for WG1 include establishing a legal framework for data management and describing the actions required to roll-out collaborative C-ITS infrastructure. Arguably this working

group is the most critical, due to the importance of collaborative communication between public and private actors in the C-ITS and HD mapping space.

- Working Group Technical Aspects (WG2) - their goal is the harmonisation of current and future C-ITS services, and to contribute to the definition and implementation of a harmonised communication profile for C-ITS pilot services on road infrastructure across Europe.
- Working Group Evaluation and Assessment (WG3) - their roles include translating the successes from other working groups into the world through cross-site tests across Europe and assessing the impact of these new C-ITS services.
- Working Group Urban C-ITS Harmonisation - WG4 is dedicated to communicating with City Authorities interested in the C-Roads Platform. For instance, one task is determining their specific requirements for C-ITS deployment.
- Working Group Digital Transport Infrastructure (WG5) - The DTI Working Group will focus on the infrastructure needs for a digital infrastructure as a whole, including Traffic Management as well as HD maps.

The C-Roads Platform currently consists of 18 European States. The core C-ITS I2V communication data being considered consists of the following services:

- Road Works Warnings (RWW)
- In-Vehicle Signage (IVS)
- Other Hazardous Location Notifications (OHLN)
- Green Light Optimal Speed Advisory (GLOSA)

I2V data is transmitted using ETSI standards (CAM and DENM), with data transmitted between infrastructure components using Datex II standards, along with ETSI GeoNetworking. WG2 is primarily focusing on the development and deployment of CAM, DENM and GeoNetworking V2X communications, while WG5 is developing the groundwork for real-time HD maps. The following paragraphs will discuss WG5 in further detail, with the information collected from non-public data sources. The non-public sources are email correspondences and the Common Digital Transport Infrastructure Elements and Standards for C-ITS Services WG5 Draft Report.

The key milestones of WG5 are as followings:

1. DTI Workplan (due Q1 2020).
2. Draft report on common and agreed DTI (Digital Transport Infrastructure – also termed the Digital Twin) elements for high quality C-ITS Services (due Q4 2020).
3. Report on common and agreed DTI elements for high quality C-ITS Services (due Q4 2022).
4. Recommendations for DTI elements to support CCAM Service implementation (due Q2 2023).



Focusing on milestone 2, the primary objective is to undertake an analysis of existing DTI across all EU member states. In more detail, this consists of the following sub-tasks:

1. Analyse and collect data from all EU member states to discover their existing C-ITS implementations.
2. Discuss and identify the common DTI elements required for high quality digital maps.
3. Analyse existing standards and data transmission protocols which are supported and used by C-Roads members, alongside third-party organisations.
4. Define transport rules which can be converted into machine readable format for mobile end users in standardised and open specifications.

The draft report does not contain outcomes yet, however, it will be interesting to investigate the outcomes of WG5 in future months and years – the decisions made in the EU will provide valuable guidance to potential future actions that could be taken in Australia. While no official releases have been made, a direct correspondence with a representative of C-Roads revealed that Datex II will be the definitive standard for traffic management and C-ITS communications in the EU going forwards. Datex II will be used for all connected and automated vehicles; there is no plan to replace Datex II with a new protocol specifically for automated vehicles, instead, Datex II will be upgraded in future years to ensure it meets the requirements (cybersecurity, maintains intellectual property, real-time processing, etc.) for automated vehicles (source: email from representative from C-Roads).

While not directly related to prior maps, C-Roads is supported by the Car 2 Car Communication Consortium (founded in 2002). Quoting from the Car 2 Car website, “the CAR 2 CAR Communication Consortium (C2C-CC) aims at assisting towards accident free traffic (vision zero) at the earliest possible date” [131]. The consortium is working forwards this goal by developing standards and protocols for V2V (vehicle to vehicle), V2I (vehicle to infrastructure) and V2P (vehicle to person) technologies, using 5.9 GHz 5G spectrum reservations. The consortium works closely with C-ITS organisations in Europe, such as C-Roads, ETSI, CCAM, the Amsterdam Group and the consortium contains private enterprise members such as Toyota, Volvo, Volkswagen and Hyundai.

### 9.3.2 TN-ITS

TN-ITS is both a digital data standard (see Section 6.2.3) and an organisation within the EU. The purpose of TN-ITS is to produce a new data standard designed to transmit information on changes in static road attributes (such as road signs and speed limits). Such data is critical for real-time HD maps and TN-ITS is being developed to enable sharing of this data from the road authorities to other digital systems, both within the Government, and externally (e.g. to HD map providers like HERE and TomTom). TN-ITS is a collaborative effort between ERTICO, HERE, Finnish Transport Infrastructure Agency, Norwegian Public Road Administration and TomTom [132]. For further details, please refer to PD CEN/TS 17268:2018 and <https://tn-its.eu/>. It is worth noting that TN-ITS is progressing in parallel to this project report and only



recently has information been released. In a release in Oct-2020, titled *The future of a Common European Mobility data space Reflection Paper* [133], significant information on recent progress in TN-ITS is included. We include Figure 35 below from this report, which provides an overview of the full data standard and transfer space with respect to C-ITS in the EU:

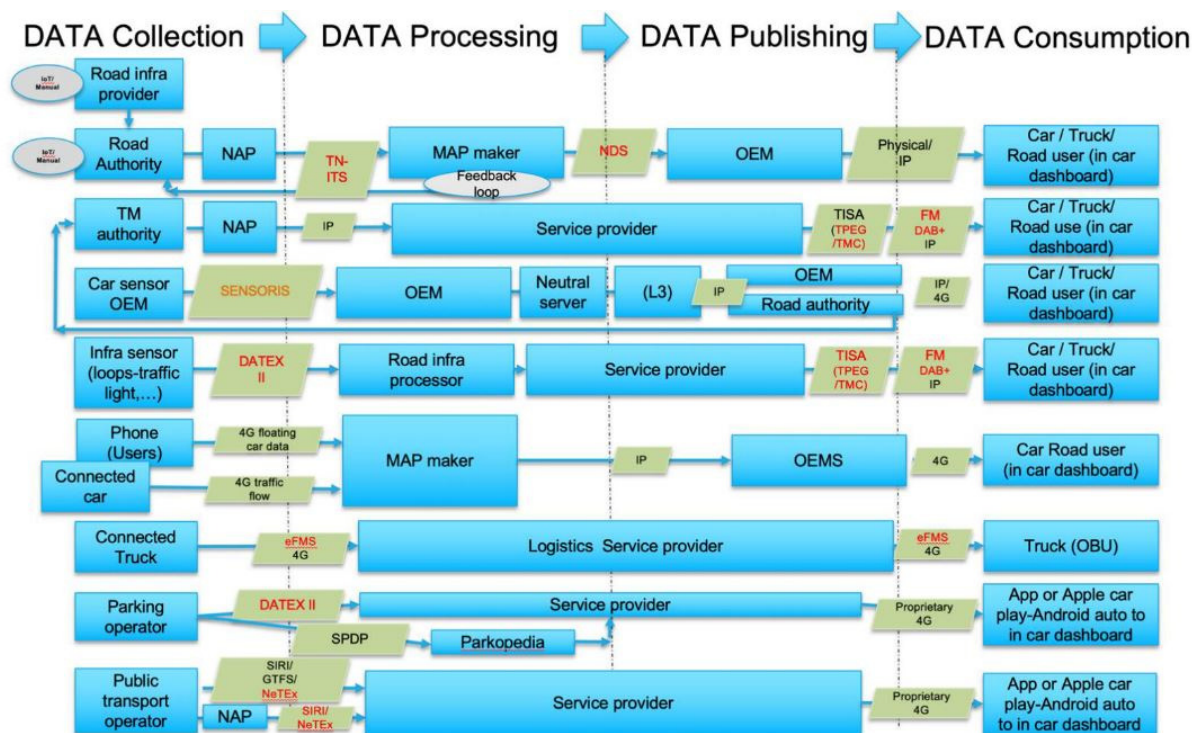


Figure 35: Overview of the mobility dataspace in the EU, as described by TN-ITS [133]

### 9.3.3 NordicWay Project

The NordicWay project (which consists of three sub-projects) is a C-ITS pilot to investigate the inter-communication between vehicles, infrastructure and network operators, with the objective of communicating safety hazards and other information from roads in Nordic countries. It is also a collaborative project, between both public and private enterprises. While NordicWay is designed for connected vehicles, and not automated vehicles, the communication protocols and systems being developed for this project are highly relevant for automated vehicles and prior HD maps. As hinted by the name, the NordicWay project is a joint effort between Finland, Norway, Sweden and Denmark.

NordicWay 1 was the first sub-project, which ran from 2015-2017. The objective of the first NordicWay project was to test C-ITS services for vehicles in the aforementioned countries, by creating a large-scale pilot project as a proof-of-concept for C-ITS service delivery using cellular communication. The C-ITS messages transferred to vehicles include:

- Location of obstacles on the road
- Location of accidents
- Weather conditions ahead

For NordicWay 1, all data was collected using probe vehicle data (data crowd-sourced from connected vehicles), with the exception of weather data, which was sent from the road authorities. Data is transferred using the Datex II format at the infrastructure level, while ETSI formats (CAM, DENM) are used to transmit data from road-side communication devices to the connected vehicles themselves.

In NordicWay 2 (2018-Present), the number of pilot sites has increased, along with the scope of C-ITS data being transmitted to connected vehicles. The C-ITS services included in NordicWay 2 include:

- Hazardous location notifications – slow/stationary vehicles, road works warning, weather conditions, emergency vehicle approaching, traffic ahead warning, obstacles and accidents.
- Signage notifications – speed limits, GLOSA, signage, parking information and management, traffic information and smart routing.

While the NordicWay project does not specifically consider HD maps, the project is unique in their progress on transmitting location referenced C-ITS data, which is essential to any future real-time HD map. The primary data format is the Datex II Level A model, with optional extensions including OpenLR for location referencing. It is worth noting that the sole use of Datex II for C-ITS communications (between infrastructure) differs from the C-Roads specifications. Another disadvantage of the NordicWay project is that they have not developed a common message transfer protocol between Datex II and ETSI formats – the mapping of data from Datex II and ETSI formats has been implemented separately by the individual pilot projects within NordicWay, with in-house solutions.

