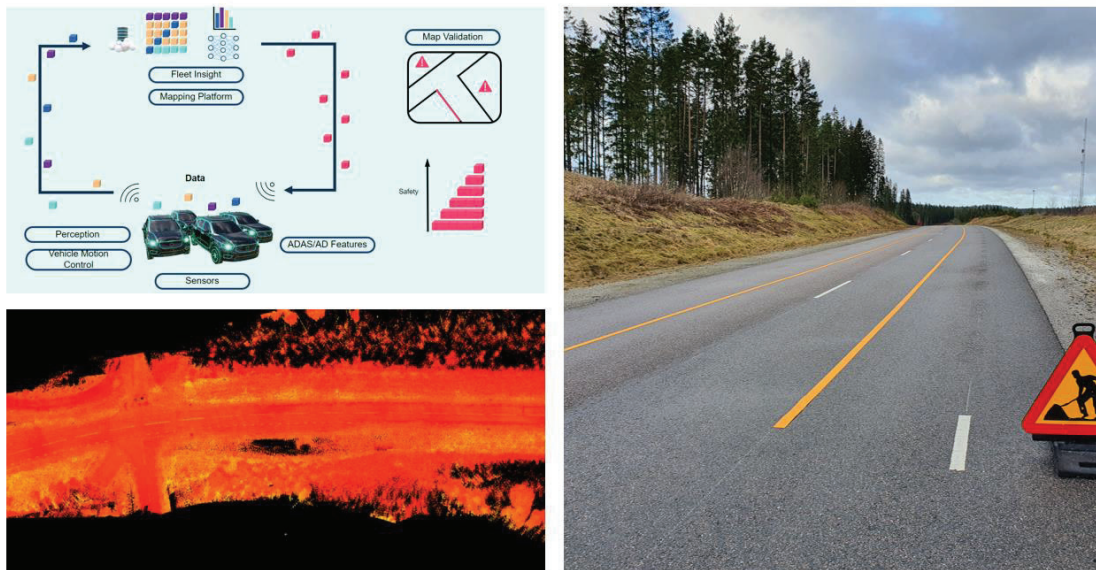


Validation of Mapping and Localization for Autonomous Vehicles

Public report



Project within: Traffic safety and automated vehicles

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1 Summary

The VAMLAV project is a Vinnova FFI-funded project with the following partners: AstaZero, Zenseact, RISE and AI Sweden. The project set out to create a dataset that includes the computer vision sensors that many Advanced Driver-Assistance System (ADAS) and Automated Driving Systems (ADS) vehicles use and complement them with a high-definition (HD)-map over a known geographic area.

The VAMLAV dataset includes sensors such as camera, Light Detection and Ranging (LiDAR), Inertial Measurement Units (IMUs), and Global navigation satellite system (GNSS) sensors. This dataset, publicly available at AI Sweden, offers a corresponding HD-map in OpenDRIVE format covering the Rural Road at AstaZero. The dataset includes adverse weather, multiple maps and drives around the track with emulated traffic work scenarios that can occur.

Beyond creating the dataset, the project aimed to validate HD-maps by comparing them to other measurement technologies. It delved deeper into localization for ADS vehicles by comparing various measurement campaigns and designing high-accuracy anchor points. This data was later used to validate and update the HD-map. By comparing different measurement systems and samples on the map, the project hopes to increase the trust in the HD-map over a longer time. This data also makes it possible to experiment more within the field of crowdsourced HD-maps from different systems while having an easier time measuring the accuracy of such maps.

Another big part of the project was related to safety therefore some data was collected where the project emulates traffic work at AstaZero. This use case is otherwise difficult to test and evaluate due to the stochastic nature of traffic work in real life. Where the system detected the traffic work with the help of map and sensor data and then distributed the information to other cars in the area.

2 Sammanfattning på svenska

VAMLAV-projektet är ett av Vinnova FFI-finansierat projekt med följande partners: AstaZero, Zenseact, RISE och AI Sweden. Projektet inleddes med målet att skapa ett dataset som inkluderar de datorseendesensorer som många fordon med avancerade förarstödsystem (ADAS) och automatiserade körsystem (ADS) använder och kompletterar dem med en högupplöst (HD) karta över ett känt geografiskt område.

VAMLAV-datasetet inkluderar sensorer som kamera, ljusdetektion och avståndsmätning (LiDAR), tröghetsmätenheter (IMUs) och Globala navigationssatellitesystem (GNSS) sensorer. Detta dataset, som är offentligt tillgängligt hos AI Sweden, erbjuder en motsvarande HD-karta i OpenDRIVE-format som täcker landsvägen vid AstaZero.

Datasetet inkluderar ogynnsamt väder, flera kartor och körningar runt banan med emulerade trafikarbetsscenarier som kan inträffa.

Utöver att skapa datasetet ämnade projektet att validera HD-kartor genom att jämföra dem med andra mätteknologier. Det fördjupade sig mer i lokalisering för ADS-fordon genom att jämföra olika mätkampanjer och designa högprecisionsankarpunkter. Denna data användes senare för att validera och uppdatera HD-kartan. Genom att jämföra olika mätsystem och prov på kartan hoppas projektet öka förtroendet för HD-kartan över en längre tid. Denna data gör det också möjligt att experimentera mer inom området för crowdsourcade HD-kartor från olika system samtidigt som det blir lättare att mäta noggrannheten av sådana kartor.

En annan stor del av projektet var relaterad till säkerhet, därför samlades en del data in där projektet emulerade trafikarbete vid AstaZero. Detta användningsfall är annars svårt att testa och utvärdera på grund av den stokastiska karaktären av trafikarbetet i verkliga livet. Där systemet upptäckte trafikarbetet med hjälp av kart- och sensordata och sedan distribuerade informationen till andra bilar i området.

3 Background

Today, multiple companies and other institutions are investigating and investing in numerous Artificial Intelligence (AI) technologies and new AI-systems. Sweden is aiming to become a hub for AI research related to many different industries with the help of the AI Sweden initiative. AI Sweden is a neutral and national arena with the aim to accelerate applied AI research and innovation in Sweden. Moreover, AI Sweden facilitates data sharing and makes important data available for both industry and academia through the so-called data factory. The automotive industry is one of the industry sectors in Sweden that is interested and investing in AI-technology, especially for Advanced Driving Assistance Systems (ADAS) vehicles, which is the first step toward Autonomous Drive (AD).

These new AI systems, implemented in different decision related systems within the autonomous vehicle - specifically the autonomous – require training, validation, and other information to ensure robustness in early and late development stages. Today companies are investing vast amount of time, effort, and money in these activities. The data needed to validate, test or train subsets of these systems are not often public or allowed to be used in products.

Free datasets that are specifically developed with the purpose of image recognition for different autonomous vehicle systems. A non-exhaustive example list of these datasets includes: KITTI (Geiger, Lenz, & Urtasun, 2012), Cityscapes (Cordts, 2016), nuScenes (Bejbom, 2020), ApolloScape (Xinyu Huang, 2018) and BDD100K (Fisher Yu, 2020).

NuScenes added an HD-map complementing the perception dataset, which opens possibilities regarding localization, mapping and simulation.

The main purpose of the previously mentioned datasets is to train different machine learning algorithms for computer vision. These machine learning algorithms are mostly used for object detection and segmentation. The datasets mentioned above were not meant for evaluating different positioning systems, path planning, except for nuScenes that also feature maps. For the possibility to evaluate, test and integrate the object detection system with future AI decision systems there is a need to integrate a road geometry map that describes the adjacent area around the road network together with the dataset.

When it comes to localization within automotive there are a couple of ways to handle it. Two designs that have competed over the years are SLAM (Simultaneous localization and mapping) and Map-Matching. Both have their pros and cons but so far, to our knowledge, the Map-Matching is the one that have AD vehicles on the street. (Waymo, 2021)

Many open datasets lack repeatability. The datasets often only include information of a specific area that was collected once. This makes it difficult to ensure repeatability (robustness) for the systems that make decisions within a vehicle. Can you ensure that the vehicle will do the same thing every time even though the environment might have changed? Examples of changes in the environment might be worn out road lines, missing road signs and/or different weather conditions. Moreover, repeatability can enable crowdsourcing and scenarios where a fleet of vehicles with equipped sensors is assumed or expected.

Therefore, the project created an open dataset that has the same information as the previously mentioned open state of the art datasets for machine learning such as BDD100K, KITTI etc. and add a road geometry map layer, usually referred to as an HD-map (Heiko G. Seif, 2016) within the industry, to complement the dataset. Moreover, the project tackles the repeatability problem by collecting data in a closed and controlled environment in different conditions: Astazero test track. By utilizing AstaZero's test track, the amount of unforeseen and uncontrollable outer influences is as low as humanly possible. It also enables the possibility of making known changes in the environment and then collect new data for the dataset. Examples include small road geometry changes, e.g., as adding new road lines, changes in landmarks e.g., removing/adding traffic signs and the collection of data over different weather and light conditions. If the dataset includes repeatability and a corresponding HD-map, it can help increase development speed for the decision system that depends on machine learning and localization systems. It will also shorten the step from virtual testing and validation to physical testing and validation on AstaZero's test track.

The controlled changes made in the environment while collecting data for the dataset also opens the possibility of creating and validating algorithms that can detect changes in the

physical world, thereby enabling more opportunities for crowdsourcing. Crowdsourcing models are being developed throughout the map industry in the fields of map creation, map features extraction and map validation. By launching a dataset that forms a benchmark suite for localization and change detection algorithms to be validated, system robustness is increased and therefore the potential for crowdsourced maps and/or map features increases significantly.

The possibility of crowdsourcing measurements from different types of sensors is a powerful tool to collect data, but the measurement uncertainty needs to be validated to ensure reliable results. GNSS positioning and anchor points are today used to align collected data and merge it with existing maps. The quality of the map is therefore dependent on the positioning uncertainty of the anchor points as well as the performance of the sensors used to perceive the anchor points.

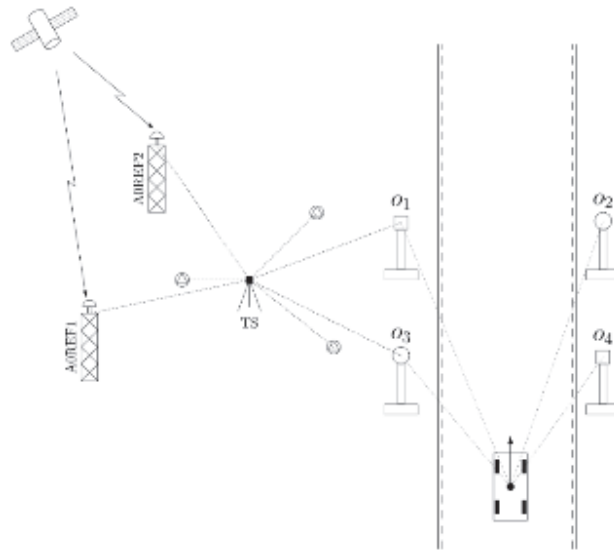


Figure 1: Illustration of how A0REF can be used to validate positioning of object observed by vehicle sensors. Position of the A0REF masts is determined by long term GNSS observations, while objects (O_1 - O_4) are related to A0REF and local reference points by total station (TS).