#### 9.3.4 SHOW (Shared automation Operating models for Worldwide adoption)

The SHOW project “aims to support the deployment of shared, connected and electrified automation in urban transport, to advance sustainable urban mobility.” The initiative is the largest automated vehicle trial in the EU, with 69 partners from 13 countries in the EU. The project commenced in January 2020 and is due to conclude in January 2024. There are 20 pilot cities spread across Europe, with a plan to operate a minimum of 12 months of continuous automated vehicle deployment in each, using Level 4 automated vehicles in urban conditions. In each pilot site, the automated vehicles will follow specific pre-mapped routes, with an emphasis on mobility as a service and logistics as a service. The SHOW project plans to use HD maps for their trials, however, whether the maps are static or dynamic (real-time updating) is yet to be determined. Real-time updating HD maps also leads to difficult questions like – should Governments be responsible for updating HD maps with major road

changes, and if so, do new standards need to be developed to facilitate this? The answer to this question may become clearer (in the EU) as the SHOW project continues over the coming years.

### 9.3.5 Germany – Kassel Trials

In this section we provide further details concerning C-ITS projects within Germany. Germany is a major pioneer of automotive technology, and thus is also investigating automated vehicles both commercially and publicly. For example, the city of Kassel, in the German state of Hessen, is performing one of the most advanced intelligent infrastructure trials in the country. Smart technologies being implemented for this trial (which is within the C-Roads Platform) include:

- Green Light Optimal Speed Advisory
- Emergency Vehicle Approaching
- Traffic signal priority
- Vulnerable Road User Protection (e.g. bicyclists)
- Road Works Warning
- Route advice for connected and cooperative vehicles
- Probe Vehicle Data (collect data from vehicles)

These types of technologies are all essential to a future transport network containing automated vehicles. The project has released a real-time feed of this data to the public through special interactive maps: <https://www.kassel.de/geoportal>. We include screenshots of two of these maps in Figure 36 and Figure 37. Kassel is achieving this using the following list of communication systems:

1. 75 roadside ITS Stations (R-ITS-S)
2. 40 vehicle ITS Stations (V-ITS-S)
3. 10 R-ITS-S in the interurban areas surrounding Kassel
4. 4 V-ITS-S in police cars (Vev-ITS-S)
5. 2 V-ITS-S in road operator vehicles (Vro-ITS-S)



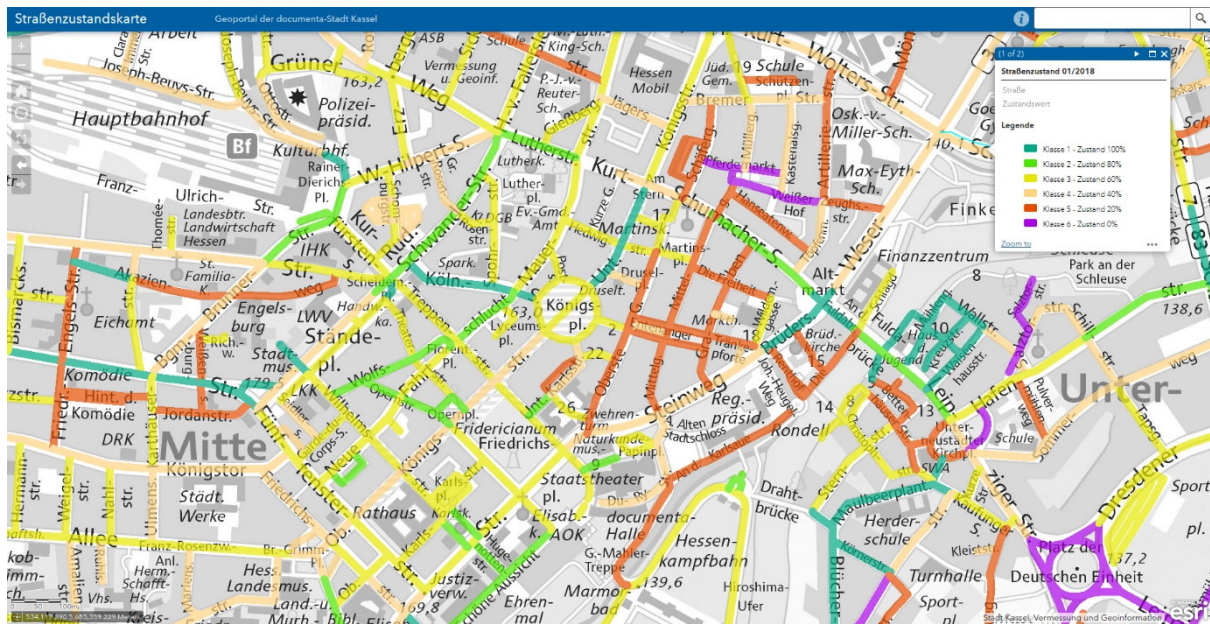


Figure 36: Road map of Kassel showing road conditions (smooth, potholed etc.) [134].

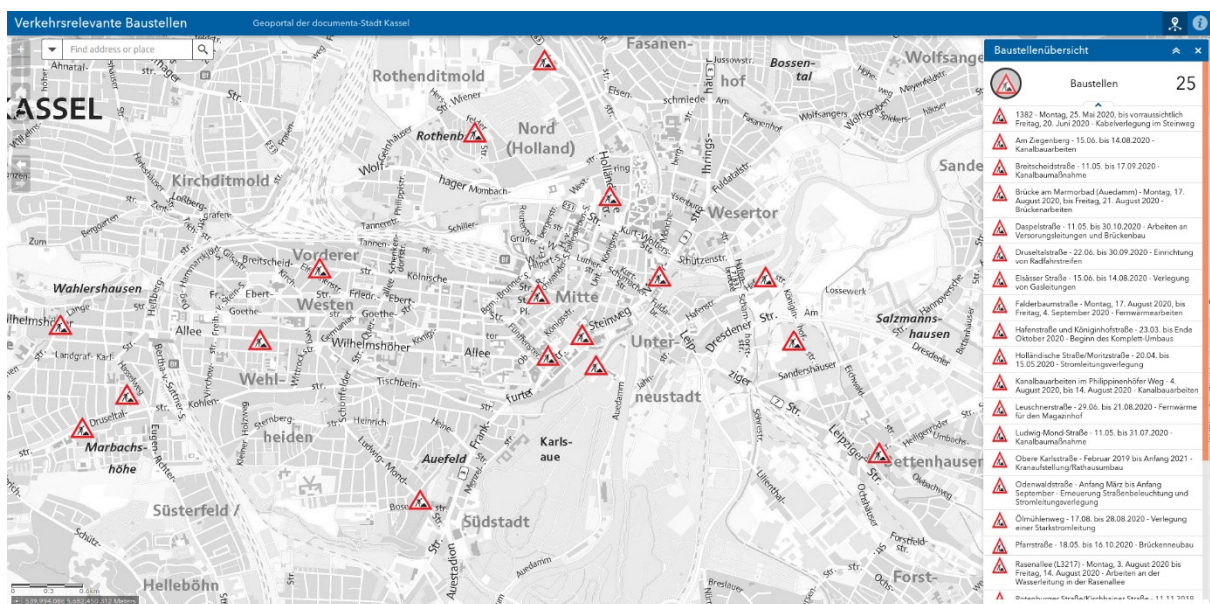


Figure 37: Map providing locations and details for all road works occurring in the city of Kassel [134].

Figure 36 provides an overview of road conditions (smooth, potholed etc.), with the roads categorized into one of six condition classes. Class 1 means very good condition, while class 6 means very poor condition. Figure 37 indicates the location and semantics of all road works occurring in the city of Kassel. Unfortunately, the road works are marked by “point features” (the road work locations are marked by a single point location) rather than as “line features” – i.e. road work start and end points. Line features are more useful for an automated vehicle, as the vehicle has an idea of exactly where to expect the road works to begin.

## 9.4 United Kingdom

Since the UK was a member of the EU prior to Brexit, the C-ITS platform was designed with the UK included in its roadmap. However in addition, the UK has also been separately working on connected and automated vehicle programs which exclusively apply to the UK. Their efforts can be summarised by three key organisations: Oxford University (and the spin-off Oxbotica), Zenzic and Ordnance Survey. These organisations are tackling the problem of prior maps for automated driving in different ways. Oxbotica is attempting to develop automated vehicles that never require prior high definition maps, nor GPS [135]. Their flagship software product is called Selenium, with the main claimed benefit being the software not requiring any prior knowledge of the vehicle's working environment.

Zenzic is a government-led collaborative organisation designed to connect Government, Industry and Academia to move to a self-driving future. Zenzic is managing a wide scope of work, ranging from legislation, insurance, smart infrastructure, telecommunications and societal factors as related to the wide-spread deployment of automated vehicles in the UK. Their efforts can be best summarised by the *UK Connected and Automated Mobility Roadmap to 2030* [136]. In collaboration with Ordnance Survey (Great Britain's National Mapping Agency), they have written a report titled *Geodata report - analysis and recommendations for self-driving vehicle testing* [29]. This report provides an in-depth analysis of the requirements for prior maps for automated vehicles, with discussion on the UK Government's role in the process. This report can be considered the UK equivalent of this project. The following paragraph outlines the key recommendations from this report, which are categorised into several categories.

A summary of the Zenzic report recommendations is as follows:

- **Data formats:** It is recommended that a point cloud is captured using terrestrial mobile mapping systems comprising LiDAR and optical sensors. LiDAR should be stored in the LAS 1.2 file format. Maps should also have multiple layers, including object layers to provide labels for features in the road environment.
- **Data quality and resolution:** Consider publicly (taxpayer) funded geospatial data collection for future automated vehicles.
- **Terminology:** common standards for terminology should be developed across the connected and automated vehicle sector and adopted by the industry at large.
- **Minimum safe requirements and standards:** while manufacturers wish to maintain their trade secrets, it is also important to have some transparency to develop a minimum set of safety critical data standards to guarantee safety in our community. Intellectual property should be impartially captured, working alongside federal standard bodies, security specialists and Government, to develop these standards while ensuring consistency, security and compliance.

- **Government data and Traffic Regulation Orders:** identification that the real-time link between road changes (due to construction, accidents or police intervention) and maps is a non-trivial piece of work.
- **Data hosting:** Neutral hosting of map data is ideal (not with commercial focus).

Ordnance Survey has also begun (in 2019) to develop HD maps in partnership with Mobileye.

## 9.5 Australia

The Australian Government is also responding to this new technology, both at a state and federal level. The primary purpose of the Australian Government's response is to prepare for the deployment of automated vehicles and other innovative transport technologies, with particular emphasis on issues such as: ensuring that the vehicles operate safely and legally, privacy protection, cybersecurity and infrastructure readiness [137]. Austroads is coordinating much of this preparation, through a variety of projects (see <https://austroads.com.au/drivers-and-vehicles/future-vehicles-and-technology/projects>).

At the state level, the Victorian Government is already considering self-driving cars [138], along with trials in most Australian states (<https://austroads.com.au/drivers-and-vehicles/future-vehicles-and-technology/trials>). In the Future Vehicles 2030 report by Austroads, the first publicly available Level 3 automated vehicle is currently expected to be a high-end S-class sometime in 2020 [139]. It will include a motorway automation feature called Drive Pilot, with the operational design domain (ODD) being defined within a high definition map. The WA Government has also completed a separate investigation into the adoption of AVs, as outlined by a report which can be found in the reference list [82].

In 2020 the Queensland Government is trialling connected vehicle infrastructure in Ipswich, called the *Ipswich Connected Vehicle Pilot*. The trial involves converting 30 red lights into smart lights by adding short range communications devices to the lights, and adding telemetry broadcasting for any roadworks in the city [140]. Additionally, 500 resident volunteers of Ipswich were offered to have special communications equipment retrofitted into their vehicles, which will send data to the cloud while also providing these drivers with visual information and warnings from the smart infrastructure. As mentioned earlier in this report, the data is being transferred using the DENM standard (ETSI EN 302 637-3), SPaTEM and MAPeM [141]. The data provided to the connected/cooperative vehicles is listed below [142]:

1. Advanced Red Light Warning – provides a warning if the cooperative vehicle is likely to go through a red light.
2. Back of Queue – early warning of a traffic queue (stopped cars).
3. In-Vehicle Speed – displays speed limits.
4. Road Hazard Warning – alerts drivers if there is an upcoming hazard on the road (such as water on the road, road closures or an accident) and advises reduced speed.
5. Road Works Warning – early warning of downstream roadworks.



6. Turning Warning Vulnerable Road-user – a warning of potential collision with a pedestrian (vulnerable road user).

Of the above list, the draft report COOPERATIVE AND HIGHLY AUTOMATED DRIVING WP-2 CITS AND AV INTEGRATION , AND BENEFITS EVALUATION considers items 5 and 6 for further evaluation with a view to assess the safety benefit they can provide in highly automated vehicles. This is particularly relevant when these ITS messages are used with actual automated vehicles, and not just ADAS. Item 6, detecting and warning about potential vulnerable road users (VRU), is best achieved using road-side VRU sensors, which then communicate this data using either MAPEM or SPaTEM (or the recently developed VAM protocol). Currently in the Ipswich trial, detection is based on the status of the pedestrian crossing button at intersections; however, this is not ideal given that many people do not press the button (particularly in the 2020 COVID-19 pandemic). Item 5 currently includes a DENM message, indicating the presence of road works, the start position and event history of the roadworks and the maximum speed during the roadwork section. Unfortunately, this is insufficient for automated vehicles, which ideally would have access to information about the new drivable path, speed limits and road geometry, to safely navigate through the roadworks [140]. In the aforementioned draft report, it is proposed to use the optional additional field (as specified in the DENM protocol) B.35 *recommendedPath* (see page 66 of ETSI\_EN\_302\_637-3 [38]). Further work is required to identify if the recommendedPath data is sufficient for automated vehicles. Additionally, integration of this data into a HD map is still required.

## 9.6 Summary of Collaboration Between Government and Industry: What is Being Assumed of the Government

This sub-section discusses what infrastructure, systems and policies Government is best placed to provide to automated vehicle manufacturers and HD map providers.

The assumptions being made of the Government vary greatly by country/union, from an expectation of heavy collaboration (between Government and Industry) in the EU, to an almost complete lack of discussion on the topic of collaboration in the US. Private map providers in the EU (TomTom, HERE, etc.) have a need for real-time data from transport authorities. While private map providers can, and currently do, populate their HD maps purely using crowd-sourced data, crowd-sourced data cannot provide prior warning of events initiated by transport authorities (e.g. road-works). TomTom and HERE have developed software interfaces for receiving traffic management data from EU traffic management systems, communicated using the Datex II format (see Sections 8.1 and 8.2).

In the US automated vehicle companies are operating in most part independently from the Government, with the exception of meeting regulatory approvals for automated vehicles to be tested on the road infrastructure. The primary assumption in the US is that the Government will legally allow for automated vehicles to be driven on the road, with minimal interference to the companies requesting permission, and no questions concerning the IP



behind the technology (Section 9.1). In the U.S., at the Federal level, the general recommendation is to avoid excessive regulatory oversight of automated vehicle development, to prevent either the stifling of innovation, or manipulation of the choice of technologies used. Such sentiment is echoed from private entities in the US. Therefore, this report recommends that any modelling based on the U.S. regarding the role of government in HD maps for automated vehicles should carefully consider any ideological differences between the two countries.

Many automated vehicle efforts, from start-ups to major manufacturers, are avoiding the problem of real-time HD maps, both explicitly and implicitly. HD maps can be “avoided” by either explicitly down-grading the relevance of a HD map (e.g. Tesla), or carefully geo-bounding the driving area of their automated vehicles to small sections of the full road network, ensuring that it is easy to map this region on their own (without collaboration). A good example is the automated vehicle trials in the US, which are focused on geo-bounded areas like Phoenix, Arizona or downtown San Francisco. This approach minimizes the costs associated with regular HD map updates and reduces the need for any collaboration (whether with other private industry or government), hence reducing exposure of their proprietary technologies.

#### 9.6.1 Is Crowd-Sourcing Sufficient?

Crowd-sourcing is mentioned throughout this report as a component of map creation and maintenance processes, but is unlikely to be entirely sufficient for maintaining HD maps for automated vehicles. There are two core reasons for this:

1. A crowd-sourced only model assumes that at least one or more automated vehicles, that is, the initiators of the crowd-sourced data, will experience the changed road environment without any prior knowledge of the change. Therefore these vehicles need to be capable of operating safely in these changed conditions without a reliable prior map. It’s unlikely this will be feasible without in-car or remote human intervention, at least until the technology develops significantly further. As the technology stands currently, 100% safety without an up-to-date prior map is not achievable. It’s possible current systems like Tesla’s new full self-driving may enable this capability, but until that approach is proven, any future policy that is heavily reliant on crowd-sourcing is likely suboptimal.
2. A crowd-sourced map update model is a *reactive*, not *pro-active* approach. In a future where fleets of automated vehicles are attempting to navigate and plan travel routes, future notification of disruptions to the road network (e.g. roadworks) will significantly improve the effectiveness of the entire fleet of automated vehicles.

The takeaway here is that even if international automated vehicle companies are suggesting that Government collaboration is not required because their fleet can manage everything internally, it’s likely that collaboration with government especially in the area of planned road

network changes like road work will improve the effectiveness of automated vehicle technology.

## 9.7 Summary of Government Role as Creator, Curator and Consumer of Maps

In this sub-section the Government's role as creator, curator and consumer of maps will be discussed. This discussion will touch on existing examples of the Government's role for a variety of different types of maps (standard maps, enhanced digital maps and high definition maps). Discussion will focus on high definition maps and also hypothesise what might be the "ideal" role for Government in the future, particularly in a future with a large uptake of automated vehicles.

Taking Australia an example, our Government creates and curates a wide collection of different maps and spatial databases. Many of these maps are publicly available, many of which can be accessed from these links: <https://info.australia.gov.au/information-and-services/business-and-industry/science-and-technology/maps-and-mapping> and <https://info.australia.gov.au/information-and-services/business-and-industry/science-and-technology/spatial-information>. From a transport infrastructure standpoint, the maps and spatial data available include road network maps, spatially referenced crash data, traffic census data, road surface data and accurate positioning of road centrelines. Australia currently lacks a Government managed Australia-wide enhanced digital map; however, the ANZLIC Spatial Information Council discusses a future scope of work to achieve such a map: <https://www.anzlic.gov.au/resources/foundation-spatial-data-framework/fsdf-themes-datasets/transport>

Here we list several examples of cases where other Governments have acted to create, curate or consume maps.

### **Germany – Geoportal:**

The German Geoportal is a web-based map, owned and managed by the German Government, which provides enhanced digital map functionality. It includes data such as: location of powerplants and high-voltage powerlines, elevation, location of natural resources, weather and river height levels and protected areas across Germany, but also significantly more detailed data in a large number of categories in specific areas of the country.

### **USA – The National Map:**

The National Map, created and operated by the U.S. Geological Survey's National Geospatial Program, provides a variety of maps visualising different data, such as topographic, OpenStreetMap, Aerial LiDAR and National Land Cover. The National Land Cover data includes classes such as open water, developed (urban), forest, grassland and pasture. The Aerial LiDAR data is from the 3D Elevation Program (3DEP), which provides extremely accurate topographic data using LiDAR – accurate to the extent of detecting urban structures and road

networks (see Figure 38 below). Rapidly updating Aerial LiDAR data is a potential mechanism for detecting road network changes for HD maps.

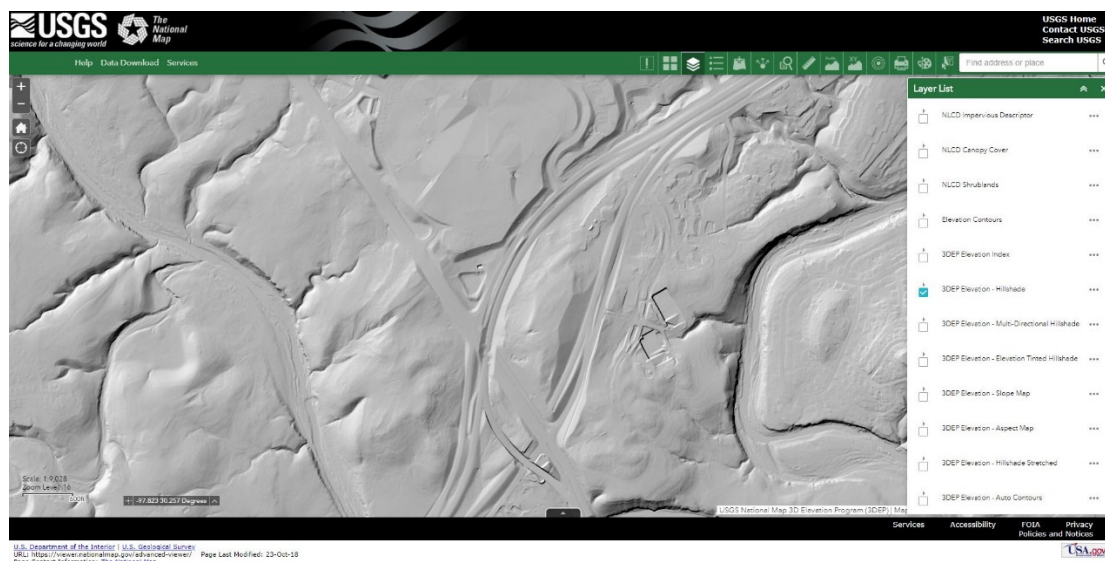


Figure 38: The US National Map, managed by Government, includes accurate aerial LiDAR data [143].