By using objects with accurate positions and well-defined geometries as anchor points the dataset will be traceable to, and validated against, the real world. This can be done by relating static and mobile objects to a geodetic reference frame such as SWEREF 99 (Jivall & Lidberg, 2000) or a local reference system such as AstaZero's A0REF, as illustrated in Figure 1. The positioning of the objects should be measured several times during the collection of the dataset to keep track of any drift of the anchor points themselves. In addition, it is possible that the objects can then be used to aid evaluation of sensor performance when collecting data at different vehicle speeds, weather conditions, seasons, and lighting conditions.

4 Purpose, research questions and method

The primary aim of the VAMLAV project is to advance the validation and evaluation processes of HD-maps for autonomous vehicles. By establishing an extensive dataset, integrated with an HD-map of the Rural Road at AstaZero, the project seeks to harness sensor data across diverse environmental conditions, providing a reliable base for testing and development. Furthermore, it intends to standardize anchor points, creating a unified system for future metrological evaluations. Central to this purpose is the enhancement of road safety, elevation of industry expertise, and the extension of virtual testing capabilities.

Some of the research questions that was raised in the project was the following.

1. **Dataset Creation:**
 - How can we comprehensively integrate an HD-map of the Rural Road at AstaZero with diverse sensor data?
 - In what ways does the time of day, season, and weather influence the collected sensor data on the Rural Road?
2. **Anchor Point Development:**
 - What are the ideal specifications and requirements for objects to serve as anchor points for HD-map validation?
 - How can these anchor points be effectively implemented at AstaZero for future metrological evaluations?
3. **HD-map Evaluation:**
 - How can HD-maps be accurately evaluated and validated against real-world scenarios?
 - What methods allow for effective coupling of datasets with traceable measurement uncertainties to common reference frames?
4. **Safety and Alerts:**
 - How will the integration of connected vehicles with HD-maps improve early warning systems for road changes and potential hazards?
5. **Building Institutional Expertise:**
 - What knowledge gaps exist within institutions like RISE, AstaZero and Zenseact concerning HD-map validation, and how can they be addressed?
 - How can the calibration and testing of AD positioning be improved through advanced reference systems?
6. **Sensor Evaluation:**
 - What methodologies allow for effective evaluation of sensor performance against standardized objects with verified positions?
 - How do different environmental factors, including weather and lighting conditions, impact sensor performance and algorithm efficiency?
7. **Virtual Testing:**
 - How can virtual testing capabilities be expanded to simulate localization systems and system robustness?

- In what ways can virtual testing environments replicate real-world challenges for sensors and algorithms?

Far from all these questions were answered, but they were thought of during the project and shows the amount of future research that is needed within the area. Also with legislation such as Intelligent speed assistance (ISA, u.d.) these questions becomes even more relevant.

5 Objective

The main objective of the project was to create an open dataset over Rural Road for self-driving cars. The dataset was intended to include HD-map data over the track Rural Road at AstaZero. In addition to the HD-map, the dataset would also include collected sensor data from the cars that have driven multiple laps around Rural Road in different weather conditions. The dataset was intended to help the development stage for robust ADAS and self-driving car systems. By providing an open dataset the hope was to encourage and increase the development speed of these AI systems that the automotive industry needs. The dataset can also be used as an early test and validation step for these system before physical testing is applied.

At the time of the project application there existed no datasets, known to us, of this kind that were open. Because the dataset would be made in a well-known and controllable geographic area and the fact that it would include repeatability and a corresponding map makes it one of a kind. The dataset will therefore enable the capability of more research within the fields: Mobility as a service, path planning, validation, crowdsourcing and community building. The project believes this kind of dataset will be in high demand and a requirement to test the decision and control system of an autonomous car that is reliant on computer vision in the future. The knowledge gained from this project has also expanded the testing and validation capability that AstaZero can offer the Swedish automotive industry and further develop knowledge about virtual testing.

The VAMLAV project also aimed at enabling future concepts for a collaborative approach to map updating and data acquisition. By having AI Sweden, industry, and institutions as partners in the project AstaZero hoped to promote cooperation between industry, universities, and institutions.

The idea is that other OEMs in the future have the possibility to upload more information/sensor data to our finished dataset, to really start the sharing of data and especially develop a hub for creating information about the road which is information that is very important from a safety perspective.

There also exists the possibility to look further into path planning algorithms in this dataset, because of the complementary HD-map. Which means users can do more of a whole system test with this dataset.

The way the project wanted to release the dataset and the fact that we have Zenseact as a project partner also opens the possibility of collaboration and using big data to develop system and

concepts when it comes to updating and making HD-maps based on the increasing number of vehicles with sensors and data sharing capabilities. In other words, more efficiently using the information the vehicle fleet gathers instead of heavily investing in new infrastructure which is in line with FFI sub-program A. By also being able to share information there exist a possibility to update them faster and thereby also react to changes in the environment faster, which is a very important feature from a safety perspective. At the same time the validation that RISE will be investigating in the project will contribute to making the HD-maps maps more reliable.

The objective changed little during the project. A lot of effort was put on the map validation work and how to validate a map. The issue here is how much trust can you have in the map over time and how to validate. Therefore, the project limited the scope a little and choose some scenarios related to safety. Also, a subset of the amount of drives became a dataset due to relevance and the issue that is releasing datasets that can include any GDPR info that makes the whole process expensive.

6 Results Methods and deliverables

The results of the project, methods used and deliverables produced are presented for each work package in sections 7 through 11, the results are summarised below.

The project has delivered:

- 20 RISE internal reports detailing the measurement analysis and results.
- Report - D2.1 Reference target specification.
- Updated public AstaZero OpenDRIVE Maps, with the updates based on Rise measurement campaigns during the project. published at AI Sweden
- Zenseact scenario documents.
- Zenseact data, sensor data published at AI Sweden.
- Changes in the environment at AstaZero for map-validation work.
- Semipermanent anchorpoint installed at AstaZero.
- VAMLAV dataset at AI Sweden (AI Sweden, u.d.)
- A highly stable mobile anchorpoint (A0REFM1)

6.1 Knowledge and Competence Development

VAMLAV has been instrumental in enhancing expertise and building knowledge in the domain of HD-map validation and evaluation, specifically for AstaZero, RISE, and Zenseact. The project has also augmented understanding of reference systems crucial for calibrating and validating AD positioning and HD-maps, with RISE spearheading these efforts.

The initiative has granted insights into the stability—both short-term and long-term—of various types of anchor points, benefitting both AstaZero and Zenseact. Furthermore, VAMLAV has allowed for an in-depth assessment of sensor efficiency, setting benchmarks using precisely defined objects with verified positions, primarily for Zenseact and potential future endeavors for AstaZero customers.

6.2 Impact and Contributions:

VAMLAV has been pivotal in catapulting AstaZero to the forefront of ADAS and AD testing, positioning it as a premier global testing site. Additionally, the project has expanded the horizons of virtual testing, enabling the virtual assessment of localization systems, system resilience, and the potential impact of varied weather conditions on sensors and algorithms in the preliminary development phase.

A cornerstone of the VAMLAV project is its alignment with the Vision Zero initiative. The dataset crafted during the project, comprising an HD-map, vision data from sensors deployed for autonomous driving, and several trials around Rural Road at AstaZero under diverse conditions, paves the way for virtual tests. This not only expedites development but also ensures cost efficiency, echoing the objectives outlined in sub-program A.

Further underscoring its commitment to Vision Zero, VAMLAV has enriched the available resources for testing the precision and robustness of localization systems for various autonomous vehicles, as elaborated upon in FFI sub-programs E and F.

6.3 External Challenges:

The global outbreak of COVID-19 has undeniably posed challenges. Such as major delays, one partner leaving the project and difficulties delivering on time.

7 WP2 Identify and Measuring Objects for Anchor Points

WP2	Identify and Measuring Objects for Anchor Points
Leader (role and responsibility)	RISE
Other participants (roles and responsibilities)	<p>Zenseact: Contribute with information about the objects they can detect. Help in discussions when designing the anchor points and if needed test so the anchor points can be detected by Zenseact's object detection algorithms. Provide input on where to place the anchor points at AstaZero.</p> <p>AstaZero: Contribute in discussions on the best suited areas along Rural Road to position the anchor points, so they don't interfere with other test track activities and then install the anchor points</p> <p>RISE: Write specification and design/build/buy the anchor points. Provide input on where to place the anchor points at AstaZero. Providing existing geodetic info for planning and interchangeability between SWEREF and A0REF, as well as establish a geodetic control network at AstaZero.</p>
Description of contents	<p>Identify what kind of objects our different systems can detect and how do we define some of their physical aspects.</p> <p>Write specification and build the anchor points that either represent an object that Zenseact's systems can detect or can be put on the object that can be detected without interfering with the object detection systems.</p> <p>Establish a geodetic control network at the AstaZero Rural Road test track.</p>
Method/approach (when relevant)	<p>Workshops to decide which objects can be used as anchor points in our maps. Try to design one mobile and one static object as anchor point for flexibility when placing the anchor point in other WP without losing too much accuracy. Document requirements & specifications, build and test the anchor points. After testing, install multiple</p>

	<p>anchor points with the density previously discussed in workshops at AstaZero Rural Road.</p> <p>Method development/planning for creating a reference system suitable for the anchor points.</p> <p>On-site surveys to establish geodetic relationships between new antennas (and to physical control points of A0REF in an applicable extent) and anchor points. Monitoring of established relationships throughout the project.</p>
Delivery	<p>2.1 : Requirements and specifications on anchor point objects.</p> <p>2.2 : Anchor points with defined geometries.</p> <p>2.3 : Test of anchor point objects, to make sure that all partners can use them.</p> <p>2.4 : Installation of static and mobile anchor points at the AstaZero Rural Road.</p> <p>2.5 : High-density scans of anchor points and their surrounding area.</p> <p>2.6 : Maintained geodetic control network for the duration of the project.</p>

WP2 ran for almost the whole duration of the project as it involved several measurement campaigns over time to maintain the geodetic control network and measure in all anchor points. This resulted in 20 Measurement reports from RISE detailing the work related to D2.6. D2.1 is a report available to all project partners (Hanquist & Bäckman, 2021), out of which some selected results are covered in section 8.1. D2.2 was reached by defining geometries of existing infrastructure, temporary road signs and the construction of A0REFM1 as described below. D2.4 was completed in May of 2022 with the installation of A0REFM1, a few weeks after that D2.3 was completed when Zenseact could confirm that all anchor points could be detected by their sensors. The D2.5 high-density scans were performed by laser scanner in two intersections with a high density of possible anchor points in April of 2021.

7.1 Requirements for reference objects

7.1.1 Requirements for connected- and AD/ADAS vehicles

The positioning requirements for connected vehicles (CV) differ widely depending on scenarios and level of automation (Williams & Barth, A qualitative analysis of vehicle positioning requirements for connected vehicle applications, 2020). Especially when considering CVs in the larger context of Cooperative, connected & automated mobility (CCAM). For example, when sharing area hazard warnings between vehicles, such as a segment of road being slippery in winter, positioning within 10 meters should be good

enough, it does not need to be more accurate as the road most likely is slippery for long stretches. The warning can be extended hundreds of meters from the detection and paired with similar warnings from other vehicles to give drivers entering the area a heads up. On the other end scenarios related to Vehicle-to-Everything (V2X) communication that is critical to the safety the requirements are higher and range from 0.1-1 m (95%) depending on application. AD/ADAS vehicles should at least be subject to the same minimum requirements as CVs, with requirements increasing with the level of automation.

7.1.2 Requirements for HD-map algorithm validation

HD-maps are sometimes likened to be used as an additional sensor for the vehicle (Giknes, 2019) (Providentia, 2021). To achieve this HD-maps strive towards being as accurate as possible to the real-world 3D environment. The positioning requirements of HD-maps differ depending on its intended use and if it is used in relative or absolute positioning. Most applications have positioning requirements ranging from 10 cm up to 5 m (95%) (Liu, Wang, & Zhang, High definition map for automated driving: Overview and analysis, 2020).

However, the HD-maps suffer the same problems as all maps. By definition they are instantly outdated as soon as they are created. This affects everything from less critical decisions such as simple navigation like where to turn left or right, passing through situational awareness map validation, e.g., accidents, hazard situations. All the way to dm-level maps where 3D objects are included, where objects can move from hour to hour, that literally are outdated as soon as something changes. To combat this, vehicles can update sections and context aware information of the map as they pass through it.

7.1.3 Metrology references

In metrology the focus lies in evaluating the measurement uncertainty from a combination of influential parameters which all affect the measurement, described in (BIPM and IEC and IFCC and ILAC and ISO and IUPAC and IUPAP and OIML). These parameters can be thermal gradients, repeatability, reproducibility, length dependent errors and much more. To correctly determine, quantify and sum them is often tricky as contributions are often underestimated or missed. A common mistake is to think that the instrument accuracy, instrument resolution, or the standard deviation of a measurement series is the same as the measurement uncertainty, when these often only are separate contributions. To estimate the measurement uncertainty correctly and can be very helpful in determining which parameters to compensate for to lower the measurement uncertainty further.

One such parameter is the reference standard used. In general, for calibration/validation the reference standard should have at least four to ten times lower measurement uncertainty than the system you want to calibrate/validate. Exceptions can be made but not without consequences.

A reference that is badly defined or unstable can significantly increase the measurement uncertainty, sometimes becoming the dominating uncertainty, which can make measurements useless if ignored. For example, a sturdy tripod with a lidar mounted on it can be set up in a room to measure how far objects in the room have been moved around during the day. This allows us to use the centre of the tripod baseplate where the lidar is mounted as a reference. The tripod itself can be accidentally moved either by someone bumping into it, or simply move by changes in the floor as the objects are moved about. Aside from these obvious factors the tripod itself is affected by mechanical stresses and thermal gradients which (at best) will slowly stabilise, introducing small movements as the tripod drifts into a stable position. If left ignored these changes in the reference can grow to become equal to or larger than the measurement uncertainty of the lidar itself. This can result in an underestimating the measurement uncertainty and putting too much trust in the measurement values. In our example this carry no real consequences but underestimating the measurement uncertainty in AD/ADAS vehicles can prove catastrophic.

The above example is an unstable reference that drifts over time, but a reference can also be badly defined, increasing the uncertainty in its position. A well-defined reference object is easy to relate secondary measurements to, or from, as it has a clearly defined point of reference. While a badly defined reference object has unclear definitions or other problematic properties which makes it difficult to use. An example of two references for 1D length measurements can be seen in Figure 2.



Figure 2: Comparison between two 1D length measurement references.

The chalk line is wide and has undefined edges which makes determining the centre of it hard, while the zero mark of the tape measure is a thin straight line which centre can be determined with significantly lower uncertainty. If one were to measure with the tape measure from the chalk line all measurements would inherit the uncertainty of both references. So, while a correctly used class I tape measure used for measuring a distance 10 m should be accurate to roughly 1.1 mm (95%). However, the actual uncertainty when measuring this distance with the chalk line being used as the reference might be closer to 1.5-2.0 mm (95%).

When moving from 1D to 3D measurements things become increasingly difficult but the principles are similar. Consider how to determine the position of an object with respect to its centre. If the object is a sphere, it is both easy to measure and has a well-defined centre. If it instead would be a hemisphere or a small segment of a sphere it becomes harder to measure and define the centre. In general, increased complexity of the object makes it harder to measure its position but can also make it hard to define where the objects centre is, increasing the uncertainty of positioning it with respect to its centre. This increasing complexity is further exemplified with three different types of objects in Figure 3.



Figure 3: Objects that illustrate increased complexity in determining the centre of the object. Glass sphere used for daily control of a coordinate measuring machine (left). Glass hemisphere used to as a reference in roundness measurements (middle). Coordinate measuring machine evaluation gauge (right).

In this example it becomes rather obvious that defining the centre of the object to the right can be difficult under the best of circumstances. If the object is only measurable from one direction where some features are hidden it might increase the measurement uncertainty exponentially.

This also highlights another question with regards to definitions, what do we mean by the 'centre' of the object? To be able to position the object in 3D with respect to its centre it requires that the centre of the object is defined. Is it the geometrical centre of the object, the centre of a 3D boundary box that the object fits within, the optical centre from a 2D image, the mass centre, the point of maximum intensity of radar reflections or the centre of a lidar point cloud. If the above definitions are taken to be exactly the same, it can introduce unnecessary errors depending on the application. Applying this to vehicle sensors mean that the radar, lidar and camera most likely perceive different centre points and depending on the object they can differ significantly. An additional problem with unclear definitions is that the centre might be defined differently between developers, map makers and vehicle manufacturers. While not critical in many cases it should be accounted for if one wants to be confident in the measurement uncertainty of a system.

If definitions are not accounted for it is entirely possible that reference objects are misused and trusted for definitions which they are not applicable for. For example, a road sign can be defined as the central base of the pole the sign is attached to, this point can be absolutely positioned with a 3D expanded measurement uncertainty of 4 cm (95%). This sign is then used as a reference in a vehicle where lidar identifies the road sign and takes the reference uncertainty to be applicable to the centre of the point cloud building up the sign. This use of the reference ignores several contributions such as pole movements,



Figure 4: Illustration of how an expanded 3D measurement uncertainty valid for the bottom of the pole can't be used as a reference value for the centre of the sign due to other uncertainty contributions such as the tilt of the sign.

pole tilt and radial offset of the sign from the pole centre, see illustration in Figure 4.

The reference measurement uncertainty is simply not valid for that definition of the sign. This erroneous measurement can then be used to update HD-maps with, resulting in an untrustworthy HD-map which is built upon underestimated measurement uncertainties.

To avoid the problems highlighted in this section anchor points should be chosen or designed with metrology in mind. They should be stable over time and have well-defined

geometries as well as coordinate systems which makes it easy for anyone using the reference.

7.2 Road sign definitions used in the project

As described above, objects need to have a clearly defined reference point and coordinate system to minimise measurement uncertainty. After measurements of several road signs with a laser scanner there was enough data to be used as input for a definition, see Figure 5.

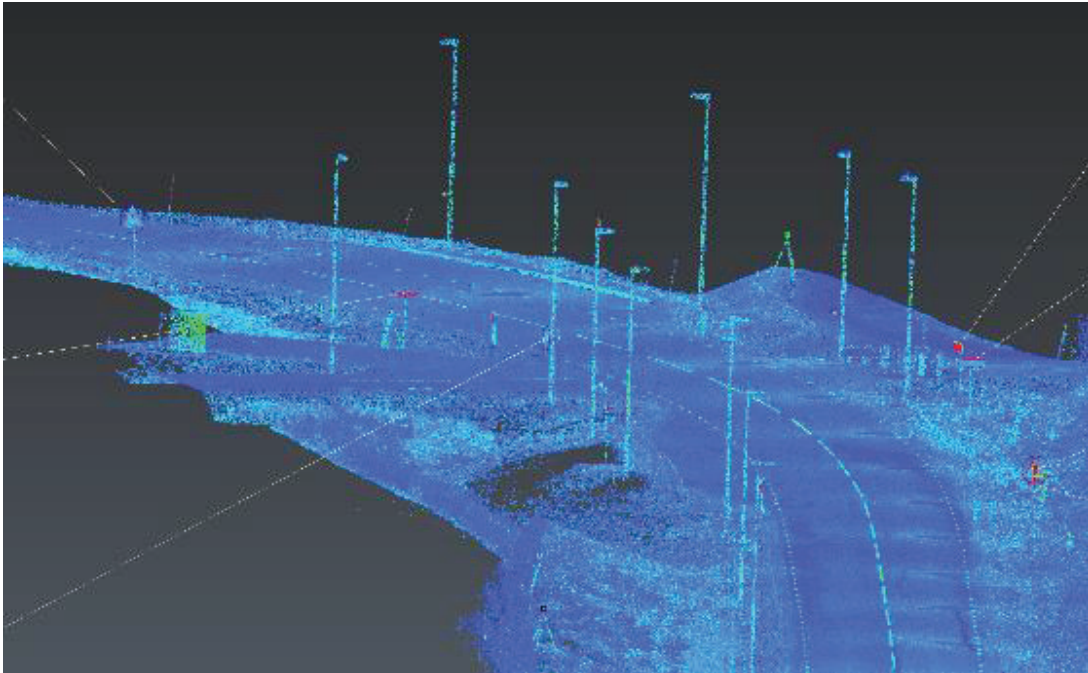


Figure 5: Example of the laser scan data used as input for creating a road sign definition.