#### UK – OS (Ordnance Survey) Maps:

Ordnance Survey is the United Kingdom’s geospatial mapping organisation. OS produces a vast range of different maps, with a focus on accuracy and detail. Their maps are not open-source – access to the advanced maps on offer requires either purchase or licensing. Advanced (premium, requires licences) maps provided by OS include:

1. **OS VectorMap Local** – a high detail street map down to 1:3000 scale (i.e. 1cm equals 30m in the world). Includes roads, railways, vegetation, buildings, boundaries, fences and water (<https://www.ordnancesurvey.co.uk/business-government/products/vectormap-local>)
2. **OS MasterMap Topography Layer** – a detailed topographic map which also includes building heights and 3D visualisations for parts of Great Britain (<https://www.ordnancesurvey.co.uk/business-government/products/mastermap-topography>)
3. **OS MasterMap Highways Network with speed data** – a detailed road map which includes speed limits and historical speeds (accurate down to 6 hourly for congestion analysis). Also includes important routing information for the roads on the map, such as one way, access restrictions, height restrictions and turn restrictions (<https://www.ordnancesurvey.co.uk/business-government/products/mastermap-highways-speed-data>).

Media releases revealed that OS partnered with Mobileye in January 2019 to produce a HD map, suitable for autonomous cars, for UK’s road network. No publicly released data or

information has been found to date – although, the authorship team is in contact with the UK Department of Transport and is expecting to receive a draft report during December 2020.

### 9.7.1 Specific Government-led examples of HD maps for automated vehicles:

The Japanese Government is spearheading efforts to develop HD maps for automated vehicles through their SIP-Adus program (as also discussed in Section 9.2). SIP-Adus stands for Strategic Innovation Promotion – Automated Driving for Universal Services. In the HD mapping space, SIP-Adus has collaborated heavily with the Japanese company Dynamic-maps. In addition, the Japanese Government has directly provided financial capital to Dynamic Maps [144]. Dynamic Maps is developing a 3D HD map for Japanese roads, along with systems from maintaining the map. As discussed in Section 9.2, Dynamic Maps are currently updating their maps using a variety of crowd-sourcing methods. Directly collecting data from Japanese transport authorities has yet to be developed, although the About Us page (<https://www.dynamic-maps.co.jp/en/about/index.html>) of Dynamic Maps mentions future plans to identify changes in roads conditions through collaboration with partners [145].

While the EU has not directly produced HD maps for automated vehicles, they are planning for HD maps earlier and in greater depth than other countries, through a range of C-ITS working groups and trials. The EU is working closely with private companies like TomTom and HERE, with real-time map products like Autostream and HERE's Self-healing map already available to consumers in the EU. Some small Government-run trials in the EU are creating HD maps for automated vehicles – for example, the SHOW project (an EU led initiative) plans to create local HD maps for specific automated vehicle trials (source: private email from research scientist at SHOW).

In summary, many Governments create, curate and consume a variety of maps at the standard digital map and enhanced digital map levels. From our research, to the best of our literature search, we conclude that currently, *no* Government is *directly* creating large-scale (country or continent-wide) HD maps. However, given the close working relationships between public and private HD mapping sectors in both the EU and Japan, either of these international public entities could be used as a model for Australian government. Arguably, based on the large number and variety of projects and partnerships in the EU (refer to Section 9.3 ), the EU would be the best “model” on which to build an Australian model of HD maps for automated vehicles.

## 9.8 Summary

Government collaboration with HD map providers and OEMs vary widely overseas, with the greatest collaboration occurring in the EU and the least collaboration in the US. While the EU is the most collaborative, they are not “ahead” of Australia in their collaborative efforts. The topic of real-time HD maps has only just begun to be considered – in fact, in many projects such as SHOW, Government-produced HD map trials are not planned until 2022. This research

report (on HD maps for automated vehicles) is currently one of the first of its kind in the world, along with a mirror report being developed for the UK.

The Australian Government appears to be one of the more pro-active Governments worldwide in the space of autonomous driving, smart infrastructure and HD mapping, but faces some unique challenges. Australia has no domestic automated vehicle manufacturing or HD map producing companies (unlike the US and EU). Therefore Australia may face difficulties in early adoption of automated vehicle technology – not because of a lack of Government interest, support or collaboration, but because our market size may not be sufficient to entice international companies to develop the local infrastructure and systems necessary to fully support automated vehicles.

## 10 Recommendations

While it is nearly universally agreed upon that prior HD maps are essential for future automated vehicles, creating and maintaining HD maps is a challenging task that will require car manufacturers, map makers and Governments to work together. This report has provided an overview of the wide variety of HD maps that are already available, along with discussion of the actions overseas Governments have taken to work alongside these HD maps.

In terms of Government's involvement in supporting HD maps for automated vehicles, the European Union appears to be taking the most pro-active approach. As discussed in Section 9.3, a large number of Government supported programs are in place to research and develop the digital infrastructure necessary to support the wide-spread adoption of HD maps across the EU. The EU also has the advantage of headquartering a large number of automotive companies, including Daimler, Volkswagen and BMW, and HD mapping companies like TomTom, HERE and Atlatec. This report finds that both Government and Industry, in the EU, are significantly participating in the task of integrating traffic management data into real-time HD mapping products. Discussions with TomTom, and research on HERE (as described in Sections 8.1 and 8.2), revealed that these companies have access to, and have developed interfaces to, traffic management data in the EU, expressed in the Datex II format. While Datex II only covers the dynamic data required for up-to-date HD maps, the TN-ITS organisation (refer to Section 9.3.2) promises to create a data standard for communicating more static road-level information; the types of data useful for HD maps. The EU appears to be the ideal test-bed for future automated vehicles and HD maps, because (phrased in contrast to Australia):

- The EU Government is prioritising the development of ITS infrastructure and has partnerships with both car manufacturers and map creators. It is also worth noting that car manufacturing is one of the most valuable exports from the EU, therefore it is not surprising that the EU is providing a high level of support and collaboration.
- A relatively high population density, enabling greater profits for every automated vehicle sold, and less expense to map the road network in HD.

Any Australian-based model for Government managed or supported HD mapping for automated vehicles could follow, or at least be inspired by, the activities within the EU in this space (as outlined in this report), but must take into account the differences in populations and car manufacturing presence. Below we describe **three different pathways** to achieve this – the choices are either to directly re-implement the ITS technologies in development in the EU, to develop our own systems inspired by “what works” in the EU, or finally, to develop our own HD maps independently (without private map suppliers). While we describe the three pathways below, we emphasise that these are just one set of suggested options and that significant discussions will be required to decide on the best way forward for both our state and our country.

**Option A: Re-implement Datex II and TN-ITS for Queensland/Australia, to support real-time HD maps supplied by international HD map providers**

Option A is the more expensive and ambitious goal, whereby the existing EU ITS standards and systems are replicated locally. As a large wealth of information exists on these standards, for Datex (standard CEN/TS 16157) and TN-ITS (CEN/TS 17268). Additionally, major European HD map suppliers TomTom and HERE have already developed software to interface with these two standards. Replicating the Datex II standard may be required for the rapid adoption of autonomous cars in Australia (unless a HD mapping company is founded in Australia). Because the existing autonomous car developers and HD map producers are headquartered and focused internationally, it may be easier to entice international companies to open a new market in Australia if their existing software is easily portable to our physical and digital infrastructure. Datex II is already well supported by the major map producers TomTom and HERE, and the luxury European car manufacturers are already utilising these technologies and standards within the European Union.

Unfortunately, replicating Datex II, which is not just a data standard for geospatial data but the entire system underpinning all traffic management centres in Europe, will require a vast amount of work and may not be practical. It also makes the assumption that automated vehicles will become mainstream; however, there is still significant maturity required for this technology before we are likely to see widespread automated vehicles operating on our roads. Based on discussions with EU representatives (C-roads and SHOW), the EU is still very much working out the future communication strategies and protocols for real-time HD maps – whether Datex II and TN-ITS is adopted by Australia or not, it is still worth working closely in collaboration with the EU in upcoming years.

**Option B: Collaborate with private map suppliers to enhance the Brisbane Metropolitan Transport Management Centre’s (and other similar) existing systems with advanced ITS data communications for future HD maps supplied by international HD map providers**

TomTom has already mapped the major roads in Brisbane in high definition, and a further 300,000km of roads across Australia with a HD mapping vehicle. Despite this activity, only standard definition maps are currently available to Australian consumers. Some of the deployment barriers are tied to lack of interest from OEMs, but also the need for further Government infrastructure. For example, a representative from TomTom stated that RTK GPS stations will likely need to be installed across the urban area, before TomTom can deploy their RoadDNA solution. Note that hexagon’s recent “RTK From the Sky” precise point positioning solution [26] is likely to render this requirement unnecessary, with centi-meter accurate GNSS available in the future without RTK GPS infrastructure. While TomTom stated in our interview that the ideal would be if the Government adopted Datex II, an alternative is to adopt OpenLR instead. OpenLR is TomTom’s publicly released location referenced data standard (sidenote: Datex II has in-built support for OpenLR). Therefore, an alternative recommendation is to develop software systems to convert existing Queensland traffic management data into the



OpenLR format, before encryption and communication to third-party map providers. This will be cheaper and lower-risk compared to overhauling our traffic management systems.