The road signs and their reference points were to be defined based on the three requirements:

1. The definition should make sense from the perspective of sensors in a vehicle
2. The definition should be measurable in the point cloud from the laser scanner
3. The definition should minimise the measurement uncertainty if possible

The first criteria forced the definition of the signs to be a plane which is aligned with the front of the signs, preferably bounded by the sign's edges. This also requires that the reference point can be related to the plane in some way, either by an offset correction from other parts of the signs supporting structure or the placing point being in the plane.

The second criteria created a problem as the front of most road signs are highly reflective. This makes measurements with a high angle of incidence impossible for laser equipment as it is simply reflected away, while a low angle of incidence can be noisy due to the high reflectivity. This directly forces some compromise to be made with respect to the third criteria, which otherwise would be best fulfilled if the measurements could be taken in the plane where the sign is defined. Instead of taking the front of the signs, the back was used with the front only being used to complement the backside measurements if the noise was low enough. This means that the thickness of the sign is included as a measurement uncertainty, but this is still lower than if any other part of the signs supporting structure would be measured with a corrective offset.

The definition used in VAMLAV for road signs was:

A plane aligned with the front of the sign, preferably bounded by the physical sign edges, with its point of reference for positioning being the centroid of the sign.

This definition is both usable by various vehicle sensors as well as high-end metrological equipment. It minimises the need for corrective offsets and their unnecessary uncertainty contributions. The dominant uncertainties become the performance of the instruments used, the post processing and the link between local coordinate systems of the instruments and global coordinates with the help of GNSS systems.

Signs that are square or rectangular in shape respectively can have their plane constructed from the detectable contour of the sign edges which can be used to create a rectangular plane. The centre of this plane is then taken as the point of reference for the positioning.

Signs that are triangular with rounded edges poses a problem as it can be troublesome to find the centroid of the triangle. Therefore, an intermediary step is used where the sides of the triangle are extrapolated out to where they intersect. These three intersecting points are then used to create a circular plane which is used as a reference plane, and which has the same centroid as the triangle. An example of this can be seen in Figure 6 below.

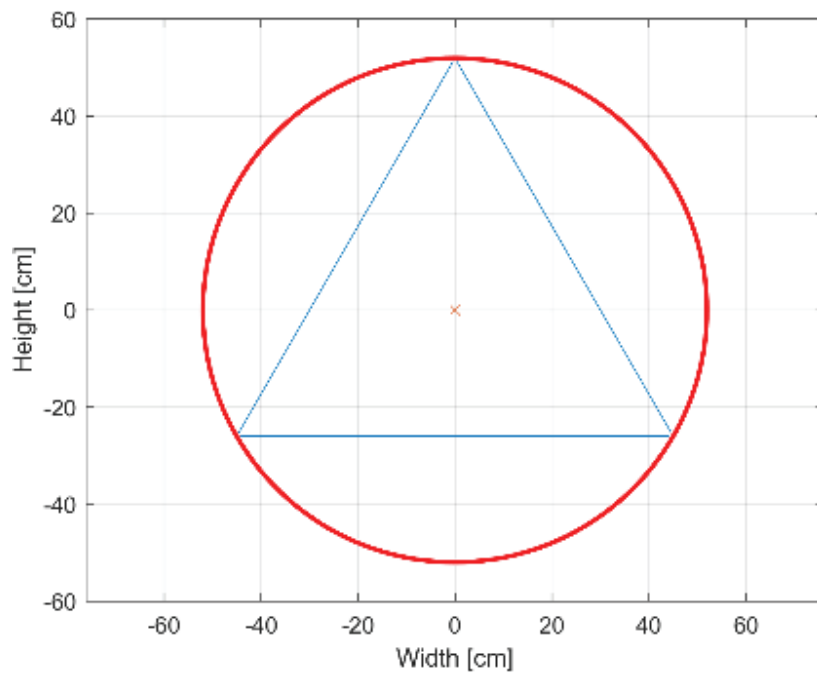


Figure 6: Centroid of a triangle and the circumscribing circle constructed from its three corners.

7.3 Stability classification of objects

For an anchor point to be used as a positioning reference with metrological requirements it does not only need to be at least four times better, it also needs to be stable over time. With this in mind Table 1 was created early in the project to be used when designing anchor points. It classifies the lowest positioning uncertainty over time that can potentially be achieved.

Class 1 objects mounted on solid bedrock have great short-term stability and it also gives them the greatest chance of being stable over several years. Objects in class 1 are often used for high grade NRTK-GNSS reference stations and other long term reference points. The official reference frame used in Sweden (SWEREF 99) was realised with 21 stations of this type (Lantmäteriet, u.d.). To reach this lowest level of positioning uncertainty requires years of continuous GNSS measurements and one needs to consider several factors such as satellite orbits, ionosphere models and continental drift.

Table 1: Early classifications in the beginning of the project for anchor points objects based on their estimated stability

<i>Class</i>		<i>Object</i>	<i>Timeframe for stability</i>	<i>Positioning over time 2σ ($\approx 95\%$)</i>
1	A	Concrete reference object on bedrock	Decades	<10 mm
	B	Pillar/mast on bedrock		<10-30 mm
2	A	Pillar/mast on concrete fundament	1 Year	20-50 mm
	B	Guard rails		30-? mm
	C	Road sign		30-80 mm
	D	Reflective poles		30-? mm
3	A	Mobile road signs	Days	30-? mm
	B	Traffic cones etc.		50-? mm

Class 2 objects are more common objects that can be found in road infrastructure today. These objects are only as stable as they were constructed to be, for example there is almost always some room for movement in road sign poles placed in a concrete base. These bases are often anchored in the gravel by the roadside, beneath the road surface or simply placed on top of the road surface. This makes them sensitive to positioning errors caused by outside interference from vehicles and passers-by, but they are also affected by rainwater, wind, and the yearly frost-thaw cycle. To reach the lowest positioning uncertainty with class 2 objects one needs to design objects in this class to be as stable as possible by eliminating sources of drift and increasing the mass of the objects to make it less prone to outside influence. To maintain a low positioning uncertainty of the objects one needs to either monitor the objects continuously or remeasure them with set intervals and account for any drift.

Class 3 objects can have good short-term stability but should not be used as positioning reference for longer periods of time. Their position is easily influenced by accidental movements, wind, vehicle turbulence and vibrations to list a few. With this said they can still be used as anchor points if their position is measured before and after their use. If excessive drift is observed between the measurements the results from the affected tests may have to be discarded or the positioning uncertainty of the reference can be increased to include the drift and the results be used accordingly.

7.4 Reference objects used in the project

7.4.1 Temporary road signs

A commercial temporary road sign warning for road work ahead was procured by RISE and denoted 'RW1', see Figure 7.



Figure 7: Temporary road works sign denoted 'RW1' used in the road work scenarios.

An uncertainty analysis was performed for the road sign with respect to the stability when measuring the object at the base and correcting the position to the centroid of the sign. The dominating uncertainty in the positioning was the error in the horizontal plane if the position was adjusted without considering which angle it is tilting gravimetrically. If the tilt of the road is compensated for the dominating uncertainty instead becomes the GNSS systems performance and the drift of the sign. The expanded 3D measurement uncertainty for the sign centre during the project was between 4.1 and 5.3 cm.

In addition, AstaZero had a different type of road sign, denoted 'RW2', see Figure 8.



Figure 8: Temporary road works sign denoted 'RW2' used in the road work scenarios.

For this sign a measurement uncertainty analysis was performed in the field. The decreased stability of the sign and a heavier gravimetric tilt where it was placed increased the expanded 3D measurement uncertainty for the sign centre to between 6.7 and 7.8 cm.

7.4.2 Mobile class 2A anchor point – A0REFM1

Within WP2 a mobile class 2A anchor point was constructed see Figure 9.



Figure 9: Anchor point A0REFM1 placed in the field at AstaZero.

It was named ‘A0REFM1’ as it could be included as a mobile part (M1) of the local reference network being developed on AstaZero (A0REF), which today consists of three Class 1B stations, out of which one is an active part of Swepos (Lantmäteriet, u.d.).

A0REFM1 was installed in May of 2022 and consist of a concrete base measuring (1.3x1.3x0.5) m for stability with a 3.0 m truss mast mounted on top. The mast itself has 8 centering plates as mounting points for magnetic retroreflector holders, one in each corner of the mast top and base. These are to aid in determining global orientation of the mast with GNSS and total stations.

On the middle of the mast is a tripod type arm mounted which can hold standard road signs, which were used as the reference object in VAMLAV. On the top of the truss mast is a 5/8” thread for a GNSS surveying antenna to be mounted, this enables the position and stability of the mast to be continuously monitored.

The equipment used to monitor the position of A0REFM1 was placed in the cabinet on the truss mast, see Figure 10.

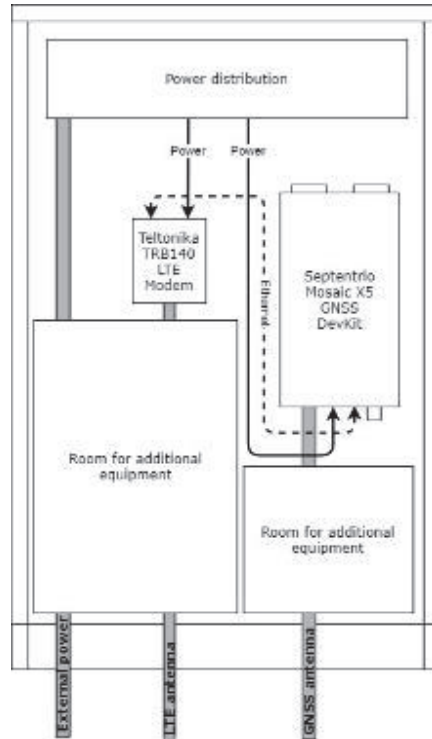


Figure 10: Equipment in the A0REFM1 cabinet.

It consisted of a Septentrio Mosaic X5 DevKit GNSS receiver used together with a Leica AS11 GNSS antenna. The receiver was connected to a Teltonika TRB140 LTE modem used together with a macab Pro-5000 LTE antenna. The system was then setup to collect RINEX data every 30 s and push it to a RISE FTP through AstaZeros LTE network.

7.5 Existing infrastructure as reference objects

Using existing infrastructure as anchor points is the easiest way to approach referencing data collected. In this case the objects in question must be geo referenced and any uncertainty contributions considered. This can be problematic as standard road signs easily can move centimetres, if not decimetres, by having a moderate breeze blowing in another direction. Measuring in these objects with NRTK-GNSS for example would not help much as the dominant uncertainty would be their stability. This was confirmed with an investigation of some of the objects on rural road.

In October 2020 a total of 78 different roadside objects on rural road were rated for stability, 9 of them were stable enough to be considered as very good candidates for references. Damages or excessive tilt directly disqualified 10 of the objects and the remaining 59 easily showed movements in several centimetres at the height of the signs.

It is worth noting that out of the 9 objects with good stability 6 were truss masts and 3 were road signs, all of which had significantly larger concrete fundaments than other objects. Considering this it was considered very likely that the stability of the reflective poles and guard rails were much more useful as anchor points. The reflective poles reach further underground than the anchor of typical road sign poles, are shorter and less top-heavy. All of this contributes to less movement of the poles, possibly making them more stable than road signs over time. The guard rails also reach deep into the ground to be able to counteract vehicles colliding with them and were therefore also considered to be good candidates. Some of these objects were chosen to be investigated during the project, see Figure 11.



Figure 11: Existing infrastructure other than road signs which were investigated. Left to right: reflective poles, cable crash barriers, classical w-shape crash barriers and pipe crash barriers.

7.5.1 Object positioning in the project

Over the duration of the project several measurement campaigns were made to measure in the existing infrastructure on AstaZero. The objects were measured over a year apart from each other and had their new position compared to their old position. The positions are compared in the coordinate systems SWEREF 99 TM (Lantmäteriet, u.d.) and SWEN17_RH2000 (Lantmäteriet, u.d.).

The results are shown below as a difference taken as (*new* – *old*), meaning for example that a positive difference in the east direction means that the object has drifted to the east. This difference is shown together with error bars for the respective 3D expanded measurement uncertainty for each measurement.

The positions of the measured infrastructure on AstaZero during the project is shown in Figure 12.

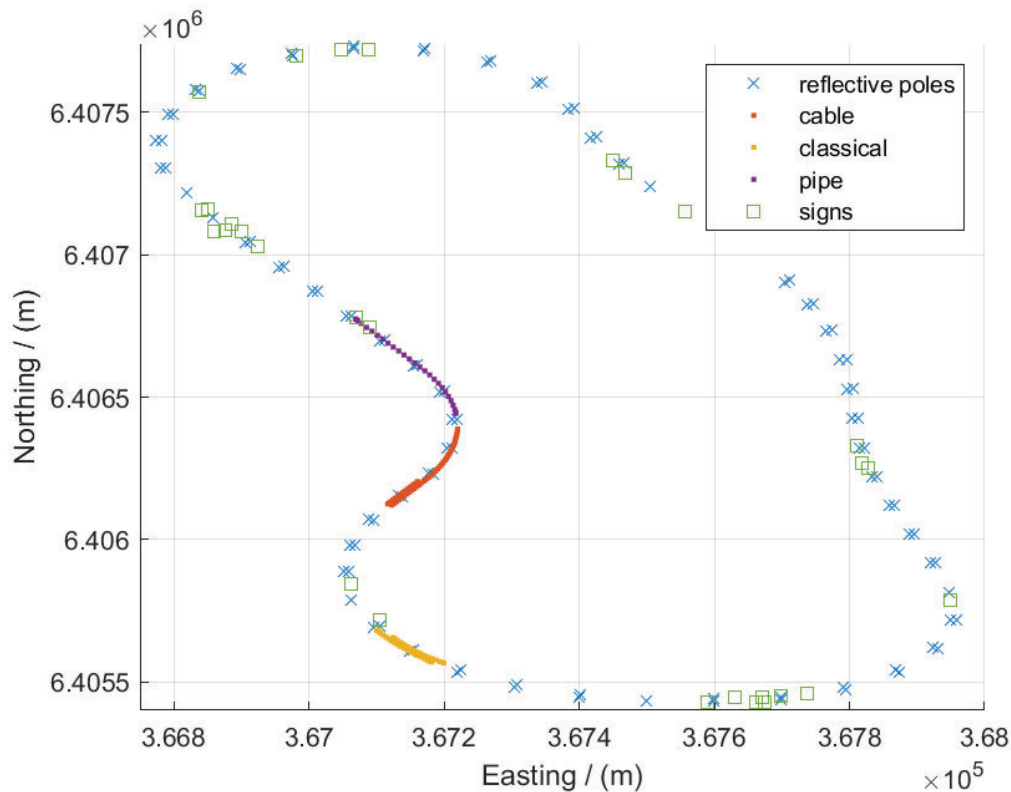


Figure 12: SWEREF 99 TM positions of the infrastructure measured around Rural Road on AstaZero.

7.5.2 Reflective poles

During the project all standing reflective poles around the Rural Road circuit were measured. The poles themselves can be seen by various sensors and the centre position of the poles is good enough for many systems, but it was also discovered early in the project that the reflectors could be clearly detected by radar. So, the pole centre positions were corrected for reflector centres of the poles to lower the positioning uncertainty, which otherwise would have to include the offset from the pole centre.

The poles were measured 2021-01-20 and re-measured in 2022-06-09. The result of the comparison between the two measurements is presented in Figure 13. The results show that the poles are in general stable, a few of them have drifted between 5-10 cm, but most of them show no significant change in the north and east coordinates.

There is a noticeable difference in height, this is however not caused by drift, but is an error thought to be introduced by the instrument setup. To be specific, the RTK-GNSS instrument used in these measurements were updated from an outdated geodetic model SWEN08_RH2000 to SWEN17_RH2000 between the measurement campaigns.

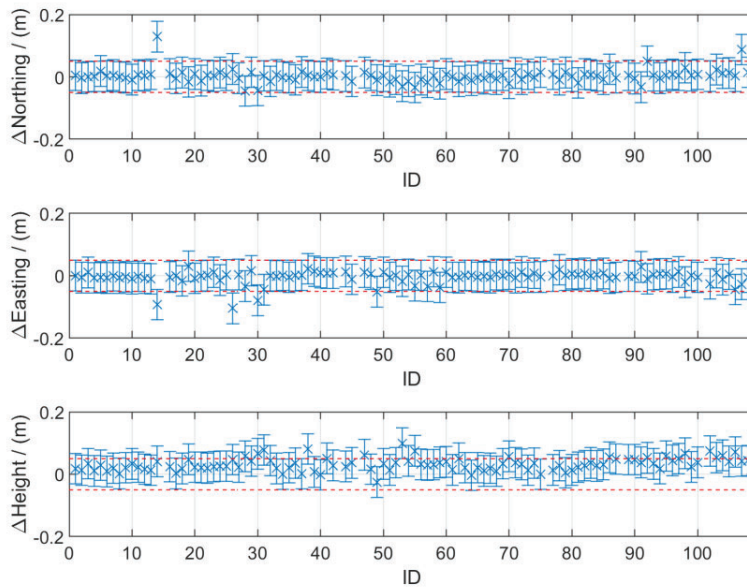


Figure 13: Difference in coordinates between new and old measurements of the reflective poles. The 3D expanded measurement uncertainty for the new and old positions are the blue error bars and red dashed lines respectively.

7.5.3 Crash barriers

Three types of crash barriers were measured, see Figure 11. As with the road sign definitions in the project the position to be measured here was one that would make sense to a vehicle sensor. Therefore, the mass centre of the classical barrier, the poles of the cable barrier and the centre of the two pipes were defined as the points of reference. The reason being that these points should correlate with the largest detection likelihood with camera, lidar, and radar.

The cable barriers were measured in 2021-03-16 and re-measured in 2021-06-09. The result of the comparison between the two measurements is presented in Figure 14.

The classical barriers were measured in 2021-03-16 and re-measured in 2021-06-09. The result of the comparison between the two measurements is presented in Figure 15.

The pipe barrier was measured in 2021-05-18 and re-measured in 2021-06-09. The result of the comparison between the two measurements is presented in Figure 16.

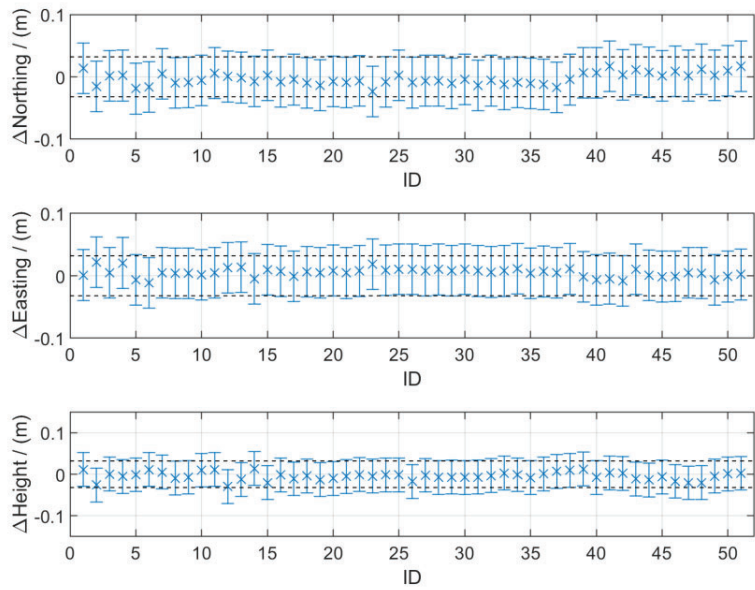


Figure 14: Difference in coordinates between new and old measurements of the cable barriers. The 3D expanded measurement uncertainty for the new and old positions are the blue error bars and black dashed lines respectively.

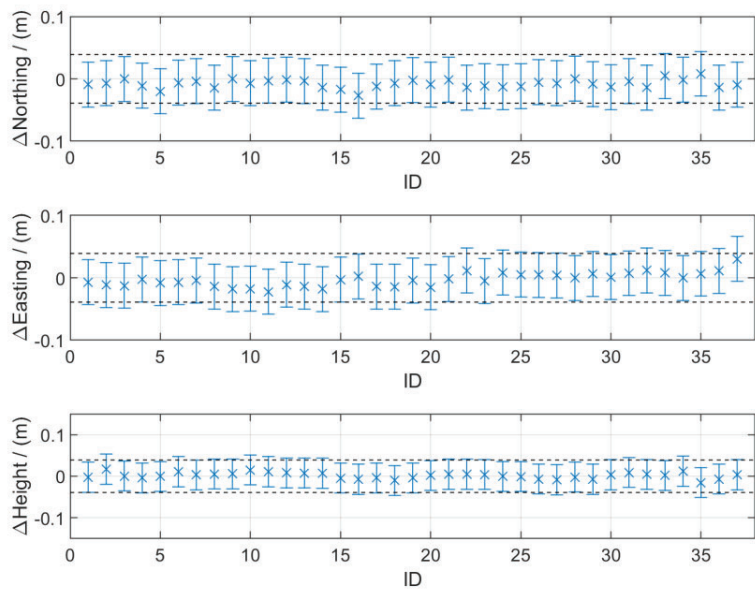


Figure 15: Difference in coordinates between new and old measurements of the classical barriers. The 3D expanded measurement uncertainty for the new and old positions are the blue error bars and black dashed lines respectively.