For this approach to work however, the raw data within the existing traffic management centre needs to be location referenced correctly. For example, the location of a road work event cannot just be “on Cavendish road”, but instead needs to be a full coordinate such as provided by GPS. It will also be necessary to provide logic level details about the road work event, such as which lanes are closed, and what is the new speed limit. Finally, while we describe TomTom as an example, other HD map suppliers should also be considered for collaboration. Two examples are HERE and Atlatec. HERE shares many similarities in the level of sophistication of their product, and they also support real-time updates through their self-healing map solution. Atlatec does not directly support real-time HD map updates at this time, but as their HD mapping solution is camera-only, they can map roads in HD at a lower cost than their competitors.

### **Option C: Independently develop a HD map of Queensland (and Australian) roads**

The third and final recommended option is for the Government to directly produce the HD maps, similar to the model being followed in the UK. In the UK, Ordnance Survey has partnered with Mobileye to produce HD maps of UK roads (see Section 9.7). Because the UK Government is jointly funding the creation of the HD map, they will maintain indefinite ownership of the HD map. This is the “public model”, where HD maps are considered equivalent to Government produced geospatial data.

Such a model has advantages including full ownership and responsibility of the map. Because HD maps are a safety critical system of an AV, owning this component will give additional assurance that future AVs will be safe on our roads. Government-led map development would also provide greater customisation ability, allowing the map to be developed to suit Australian road conditions. Public ownership of map data could also help prevent automated vehicle monopolies. A monopoly could occur if a HD map producer like TomTom gets bought out by a major car manufacturer or technology corporation, potentially limiting the automated vehicle market in Australia to a single car company. Many of the concerns already expressed about the level of control and influence exerted by the major technology companies could be exacerbated were they to have full ownership of the map data driving automated vehicles in Australia.

Government-led map development also poses a number of challenges. It would be a very costly exercise, and it’s likely there would need to be at least some collaboration with industry for this approach to be feasible. Government is also not technically set up to lead major technology projects; feasibility would once again depend on the ability to draw on the significant technical resources provided by the research sector in Australia including universities and applied research organisations like CSIRO’s Data61. This con is also a potential

positive – a major sovereign project creating a nation-wide HD map capability could act as a magnet for attracting and retaining talent to Australia.

### 10.1.1 Final Considerations

One of the scope questions of this report was: “what are the challenges in working together?” (between Government and HD map providers). A significant challenge for Australia is the willingness of overseas companies to invest in establishing both dialogue and the digital and physical infrastructure to enable the creation and maintenance of HD maps in Australia. Static HD maps may serve as a low cost entry mechanism - the development of “static” HD maps (with no real-time update component) has a low barrier to entry, with HD map suppliers like TomTom already having mapped many of our major roads. However, the critical real-time component is the second challenge that requires collaboration.

It is likely important to not be too “ambitious” with any future plan. The reality is that real-time accurate HD maps for an entire city, for every road and street in the city, is a massive endeavour that will not only be initially expensive, but will require a staggering amount of data collection and installation of sensor and communications technology across the entire road network (every red light will require a V2I sensor, etc.). Additionally, our existing traffic management communications systems will need to (potentially) be updated, to facilitate encrypted communications onto the open-web, to send traffic management data to HD map suppliers like HERE and TomTom. Not only that, “going too fast” has risks in terms of misjudging the technology; COVID-19 has changed much of our way of life and shown that the future is unknown, and has added to already present delays in the widespread development and deployment of AV technology [146].

A possible approach is to incentivize industry (through grants) to develop trial suburbs where automated vehicles are legalised and supported through real-time HD maps - which is why this report recommends initially limiting the next steps to a small, geo-bounded trial in an urban area. A geo-bounded trial will limit the number (and thus cost) of V2I sensors and communications infrastructure that will need to be installed for the project. It will also identify “pain-points” and potential budget risks in a smaller, lower cost project than the alternative, which is supporting real-time HD maps across a whole city, state or country. Further details of these possibilities are provided in Section 11.

## 11 Avenues for Future Work

The findings made to date give rise to a number of exciting potential avenues for future work. Two specific proposals are overviewed below; one, an “in-house” trial and the other involving collaboration with a major HD map supplier. These proposals are intended to act as exemplars for what could be done to further studies and understanding in this area, but there are many other opportunities beyond just these two.

### Option A: Sovereign HD Mapping Capability



*Figure 39: Automated vehicle capabilities could be evaluated with the Zoe 1 research platform and Zoe 2 autonomous platform.*

An automated vehicle trial using the Zoe 1 and 2 platforms could evaluate the capability of an automated vehicle to safely navigate Queensland roads, except with a continuously available prior HD map. The HD map will be custom developed “in-house”, using the talent pool available at QUT. In consultation with TMR, a designated set of roads in Brisbane will be used as the trial area. The set of roads should include a variety of motorways, major roads and streets. The Zoe vehicle will initially be driven manually in a data collection mode during good environmental conditions (day-time, no rain, light-traffic), and the gathered data will be used to create a custom highly detailed HD map of the test area. This process would simulate the core components of the standard mapping routine used by leading AV developers. At this stage, pre-collected data from TMR could also be used to aid the construction of the map. For instance, TMR has pre-collected driven LiDAR, driven georeferenced images, aerial LiDAR and aerial images.

Stage 2 of the project would involve driving the Zoe 1 vehicle in a variety of poor conditions (night-time, rain, heavy-traffic) and **in particular changed conditions** (roadwork, accident simulation), with an evaluation of typical AV tasks (sign recognition and so forth) when using the HD map, to form a baseline.

The third stage of the project would investigate adding real-time update capability to the HD mapping system using Government-managed construction and traffic data, with a further re-evaluation of performance. The validation process would occur in an offline fashion, i.e. the Zoe 1 vehicle would not be operating in autonomous driving mode in real-time, since the required legislation and safety validation is yet to be established (however further follow-up projects may be able to trial a real-time automated vehicle e.g. Zoe 2 using safety drivers). The purpose of the trial will be to evaluate the readiness of automated vehicles on Queensland roads, when both the automated vehicle software and the prior HD maps are custom developed for Queensland roads. Further work could also investigate whether the HD map can be updated “indefinitely”, using existing real-time data collected by TMR.

### **Option B: Collaborative HD Mapping**

This trial would investigate the utility of industry-government collaboration on HD mapping for automated vehicles. Like Option A, we suggest a second automated vehicle trial using one of the Zoe platforms, to evaluate the performance of an automated vehicle driving on Queensland roads, when a prior HD map is also used. Unlike Option A, in this proposal we suggest contacting industry to trial use of their state-of-the-art HD map solution instead. Based on our interviews and research compiled in this report, the authors suggest that such an arrangement could be made with a company like TomTom or equivalent. Using TomTom as an example, the company has already mapped 300,000km of Australian roads in high definition. With appropriate agreements (e.g. a non-disclosure agreement), TMR, TomTom and QUT could gain full access to the HD map data, for the purposes of a research trial. While we use TomTom as an example here, any HD map provider who has mapped (or can at short notice map) a sufficient number of roads in Brisbane can be considered for this trial.

In this proposed first stage of the project, the data collected by the Zoe vehicle will be compared to the prior HD map supplied by TomTom, and the effectiveness of both the automated vehicle and the prior HD map will be evaluated. We suggest an analysis of map-aided traffic sign detection rates, hazard detection, lane detection and localisation performance. We would collect data over multiple times-of-day and weather conditions, with an emphasis on Australian conditions that are not typically encountered overseas.

A second stage of this project could then investigate developing communication mechanisms whereby government can indicate the presence of road work to the private map provider, and in reverse, how private map providers could communicate “discovered” changes back to government. The focus here would be on investigating the range of fidelity options (and communications standards) by which information could be conveyed between government

and private map providers. Both low-fidelity (simply indicating that there has been a change in road conditions) and high-fidelity (transmitting an updated digital or HD map to the private map provider with information on lane closures, updated speed limits, lane width changes and the presence of construction workers) approaches could be investigated.

To answer this question fully would require an investigation of what updated map information is needed for an automated vehicle to successfully autonomously navigate a changed set of environmental conditions. This investigation could potentially be performed using the Zoe 2 vehicle in autonomous mode, with appropriate safeguards.

Broadly speaking, further studies like the ones proposed here could involve both primarily technological investigations – for example further investigations into the technical aspects of creating, mapping, and maintaining HD maps – and broader studies that investigate the interactions between government, private map providers (whether stand alone or as part of autonomous vehicle companies). Such studies are likely to yield benefits both in terms of answering specific questions about autonomous vehicles and mapping technology, but also in generating broader insights into the generation and usage of HD maps of our road network with widespread applications beyond just their usage by autonomous vehicles.

## 12 Conclusion

Mapping for automated vehicles is a rich and evolving field, with rapid growth in technology over the last few years. It is almost universally considered essential, with the notable exception of Tesla, that an automated vehicle needs access to a prior high definition map of the environment it navigates in, for reliable and safe operation. Many examples of both map creators and consumers have been discussed in this report, with technical details as well as Government responsibilities discussed.

This literature review has revealed a general lack of a coordinated response to integrate Government infrastructure data (often termed the “Digital Infrastructure”) and commercial solutions of high definition (HD) maps for automated vehicles. This is in contrast to the development of relatively mature frameworks and specifications for low detail maps as well as connectivity and communications in the automated vehicle domain. The biggest roadblocks include a lack of joint public private discussions on this topic, a lack of intellectual property sharing agreements between corporations and Governments, and a lack of digital infrastructure to support real-time map updates. Any collaboration is currently limited to pilot programs, which generally are suburb sized. Some work in these spaces has begun to occur within the EU, with intelligent transport system projects such as C-Roads, TN-ITS, NordicWay, SHOW and trials in Kassel, Germany. Collectively these projects are defining what the future models of both infrastructure to vehicle and infrastructure to HD map communications might look like. HD maps for automated vehicles have begun to be created by both specialist mapping companies like TomTom and HERE, alongside automated vehicle companies like Waymo, and ADAS OEM systems manufacturers like Mobileye.

In order to deploy safety-critical real-time HD maps for automated vehicles, the following key challenges need to be overcome:

- A unified framework for the real-time communication of road work locations and related semantic information (such as which lanes are closed) to HD map providers.
- Expansion of the existing 2D location referencing into 3D.
- A system for communicating changes to static road elements (such as road signs) to the HD map providers.
- Policy decisions on whether HD maps should be owned and operated privately or publicly, or in a some form of hybrid model.

The EU is currently attempting to address the above challenges, by collaborating with private HD map producers like TomTom and HERE to produce and enhance the data standards Datex II and TN-ITS. However, further work in the EU will be required, to ensure that these communications systems meet safety critical ratings (SIL – Safety Integrity Levels), are cybersecure, and reference locations in a 3D coordinate system.