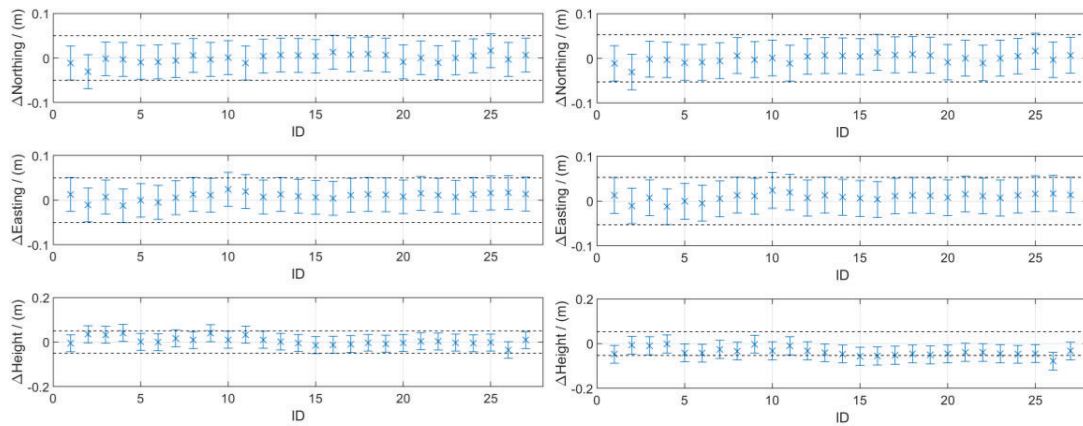


Figure 16: Difference in coordinates between new and old measurements of the pipe barrier for the upper (left) and lower (right) pipe. The 3D expanded measurement uncertainty for the new and old positions are the blue error bars and black dashed lines respectively.

All barriers were very stable over the time they were measured. The one notable difference is the pipe barriers height, which is slightly worse, also where the lower pipe was worse off than the upper one. This could probably be caused by an error in estimating the height offset between the measurement point and the lower pipe, or simply an underestimation in the uncertainty of this correction.

7.5.4 Road signs

The road signs were originally planned to be measured in two areas of interest where there were a lot of road signs, see northwest and south cluster in Figure 12. This was done in 2021-03-16 with a Leica HDS 7000 laser scanner which was geo referenced with laser scanner targets positioned with an RTK-GNSS system. This initial measurement had a 3D expanded measurement uncertainty of under 4 cm. Towards the end of the project this resource was not available, so they were measured in at their concrete base by RTK-GNSS instead. However, there was not enough resources left in the project to do a proper height correction with a measurement uncertainty analysis. Instead, the uncertainty was increased, and the position was only compared in SWEREF 99 TM. The result of this comparison for a few of the signs is shown in Figure 17.

The large difference is caused by not correcting for the offset between the road sign centre and the measured point, the main error source being the tilt of the poles, see sign ID 4 as an example. This result gives little information about the stability of the road signs, but it highlights the importance of positioning errors that occur from not measuring at the same point of an object with different systems. If uncorrected, huge errors can arise or uncertainties increase significantly.

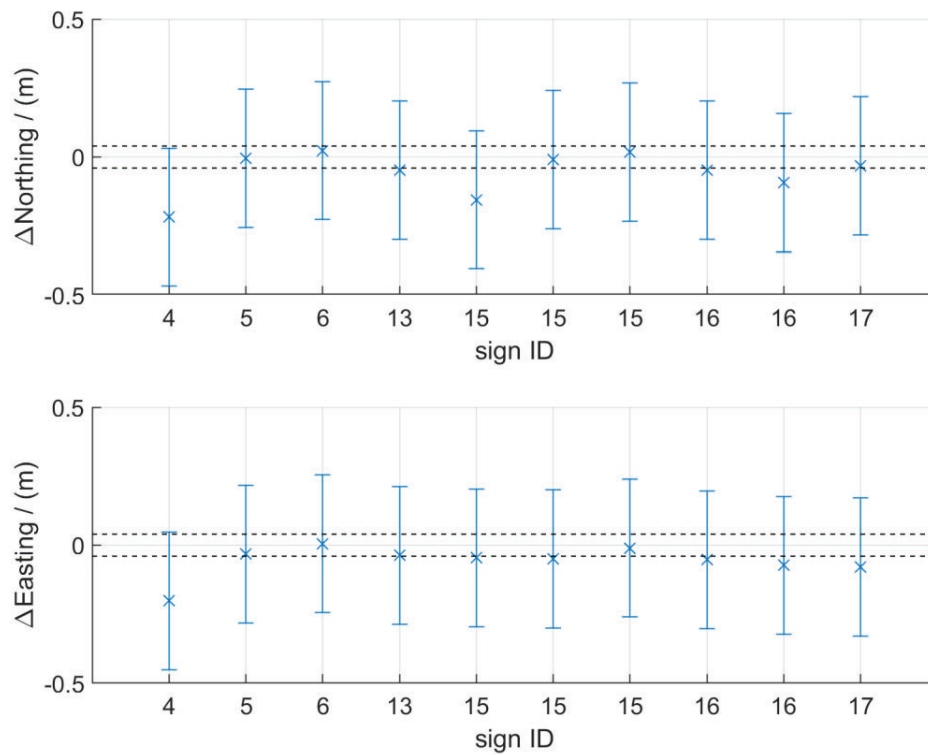


Figure 17: Difference in SWEREF 99 TM between new (RTK-GNSS) and old (Laser scanner) measurements of the a few of the road signs. The 3D expanded measurement uncertainty for the new and old positions are the blue error bars and black dashed lines respectively.

7.6 Choosing reference objects

Based on measurement results during the project Table 1 was adjusted with improved estimates, shown in Table 2. Overall, the positioning over time was increased from mm to cm as to better indicate the uncertainty in the stability.

Table 2: Classifications of anchor points objects based on their estimated stability adjusted after project results from measurement campaigns.

<i>Class</i>		<i>Object</i>	<i>Timeframe for stability</i>	<i>Positioning over time 2σ ($\approx 95\%$) [cm]</i>
1	A	Concrete reference object on bedrock	Decades	<1
	B	Pillar/mast on bedrock		<1-3
2	A	Pillar/mast on concrete fundament	1 Year	1-3
	B	Guard rails		1-4
	C	Road sign		5-15
	D	Reflective poles		1-5
3	A	Mobile road signs	Days	1-10
	B	Traffic cones etc.		1-100

Class 2 objects were measured in separate campaigns, and it was shown that both 2A and 2B objects were more stable than initially thought, while road signs were much more unstable than initially estimated. Class 3 objects are often very susceptible to outside disturbances and was found to drift significantly more than initially estimated.

7.6.1 Class 2 objects adjusted stability

The anchor point constructed within the project had an antenna mounted 3.5 m above the ground which was monitored with GNSS which was then post processed to a RTK-GNSS solution. Between 2022-05-06 and 2022-06-25 this resulted in a standard deviation in the horizontal plane of 8.2 mm with a 3D standard deviation of 16.7 mm. Since the road sign was mounted at an arm roughly 2,3 m above ground it should have a better stability than what was measured by the antenna.

Three different types (wire, pipe and w-shape) of guard rails were measured in the project and their mean drift ranged from 1.6-2.2 cm. This stability is likely an effect of the depth into the ground they need to have to be able to act as crash barriers. This means that they can act as one of the more stable reference objects found in existing infrastructure. On the other hand, if they have performed the task they were constructed for, stopping a vehicle from going of the road, they will be unable to act as a reference anymore. So, to properly

use them as references one needs to be able to determine if they have been damaged or not, which could be tricky.

The mean drift of the reflective poles investigated was 2.8 cm, also an effect of how deep they are installed into the ground. Not as stable as the guard rails, but on the other hand they are far more common on the road. If they have been hit by a vehicle they are often destroyed or have tilted over heavily, which is easier to spot compared to damage on guard rails.

Road signs were surprisingly unstable, this is caused by having the long pipe simply sliding down in a concrete base that is sitting in gravel. The gap between the base and pipe can itself allow for several centimetres of movement of the road sign centre, which can easily be moved by wind. Then the base stability is only as good as the installation in the ground, sometimes the base is not covered properly by gravel, which when mounted in the slope of a ditch means they can tilt heavily. Movements over time, together with frost and thaw cycle, can create gaps between the gravel and the base, which can easily result in 10 cm movements of the sign centre.

7.6.2 Class 3 objects adjusted stability

The mobile nature of class 3 objects makes them drift quite a lot compared to others, mainly from outside mechanical influence but also from wind and vibrations. During the project they drifted significantly more than any other objects. The act of measuring them could often be enough to make them move, even the ones with sturdy bases. A cause for this could be human subconscious carelessness, if you think “this object is not that important” you could subconsciously be less careful when handling it. The opposite is often true in laboratory visitors, the visitor is often very cautious as they do not know what to touch without damaging it because “everything is probably important and sensitive”. So, it stands to reason that the carelessness could arise in a similar way.

As an example, the ‘RW1’ road sign drifted between 0.4 and 1.3 cm when used in the project, while ‘RW2’ drifted between 1.5 and 2.6 cm. The main cause for this is probably that the ‘RW1’ sign can be measured without moving it and had well defined holes that could act as measurement points. While the ‘RW2’ sign had no well-defined points to measure, so the measurement points were defined by using a folding rule. The ‘sign’ part also had to be removed from the base when measuring the sign.

Temporary lane markers were also laid out on the track in the road work simulations, these drifted between 4.8 and 6.9 cm during all scenarios. They are much lighter and can move from the car driving over them, wind or simply someone nudging them.

A Vulnerable Road User (VRU), a doll on a heavy base, was also used in the project. The doll itself was not very stable and moved around in the wind a lot, as such it was not easy to measure. Instead, the base was measured, resulting in drifts between 0.3 and 35.0 cm, where the largest drifts were caused by the doll falling over and having to be fixated to

the base again. While the base was very stable nothing could be said of the doll, which is the object of interest for AD/ADAS vehicles, so the measurement uncertainty for the object was simply increased to fit in any drift, rotation, and movements of the doll.

7.6.3 Choosing reference objects based on stability and function

When considering the results from WP2 the choice of reference objects should be considered together with the level of performance needed. For tasks where positioning requirements are high, objects that are clearly defined, with a suitable stability and clear detectability should be the goal. For low positioning requirement tasks even temporary objects can be of use, but an additional uncertainty should be included when they are being used. As for the object above the recommendations are as follows.

Road signs

Road signs are probably most useful for what they are constructed to provide, giving information regarding traffic situations and rules. Their poor stability, design difference and differing mounting points include too many possible errors with regards to positioning. They should therefore be used mainly in very coarse positioning.

Reflective poles

The reflective poles of the type investigated in this project were surprisingly stable throughout the project. If hit by a vehicle, chances are it will be destroyed or have large enough deviations to be discounted simply by looking at the measurement data. Having references that are clear if they are damaged or not is beneficial as they can be flagged in the HD-map and ignored, something that is much harder for other objects whose stability might have been impacted but show no clear indication of this. This together with the vast quantity of them probably make them a good candidate as positioning references. In poor conditions, winter especially, they are probably a suitable candidate to replacing lane markings in certain positioning tasks.

Crash barriers

Crash barriers are as expected very stable for the most part. However, it was observed within the project that barriers that have been hit by a vehicle can sometimes be moved by hand several centimetres without showing any indication of having been hit. This might not impact their function, but it makes it hard or near impossible to identify which barriers have a reduced stability. Variations in their construction, placement and quantity on the road might make them slightly less useful as references compared to reflective poles.

Temporary objects

In general, temporary objects are great for testing function and detection. However, they should not be trusted as positioning references since they can be moved by everything from wind to a person bumping into them. If temporary objects are used as position references their position should be monitored by means suitable to the task they are used as a reference for. Meaning that if a temporary object is used to verify 8 cm (95%) positioning performance by a certain sensor, the temporary objects position uncertainty (including stability and drift) should be lower than 2 cm (95%). This can quickly become impractical or impossible to achieve due to stability and drift.

Purpose-built references

For performance testing and validation purpose-built objects beat everything else as they can be designed for a specific test or sensor in mind. Instability and uncertainties can be eliminated in the design phase, and they can be monitored over time. The obvious drawback is a high cost which makes it unreasonable to establish vast quantities of them. They most likely make the most sense on test tracks and alongside research and development. It is however a valid idea to have some high-quality references out in traffic which vehicle systems can be verified against. Whether it would be a few purpose-built references on select locations or some objects already existing which can be monitored in some way to assure quality remains to be seen.

8 WP3 Update Existing OpenDRIVE

This section will describe the OpenDRIVE HD-map what it is, how it was maintained and changed during the project. How they compare to the RISE measurements and the code libraries used and developed during the project to be able to handle the HD-maps.

WP3	Update Existing OpenDRIVE Map
Leader (role and responsibility)	AstaZero
Other participants (roles and responsibilities)	<p>Zenseact: Give information about all objects their object detecting system can detect and provide information about how they define the objects position.</p> <p>RISE: Provide the high-density scans and geodetic relationship for the anchor points and surrounding area from WP 2.</p>
Description of contents	Update the existing OpenDRIVE map of Rural Road to an HD-map and with the necessary objects that other project partner's needs. Integrate the anchor point and align the map with the measured anchor points.
Method/approach (when relevant)	<p>Workshop where we describe all the necessary objects for all project partners and their definitions.</p> <p>Put the necessary objects and anchor points in to the OpenDRIVE map. The added information to the OpenDRIVE map will be extracted with a mixture of LIDAR measurement and by measuring object with the geodetic control network (the anchor points).</p>
Delivery	<p>3.1 A complete High Defined OpenDRIVE map over Rural Road at AstaZero. With all the necessary objects and anchor points.</p> <p>3.2 When new anchor points are installed or moved at AstaZero. The OpenDRIVE map will be updated accordingly with new tags describing the anchor points.</p>

WP3 ran for the whole duration of the project, tools and maintenance of the maps were developed during the project and small POC were created that expanded on HD-map creation, not only updating existing OpenDRIVE HD-maps. Following subchapters describes the changes done, comparison to RISE and tools developed and used during the work package.

8.1 HD-Map OpenDRIVE

OpenDRIVE (ASAM, u.d.) is an open-source file format maintained by ASAM (Association for Standardization of Automation and Measuring Systems, u.d.) specification for representing road networks and their attributes. The format was developed by a consortium of companies and research organizations, including Audi, BMW, Daimler, and the Fraunhofer Institute for Computer Graphics Research. OpenDRIVE provides a detailed representation of the road geometry, including the shape, width, and curvature of the road, as well as the lane markings, traffic signs, and other infrastructure elements along the road.

OpenDRIVE has numerous applications in the field of testing and validation of autonomous vehicles. One key use case is the development of simulation environments for testing and validating autonomous vehicle control systems. OpenDRIVE can be used to create 3D simulations of real-world road networks, enabling developers to test the performance of autonomous vehicle control systems in a variety of scenarios, including hazardous weather conditions, complex traffic patterns, and unexpected obstacles.

Another application is the development of HD-maps for autonomous driving. HD-maps are highly detailed maps that include information about the road geometry, such as the location and shape of obstacles, as well as the location of infrastructure elements along the road. OpenDRIVE can be used to create these maps, which can be used by autonomous vehicles to navigate the road network safely and efficiently.

While OpenDRIVE has numerous benefits for testing and validation of autonomous vehicles, there are also several challenges associated with its use. One key challenge is the creation and maintenance of accurate and up to date OpenDRIVE files. As road networks change over time, it is essential to ensure that the OpenDRIVE files used for testing and validation reflect these changes.

Another challenge is the integration of OpenDRIVE with other simulation and testing tools. To be effective, OpenDRIVE must be integrated with other tools used for testing and validation, such as simulation engines and testing frameworks. This integration can be complex, and it is essential to ensure that the various tools work together seamlessly.

In conclusion, OpenDRIVE is a valuable tool for testing and validation of autonomous vehicles, with numerous applications in the development of simulation environments and HD-maps. However, there are also several challenges associated with its use, including the creation and maintenance of accurate OpenDRIVE files and the integration of OpenDRIVE with other testing and simulation tools.

8.1.1 OpenDRIVE at AstaZero

AstaZero provides a public OpenDRIVE map of a part of its test-track called Rural Road. This was based on a map created by a third-party company called 3D-mapping that created it by the request from AstaZero. This was a procedure of scanning the whole track and generating the OpenDRIVE map from the data. This had uncertainties that varied from the optimal 1-3 cm to a worst uncertainty of about 30 cm depending on external factors such as weather and conditions. This map will also be updated with the differences found from the measurements provided by RISE and saved into a few variations based on the times that the data from RISE was measured.

The following pictures shows the Rural Road OpenDRIVE map opened in an application called RoadRunner (MathWorks, u.d.), an application that has support for the OpenDRIVE specification and can render it to a 3D image. Figure 18 shows the rural road as described in RoadRunner as a purely OpenDRIVE representation.

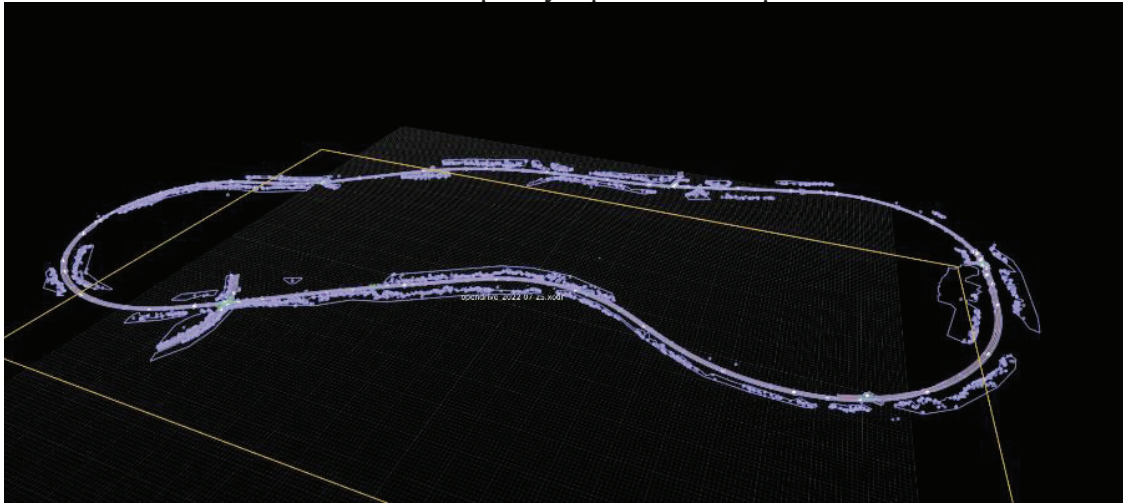


Figure 18 RoadRunner OpenDRIVE 3D Representation of Rural Road in AstaZero

Figure 19 shows the same map but where the objects and road have been assigned models and meshes as to give a more realistic look regarding how the road might look. Note that these models and meshes were chosen from the available resources and as such can only be considered an example representation, not taken directly from the road.

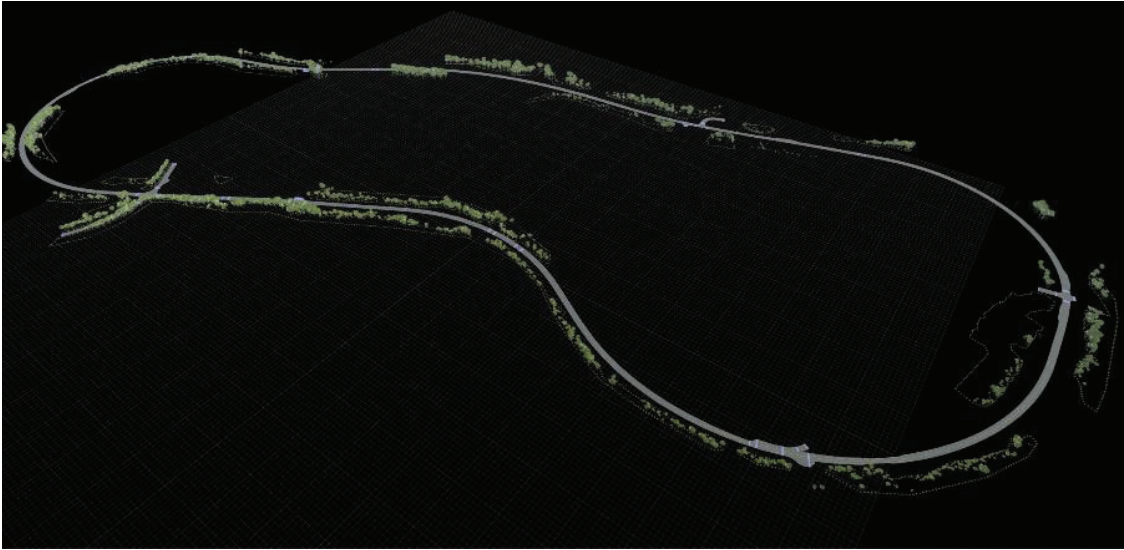


Figure 19 RoadRunner 3D repr. models and mesh Rural Road, AstaZero

Figure 20, Figure 21 and Figure 22 are variation of the same road, focused on the parts of the road where the road-work scenarios are placed, and each image is focused on a different scenario. They are of the roadwork scenarios described in section 10.2.1, in the same order.