In this report we propose a set of recommendations, considering a range of possible strategies that encompass different policy directions and varying degrees of collaboration with international public and private actors. The Avenues of Future Work section provides a set of short-term opportunities for future projects in this space, in order to better understand what HD mapping systems will suit the Australian context. Such short term trials would enable decisions based on quantifiable data that reflect Australian conditions, since the models that work in the EU and related countries may not be directly repeatable due to differences in road rules, climate and the private landscape (e.g. a lack of domestically headquartered automated vehicle companies).

To conclude, this report has provided an in-depth review of existing prior maps for automated driving, discovered the progress to-date of international Governments in this space, discussed the data standards and map maintenance requirements of these maps, and considered the range of possible roles of Government in developing, maintaining and consuming prior maps.

## 13 References

- [1] J. P. Leite, "A brief History of GPS In-Car Navigation - NDrive." [Online]. Available: <https://ndrive.com/brief-history-gps-car-navigation/>. [Accessed: 20-Jul-2020].
- [2] R. Liu, J. Wang, and B. Zhang, "324-341. c The Royal Institute of Navigation," *J. Navig.*, vol. 73, 2020.
- [3] J.-C. Pandazis, "Next MAP for transport telematics applications: FINAL REPORT," 2002.
- [4] R. Herrtwich, "The evolution of the HERE HD Live Map at Daimler." [Online]. Available: <https://360.here.com/the-evolution-of-the-hd-live-map>. [Accessed: 20-Jul-2020].
- [5] E. L. Chao and M. Kratsios, "Ensuring American Leadership in Automated Vehicle Technologies Automated Vehicles 4.0," 2020.
- [6] K. Chellapilla, "Rethinking Maps for Self-Driving. Maps are a key component to building... | by Lyft Level 5 | Lyft Level 5 | Medium." [Online]. Available: <https://medium.com/lyftlevel5/https-medium-com-lyftlevel5-rethinking-maps-for-self-driving-a147c24758d6>. [Accessed: 17-Jul-2020].
- [7] M. Cantu, "Ford Integrates Waze Traffic and Navigation App Into Sync 3." [Online]. Available: <https://www.motortrend.com/news/ford-integrates-waze-traffic-and-navigation-app-into-sync-3/>. [Accessed: 04-Aug-2020].
- [8] TomTom, "ADAS Map Highly accurate map content for driver assistance."
- [9] "Waypoint - The official Waymo blog: Building maps for a self-driving car." [Online]. Available: <https://blog.waymo.com/2019/09/building-maps-for-self-driving-car.html>. [Accessed: 17-Jul-2020].
- [10] "Analysis of geospatial data requirement to support the operation of autonomous cars Project Report SDFE-Danish Ministry of Energy, Utilities and Climate," 2017.
- [11] K. Efland and H. Rapp, "Semantic Maps for Autonomous Vehicles | by Lyft Level 5 | Lyft Level 5 | Medium." [Online]. Available: <https://medium.com/lyftlevel5/semantic-maps-for-autonomous-vehicles-470830ee28b6>. [Accessed: 28-Oct-2020].
- [12] "Apollo." [Online]. Available: <https://apollo.auto/developer.html>. [Accessed: 05-Aug-2020].
- [13] M. D. Wheeler, "HIGH DEFINITION MAP AND ROUTE STORAGE MANAGEMENT SYSTEM FOR AUTONOMOUS VEHICLES," 0189323, 2018.
- [14] S. Gordon, "California Driver Handbook," 2020.
- [15] "Matt Canavan says hook turns are a 'stupid way' to manage traffic. Are they? - ABC News." [Online]. Available: <https://www.abc.net.au/news/2019-08-15/fact-file-hook-turns-melbourne-matt-canvan-adani/11404870>. [Accessed: 06-Aug-2020].
- [16] L. Ipsum, "Way mo' miles, way mo' data - Digital Innovation and Transformation."

- [Online]. Available: <https://digital.hbs.edu/platform-digit/submission/way-mo-miles-way-mo-data/>. [Accessed: 23-Nov-2020].
- [17] D. Ferguson and W.-Y. Lo, "USE OF ENVIRONMENTAL INFORMATION TO AD IMAGE PROCESSING FOR AUTONOMOUS VEHICLES," 9387854.
- [18] TomTom, "TomTomRoadDNA."
- [19] R. Mur-Artal, J. M. M. Montiel, and J. D. Tardos, "ORB-SLAM: A Versatile and Accurate Monocular SLAM System," *IEEE Trans. Robot.*, vol. 31, no. 5, pp. 1147–1163, 2015.
- [20] "ORB-SLAM Project Webpage." [Online]. Available: <https://webdiis.unizar.es/~raulmur/orbslam/>. [Accessed: 23-Nov-2020].
- [21] S. J. Han, J. Kang, Y. Jo, D. Lee, and J. Choi, "Robust Ego-motion Estimation and Map Matching Technique for Autonomous Vehicle Localization with High Definition Digital Map," in *9th International Conference on Information and Communication Technology Convergence: ICT Convergence Powered by Smart Intelligence, ICTC 2018*, 2018, pp. 630–635.
- [22] S. Bauer, Y. Alkhorshid, and G. Wanielik, "Using high-definition maps for precise urban vehicle localization," in *IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC*, 2016, pp. 492–497.
- [23] S. Elhabian, A. Farag, and A. Farag, "A Tutorial on Rigid Registration Iterative Closed Point (ICP)," 2009.
- [24] H. Eber Sobreira *et al.*, "Map-Matching Algorithms for Robot Self-Localization: A Comparison Between Perfect Match, Iterative Closest Point and Normal Distributions Transform," *J. Intell. Robot. Syst.*, vol. 93, pp. 533–546, 2019.
- [25] L. Wang, Y. Zhang, and J. Wang, "Map-Based Localization Method for Autonomous Vehicles Using 3D-LIDAR," *IFAC-PapersOnLine*, vol. 50, no. 1, pp. 276–281, Jul. 2017.
- [26] Hexagon, "Hexagon's 'RTK From the Sky' brings instant GNSS accuracy worldwide | Hexagon Positioning Intelligence." [Online]. Available: <https://hexagonpositioning.com/about-us/press-releases/hexagons-rtk-from-the-sky-brings-instant-gnss-accuracy-worldwide>. [Accessed: 07-Dec-2020].
- [27] R. Zhang, C. Chen, Zeng, and D. Wheeler, "VISUAL ODOMETRY AND PAIRWISE ALIGNMENT FOR HIGH DEFINITION MAP CREATION," 10598489, 2020.
- [28] L. Yang and Cui, "LANE NETWORK CONSTRUCTION USING HIGH DEFINITION MAPS FOR AUTONOMOUS VEHICLES," 10545029, 2020.
- [29] Zenzic, "Geodata report-analysis and recommendations for self-driving vehicle testing Zenzic consultation findings Geodata report-analysis and recommendations for self-driving vehicle testing, Zenzic consultation findings," 2020.
- [30] "The Home of Location Technology Innovation and Collaboration | OGC." [Online]. Available: <https://www.ogc.org/>. [Accessed: 28-Aug-2020].

- [31] V. Labs, “Map-based Lane Keeping with HERE HD Live Map,” 2018.
- [32] NordicWay, “NordicWay 2 Architecture , Draft,” pp. 1–23, 2019.
- [33] C-Roads Platform, “C-ITS IP Based Interface Profile.”
- [34] TN-ITS, “About Us | TN-ITS.” [Online]. Available: <https://tn-its.eu/about-us>. [Accessed: 28-Oct-2020].
- [35] Atlatec, “Atlatec sample data.” [Online]. Available: <https://www.atlatec.de/getsampled.html>. [Accessed: 10-Sep-2020].
- [36] A. Chidambara Raj, A. Sozio, and M. van der Velden, *Guidance and Readability Criteria for Traffic Sign Recognition Systems Reading Electronic Signs*. 2020.
- [37] D. Pannen, M. Liebner, W. Hempel, and W. Burgard, “How to Keep HD Maps for Automated Driving up to Date,” in *2020 IEEE International Conference on Robotics and Automation*, 2020.
- [38] ETSI EN 302 637-3, “Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 3: Specifications of Decentralized Environmental Notification Basic Service,” *Etsi*, vol. 0, no. 1.3.1, pp. 1–74, 2019.
- [39] “Homepage - SENSORIS.” [Online]. Available: <https://sensor-is.org/>. [Accessed: 23-Jul-2020].
- [40] “SENSORIS: Collaboration Body for Data Exchange | HERE.” [Online]. Available: <https://www.here.com/vision/sensoris>. [Accessed: 09-Nov-2020].
- [41] “TomTom Traffic Incidents – Intermediate Service – DATEX II | Intermediate Traffic Service | Intermediate Traffic Service | TomTom Developer Portal.” [Online]. Available: <https://developer.tomtom.com/intermediate-traffic-service/intermediate-traffic-service/tomtom-traffic-incidents-intermediate-service-datex-ii>. [Accessed: 21-Sep-2020].
- [42] “Developer Guide - Traffic Data Service - HERE Developer.” [Online]. Available: [https://developer.here.com/documentation/traffic-data-service/dev\\_guide/topics/concept-datex.html](https://developer.here.com/documentation/traffic-data-service/dev_guide/topics/concept-datex.html). [Accessed: 21-Sep-2020].
- [43] BSI Standards Publication, “PD CEN / TS 16157 - 9 : 2020 BSI Standards Publication Intelligent transport systems – DATEX II data exchange specifications for traffic management and information,” 2020.
- [44] S. Fitzgerald, “C-ITS Pilot Security Credential Management System: Evaluation and Research.” [Online]. Available: <https://imoveaustralia.com/project/c-its-pilot-security-credential-management-system/>. [Accessed: 22-Nov-2020].
- [45] “Intelligent Transportation Systems - Security Credential Management System (SCMS).” [Online]. Available: <https://www.its.dot.gov/resources/scms.htm>. [Accessed: 22-Nov-2020].
- [46] T. Ort *et al.*, “MapLite: Autonomous Intersection Navigation without a Detailed Prior

- Map,” in *2020 IEEE International Conference on Robotics and Automation*, 2020.
- [47] J. M. Anderson, N. Kalra, K. D. Stanley, P. Sorensen, C. Samaras, and O. A. Oluwatola, *Autonomous Vehicle Technology: A Guide for Policymakers*. 2016.
- [48] A. Karpathy, “(291) Andrej Karpathy - AI for Full-Self Driving - YouTube.” [Online]. Available: <https://www.youtube.com/watch?v=hx7BXih7zx8>. [Accessed: 21-Jul-2020].
- [49] A. Karpathy, “(291) CVPR’20 Workshop on Scalability in Autonomous Driving - YouTube.” [Online]. Available: [https://www.youtube.com/playlist?list=PLS10R-eAASUIAIUWbBgxF9\\_4Elj9bdb2U](https://www.youtube.com/playlist?list=PLS10R-eAASUIAIUWbBgxF9_4Elj9bdb2U). [Accessed: 21-Jul-2020].
- [50] R. Heilweil, “Tesla’s Autopilot keeps causing its cars to crash - Vox.” [Online]. Available: <https://www.vox.com/recode/2020/2/26/21154502/tesla-autopilot-fatal-crashes>. [Accessed: 21-Jul-2020].
- [51] “Tesla Autopilot to Avoid Potholes via HD Maps - AutoPilot Review.” [Online]. Available: <https://www.autopilotreview.com/tesla-autopilot-hd-maps/>. [Accessed: 28-Aug-2020].
- [52] EDMap, “Enhanced Digital Mapping Project Final Report,” 2004.
- [53] “The standard for map data - NDS Association.” [Online]. Available: <https://nds-association.org/>. [Accessed: 21-Jul-2020].
- [54] R. Dolgov, “NDS + ADASIS: Bringing maps to vehicle and driving functions,” 2019.
- [55] “Safespot.” [Online]. Available: <http://www.safespot-eu.org/>. [Accessed: 19-Oct-2020].
- [56] H. Shimada, A. Yamaguchi, H. Takada, and K. Sato, “Implementation and Evaluation of Local Dynamic Map in Safety Driving Systems,” *J. Transp. Technol.*, vol. 05, no. 02, pp. 102–112, 2015.
- [57] ETSI, “TR 102 863 - V1.1.1 - Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Local Dynamic Map (LDM); Rationale for and guidance on standardization,” 2011.
- [58] SAFESPOT, “SAFESPOT INTEGRATED PROJECT IST-4-026963-IP Building of the Global System Reference Architecture,” 2010.
- [59] TomTom, “Extending the vision of automated vehicles with HD Maps and ADASIS.”
- [60] TomTom, “OpenLR™ White Paper,” 2009.
- [61] “Strategic Partners | Building an Autonomous World | HERE.” [Online]. Available: <https://www.here.com/strategic-partners>. [Accessed: 24-Jul-2020].
- [62] HERE Technologies, “HERE Road Signs,” 2018.
- [63] SOCRATES, “SETTING THE STAGE FOR THE DEPLOYMENT OF INTERACTIVE TRAFFIC MANAGEMENT,” 2019.

- [64] Mercedes-Benz, “Introducing DRIVE PILOT: An Automated Driving System for the Highway.”
- [65] Mapbox, “Company | Mapbox.” [Online]. Available: <https://www.mapbox.com/about/company/>. [Accessed: 22-Sep-2020].
- [66] B. Thompson, “HD vector maps open standard. By: Blake Thompson | by Mapbox | maps for developers.” [Online]. Available: <https://blog.mapbox.com/hd-vector-maps-open-standard-335a49a45210>. [Accessed: 22-Sep-2020].
- [67] Eric Gundersen, “Mobileye RoadBook: high-precision HD maps distributed at scale | by Mapbox | maps for developers.” [Online]. Available: <https://blog.mapbox.com/mobileye-roadbook-high-precision-hd-maps-distributed-at-scale-9b4e692d29f>. [Accessed: 22-Sep-2020].
- [68] “Preparing for the Future of Transportation: Automated Vehicles 3.0 | US Department of Transportation.” [Online]. Available: <https://www.transportation.gov/av/3>. [Accessed: 14-Jul-2020].
- [69] “TRI-AD enables successful creation of HD maps for automated driving on surface roads | Corporate | Global Newsroom | Toyota Motor Corporation Official Global Website.” [Online]. Available: <https://global.toyota/en/newsroom/corporate/31898884.html>. [Accessed: 14-Jul-2020].
- [70] Denzo, “Autonomous vehicle using digital map as a soft infrastructure,” 2008.
- [71] “Toyota collaborations create HD maps for automated driving | Traffic Technology Today.” [Online]. Available: <https://www.traffictechnologytoday.com/news/mapping/toyota-collaborations-create-hd-maps-for-automated-driving.html>. [Accessed: 22-Sep-2020].
- [72] QCIF, “QCIF - Researchers can access Queensland roads and surrounding terrain data via QRIScloud.” [Online]. Available: <https://archive-www.qcif.edu.au/index.php/news/471-researchers-can-access-queensland-roads-and-surrounding-terrain-data-via-qrisccloud>. [Accessed: 09-Dec-2020].
- [73] Apollo, “Reliable and safe maps for automated driving.”
- [74] United States Government Accountability Office, “AUTOMATED VEHICLES Comprehensive Plan Could Help DOT Address Challenges Report to Congressional Committees,” 2017.
- [75] TomTom, “Behind the map: how we keep our maps up to date | TomTom Blog.” [Online]. Available: <https://www.tomtom.com/blog/maps/continuous-map-processing/>. [Accessed: 22-Jul-2020].
- [76] TomTom, “What are the differences between the TomTom ADAS and HD Maps? | TomTom Blog.” [Online]. Available: <https://www.tomtom.com/blog/autonomous-driving/adas-map-vs-hd-map/>. [Accessed: 22-Jul-2020].
- [77] TomTom, “(291) TomTom: Demonstrating Lane Level Localization for Autonomous



- Driving - YouTube.” [Online]. Available: <https://www.youtube.com/watch?v=86U4sxCpRf8>. [Accessed: 22-Jul-2020].
- [78] ABI Research, “HERE The Future of Maps,” 2018.
- [79] “Mapping cars hit Australian roads fitted with world-first satellite positioning technology - Geospatial World.” [Online]. Available: <https://www.geospatialworld.net/news/mapping-cars-hit-australian-roads-fitted-with-world-first-satellite-positioning-technology/>. [Accessed: 24-Jul-2020].
- [80] “Trial of accurate positioning | Geoscience Australia.” [Online]. Available: <https://www.ga.gov.au/scientific-topics/positioning-navigation/positioning-australia/trial-of-accurate-positioning>. [Accessed: 24-Jul-2020].
- [81] “VicRoads joins national GPS accuracy trials - Networking - iTnews.” [Online]. Available: <https://www.itnews.com.au/news/vicroads-joins-national-gps-accuracy-trials-479822>. [Accessed: 24-Jul-2020].
- [82] J. Dawson, “Positioning Australia,” 2019.
- [83] “Safety Report – Waymo.” [Online]. Available: <https://waymo.com/safety/>. [Accessed: 28-Jul-2020].
- [84] Waymo, “Waymo Safety Report On the Road to Fully Self-Driving.”
- [85] P. Sun *et al.*, “Scalability in Perception for Autonomous Driving: Waymo Open Dataset.”
- [86] “Data – Waymo.” [Online]. Available: <https://waymo.com/open/data/>. [Accessed: 28-Jul-2020].
- [87] “NVIDIA DRIVE Mapping | NVIDIA Developer.” [Online]. Available: <https://developer.nvidia.com/drive/drive-mapping>. [Accessed: 24-Jul-2020].
- [88] “NVIDIA Teams Up With Mapping Companies for Localization | NVIDIA Blog.” [Online]. Available: <https://blogs.nvidia.com/blog/2019/01/07/hd-mapping-drive-localization/>. [Accessed: 24-Jul-2020].
- [89] “NVIDIA DRIVE - Autonomous Vehicle Development Platforms | NVIDIA Developer.” [Online]. Available: <https://developer.nvidia.com/drive>. [Accessed: 24-Jul-2020].
- [90] “Maps for Self-Driving Cars | Maps for Automated Driving.” [Online]. Available: <https://www.sanborn.com/highly-automated-driving-maps-for-autonomous-vehicles/>. [Accessed: 14-Jul-2020].
- [91] Aptiv, “SAFETY FIRST FOR AUTOMATED DRIVING,” 2019.
- [92] Hyundai-Aptiv AD LLC, “Quarterly AV Testing Report,” 2020.
- [93] Apollo, “Apollo Development Route.” [Online]. Available: [https://apollo.auto/about/development\\_route.html](https://apollo.auto/about/development_route.html). [Accessed: 23-Nov-2020].
- [94] Apollo Auto, “Deep Dive on Apollo 2.5. How the new release will put us on the... | by Apollo Auto | Apollo Auto | Medium.” [Online]. Available:

- <https://medium.com/apollo-auto/deep-dive-on-apollo-2-5-1e716ec94617>. [Accessed: 23-Nov-2020].
- [95] Apollo, “apollo/modules/map/data at master · ApolloAuto/apollo.” [Online]. Available: <https://github.com/ApolloAuto/apollo/tree/master/modules/map/data>. [Accessed: 23-Nov-2020].
- [96] Intel, “The Why and How of Making HD Maps for Automated Vehicles | Intel Newsroom.” [Online]. Available: <https://newsroom.intel.com/articles/why-how-making-hd-maps-automated-vehicles/#gs.m5nqv4>. [Accessed: 23-Nov-2020].
- [97] M. Roads, “P1-007: How Automated Vehicles Will Interact with Road Infrastructure Now and in the Future,” pp. 1–133.
- [98] “Home - Aerometrex.” [Online]. Available: <https://aerometrex.com.au/>. [Accessed: 19-Aug-2020].
- [99] “AI Imagery | Nearmap AI | Nearmap.” [Online]. Available: <https://www.nearmap.com/us/en/products/ai-aerial-maps>. [Accessed: 19-Aug-2020].
- [100] “About Delivery – Wing.” [Online]. Available: <https://wing.com/about-delivery/>. [Accessed: 09-Dec-2020].
- [101] “Home - AND.” [Online]. Available: <https://www.and.com/>. [Accessed: 20-Aug-2020].
- [102] S. Antipolis, “ETSI - ETSI experts complete specifications for Vulnerable Road Users.” [Online]. Available: <https://www.etsi.org/newsroom/news/1852-2020-11-etsi-experts-complete-specifications-for-vulnerable-road-users>. [Accessed: 08-Dec-2020].
- [103] NHTSA, “Automated Vehicles for Safety | NHTSA.” [Online]. Available: <https://www.nhtsa.gov/technology-innovation/automated-vehicles>. [Accessed: 18-Nov-2020].
- [104] “Ranked: The Autonomous Vehicle Readiness of 20 Countries.” [Online]. Available: <https://www.visualcapitalist.com/ranked-the-autonomous-vehicle-readiness-of-20-countries/>. [Accessed: 27-Jul-2020].
- [105] “Cooperative Driving Automation | FHWA.” [Online]. Available: <https://cms7.fhwa.dot.gov/research/operations/Cooperative-Driving-Automation>. [Accessed: 17-Jul-2020].
- [106] Autonews, “U.S. DOT announces \$60 million in AV research grants.” [Online]. Available: <https://www.autonews.com/mobility-report/us-dot-announces-60-million-av-research-grants>. [Accessed: 17-Jul-2020].
- [107] P. Tarpley and S. Jansma, “Autonomous vehicles: The legal landscape in the US | Publications | Knowledge | Global law firm | Norton Rose Fulbright,” <https://www.nortonrosefulbright.com/en-af/knowledge/publications/imported/2018/07/18/05>.
- [108] Thompson, “PennDOT Receives \$8.4 million Federal DOT Grant | Congressman Glenn Thompson.” [Online]. Available: <https://thompson.house.gov/media-center/press->

- releases/penndot-receives-84-million-federal-dot-grant. [Accessed: 17-Jul-2020].
- [109] A. Lopez *et al.*, “PENNSYLVANIA JOINT STATEWIDE CONNECTED AND AUTOMATED VEHICLES STRATEGIC PLAN Final Report,” 2018.
- [110] Horizon, “AUTONOMOUS VEHICLES,” 2018.
- [111] J. Katseff, S. Peloquin, M. Rooney, and T. Wintner, “US infrastructure gap | McKinsey.” [Online]. Available: <https://www.mckinsey.com/industries/capital-projects-and-infrastructure/our-insights/reimagining-infrastructure-in-the-united-states-how-to-build-better#>. [Accessed: 13-Oct-2020].
- [112] “SoftBank makes self-driving push in Japan - Nikkei Asian Review.” [Online]. Available: <https://asia.nikkei.com/Business/SoftBank2/SoftBank-makes-self-driving-push-in-Japan>. [Accessed: 27-Jul-2020].
- [113] P. Lyon, “World’s Biggest-Ever Self-Driving Experiment To Coincide With Tokyo Olympics.” [Online]. Available: <https://www.forbes.com/sites/peterlyon/2020/01/28/tokyo-olympics-to-coincide-with-biggest-self-driving-demonstration-in-history/#a1c73251797a>. [Accessed: 14-Oct-2020].
- [114] “jidouten-lab (Google Translated).” [Online]. Available: [https://translate.google.com/translate?hl=en&sl=ja&u=https://jidouten-lab.com/u\\_nissan-skyline-matome&prev=search&pto=aue](https://translate.google.com/translate?hl=en&sl=ja&u=https://jidouten-lab.com/u_nissan-skyline-matome&prev=search&pto=aue). [Accessed: 14-Oct-2020].
- [115] “Services provided: Current maintenance status | Dynamic Map Infrastructure Co., Ltd.” [Online]. Available: [https://translate.googleusercontent.com/translate\\_c?depth=1&hl=en&prev=search&pto=aue&rurl=translate.google.com&sl=ja&sp=nmt4&u=https://www.dynamic-maps.co.jp/service/map.html&usg=ALkJrhjdy9HVVGX5PjtwjDuGltL9W4U2wQ](https://translate.googleusercontent.com/translate_c?depth=1&hl=en&prev=search&pto=aue&rurl=translate.google.com&sl=ja&sp=nmt4&u=https://www.dynamic-maps.co.jp/service/map.html&usg=ALkJrhjdy9HVVGX5PjtwjDuGltL9W4U2wQ). [Accessed: 14-Oct-2020].
- [116] “Dynamic Maps (Google Translated).” [Online]. Available: <https://translate.google.com/translate?hl=en&sl=ja&u=https://www.dynamic-maps.co.jp/&prev=search&pto=aue>. [Accessed: 14-Oct-2020].
- [117] “Cross-ministerial Strategic Innovation Promotion Program (SIP)/ Automated Driving for Universal Services/ Update of High-precision Three-dimensional Map with Vehicle Probe Data Progress Report,” 2020.
- [118] Dynamic Map, “Cross-ministerial Strategic Innovation Promotion Program (SIP)/ Automated Driving for Universal Services/ Update of High-precision Three-dimensional Map with Vehicle Probe Data Progress Report,” no. March, 2020.
- [119] Director Cabinet Office General for Science Technology and Innovation, “Cross-ministerial Strategic Innovation Promotion Program (SIP) Automated Driving for Universal Services R&D Plan,” 2019.
- [120] M. Schaub, “KWM | China: Mapping the Future.” [Online]. Available: <https://www.kwm.com/en/de/knowledge/insights/china-mapping-the-future-trends->

- autonomous-vehicles-20200602. [Accessed: 17-Jul-2020].
- [121] “China issues roadmap for rapid development of self-driving cars - Reuters.” [Online]. Available: <https://www.reuters.com/article/us-china-autos-autonomous/china-issues-roadmap-for-rapid-development-of-self-driving-cars-idUSKCN12Q0OZ>. [Accessed: 23-Jul-2020].
- [122] “China Industry Innovation Alliance for the Intelligent and Connected Vehicles.” [Online]. Available: <http://www.caicv.org.cn/index.php/introduce?id=1>. [Accessed: 27-Jul-2020].
- [123] ERTICO, “history » ERTICO.” [Online]. Available: <https://ertico.com/history/>. [Accessed: 09-Dec-2020].
- [124] European Commission, “What we do | Mobility and transport.” [Online]. Available: [https://ec.europa.eu/transport/road\\_safety/what-we-do\\_en](https://ec.europa.eu/transport/road_safety/what-we-do_en). [Accessed: 09-Dec-2020].
- [125] “Cooperative, connected and automated mobility (CCAM) | Mobility and Transport.” [Online]. Available: [https://ec.europa.eu/transport/themes/its/c-its\\_en](https://ec.europa.eu/transport/themes/its/c-its_en). [Accessed: 23-Jul-2020].
- [126] C-ITS Platform, “C-ITS Platform Final report,” 2016.
- [127] C-ITS Platform, “C-ITS Platform Final report Phase II,” 2017.
- [128] T. Alkim *et al.*, “EUROPEAN COMMISSION DG Research and Innovation-RTD HORIZON 2020 PROGRAMME SOCIETAL CHALLENGES-SMART, GREEN AND INTEGRATED TRANSPORT Coordination and Support Action-Grant Agreement Number 724086 Document Control Sheet Work area: WP3 and WP4 Document title:”
- [129] “Data for Road Safety.” [Online]. Available: <https://www.dataforroadsafety.eu/>. [Accessed: 23-Jul-2020].
- [130] “About Activities: C-Roads.” [Online]. Available: <https://www.c-roads.eu/platform/activities/about-activities.html>. [Accessed: 24-Sep-2020].
- [131] “CAR 2 CAR Communication Consortium.” [Online]. Available: <https://www.car-2-car.org/>. [Accessed: 09-Dec-2020].
- [132] “Working Groups | TN-ITS.” [Online]. Available: <https://tn-its.eu/working-groups>. [Accessed: 23-Nov-2020].
- [133] F. Daems, “The future of a Common European Mobility data space Reflection paper,” 2020.
- [134] “Stadtplan und Themenkarten | kassel.de: Der offizielle Internetauftritt der Stadt Kassel.” [Online]. Available: <https://www.kassel.de/geoportal>. [Accessed: 12-Aug-2020].
- [135] “Our Technology | Oxbotica.” [Online]. Available: <https://www.oxbotica.com/our-technology/>. [Accessed: 29-Jul-2020].

- [136] Zenzic, “UK Connected and Automated Mobility Roadmap,” 2019.
- [137] Australian Government Department of Transport, “Preparing for Automated Vehicles.” [Online]. Available: <https://www.infrastructure.gov.au/transport/automatedvehicles/preparing-for-automated-vehicles.aspx>. [Accessed: 09-Dec-2020].
- [138] “Parliament of Victoria - Automated Vehicles.” [Online]. Available: <https://www.parliament.vic.gov.au/publications/research-papers/download/36-research-papers/13839-automated-vehicles>. [Accessed: 16-Jul-2020].
- [139] A. Somers Publisher, D. Yee, and J. Wall, *Future Vehicles 2030*. 2030.
- [140] Q. Government, “Ipswich Connected Vehicle Pilot | Transport and motoring | Queensland Government.” [Online]. Available: <https://www.qld.gov.au/transport/projects/cavi/ipswich-connected-vehicle-pilot>. [Accessed: 07-Oct-2020].
- [141] P. D. C. E. N. Iso and C. Its, “PD CEN ISO / TS 19091 : 2019 BSI Standards Publication Intelligent transport systems – Cooperative ITS – Using V2I and I2V communications for applications related to signalized,” 2019.
- [142] S. G. Dehkordi, S. Glaser, A. Bond, and A. Rakotonirainy, “COOPERATIVE AND HIGHLY AUTOMATED DRIVING WP-2 C-ITS AND AV INTEGRATION , AND BENEFITS EVALUATION,” pp. 1–63, 2020.
- [143] “The National Map.” [Online]. Available: <https://www.usgs.gov/core-science-systems/national-geospatial-program/national-map>. [Accessed: 18-Nov-2020].
- [144] “Company Profile | Dynamic Map Platform Co., Ltd.” [Online]. Available: <https://www.dynamic-maps.co.jp/en/company/index.html>. [Accessed: 18-Nov-2020].
- [145] “About Us | Dynamic Map Platform Co., Ltd.” [Online]. Available: <https://www.dynamic-maps.co.jp/en/about/index.html>. [Accessed: 18-Nov-2020].
- [146] G. Turner, “Report: Pandemic Expected to Impact Autonomous Vehicle Industry - DBusiness Magazine,” 2020. [Online]. Available: <https://www.dbusiness.com/daily-news/report-pandemic-expected-to-impact-autonomous-vehicles-industry/>. [Accessed: 20-Nov-2020].