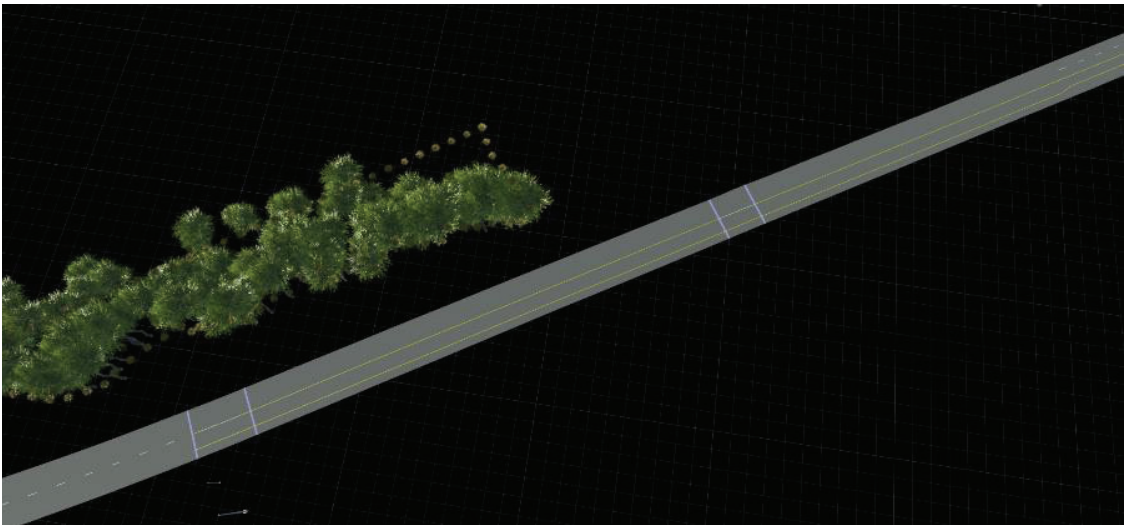


Figure 20 Roadwork Scenario 1 - Yellow lines

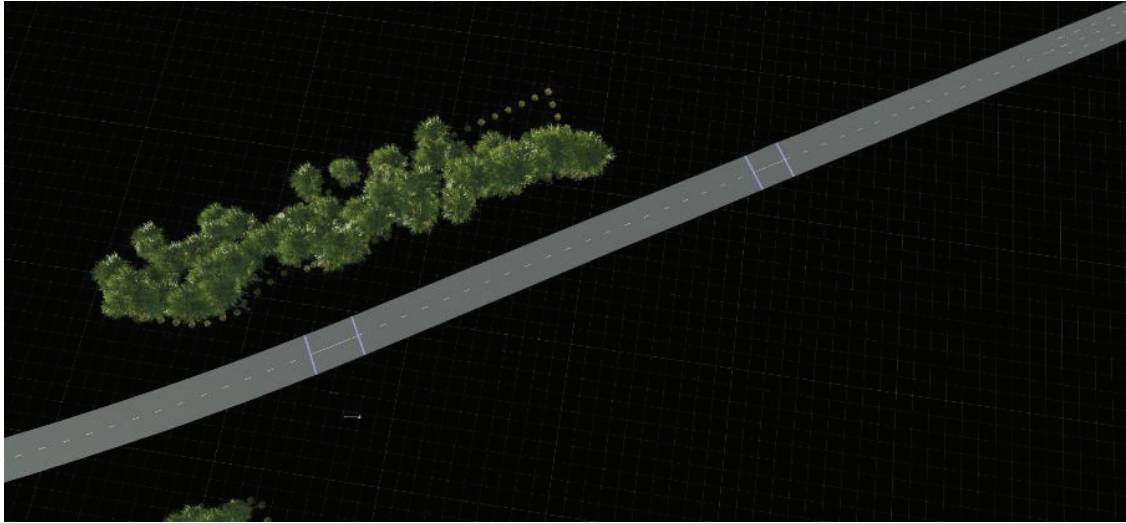


Figure 21 Roadwork Scenario 2 – No lines

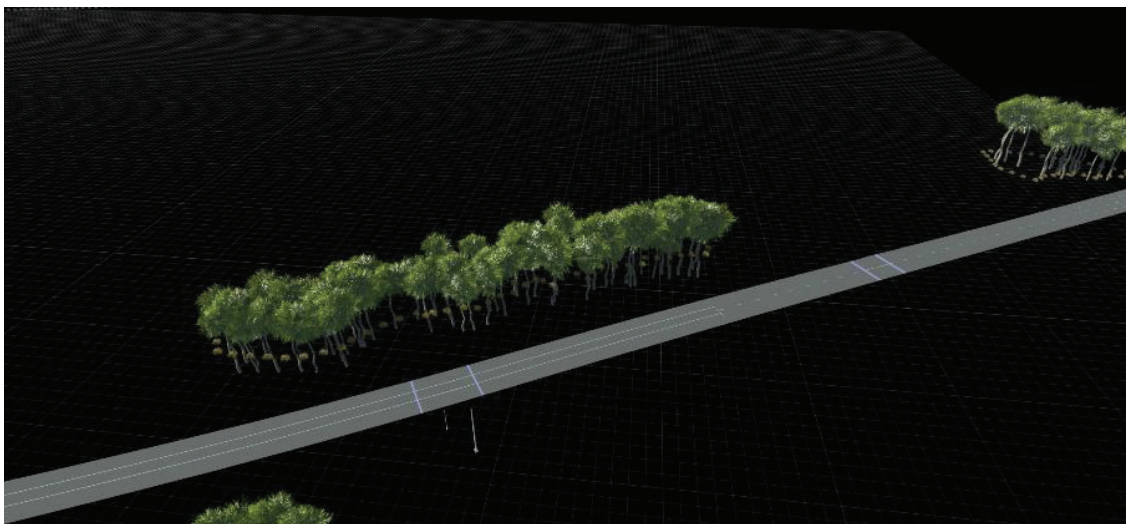


Figure 22 Roadwork Scenario 3 - Centred middle lane

Figure 23, Figure 24 and Figure 25 shows the same scenarios but without the meshes.

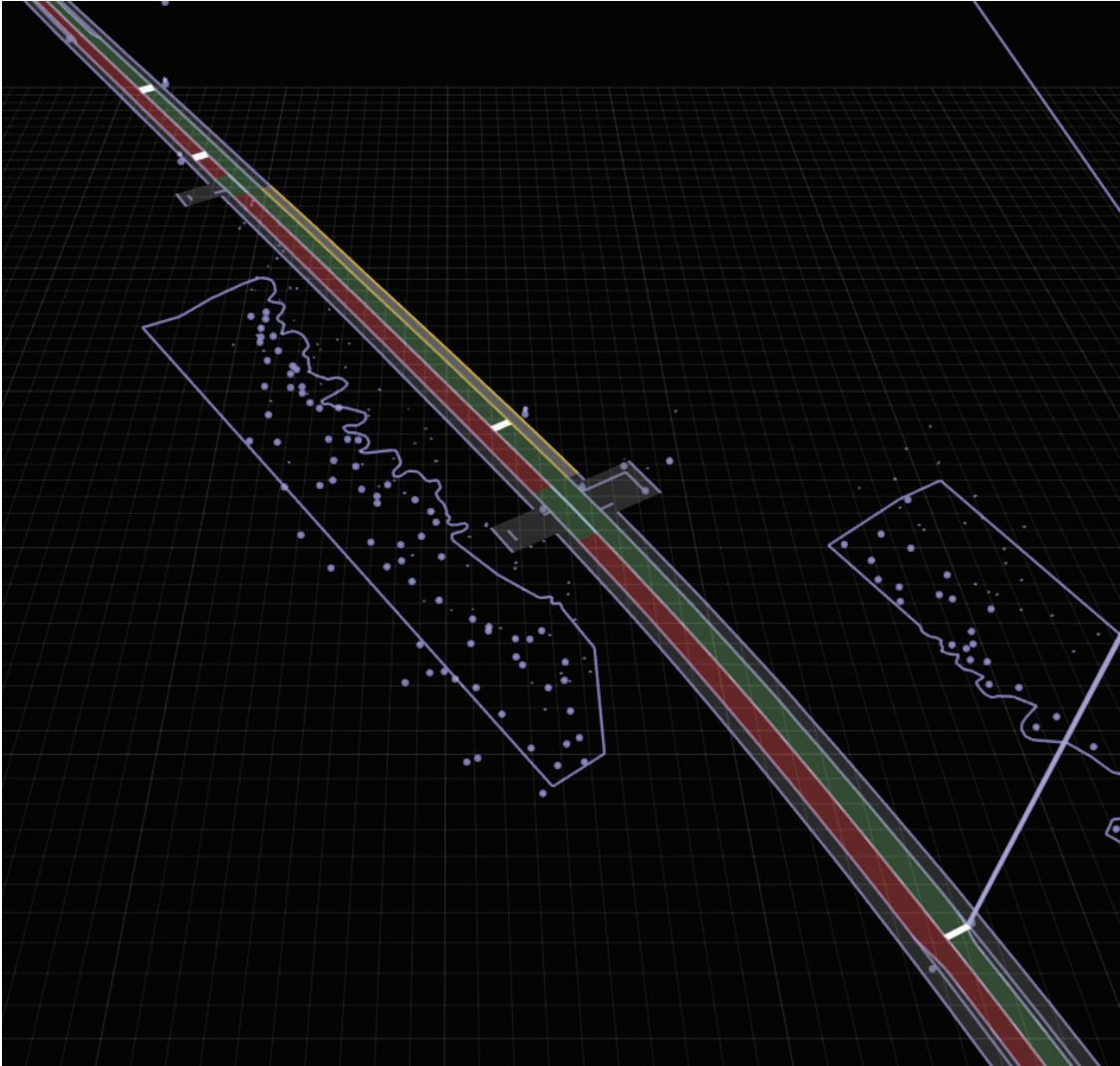


Figure 23 Roadwork Scenario 1 - Yellow lines - No Mesh

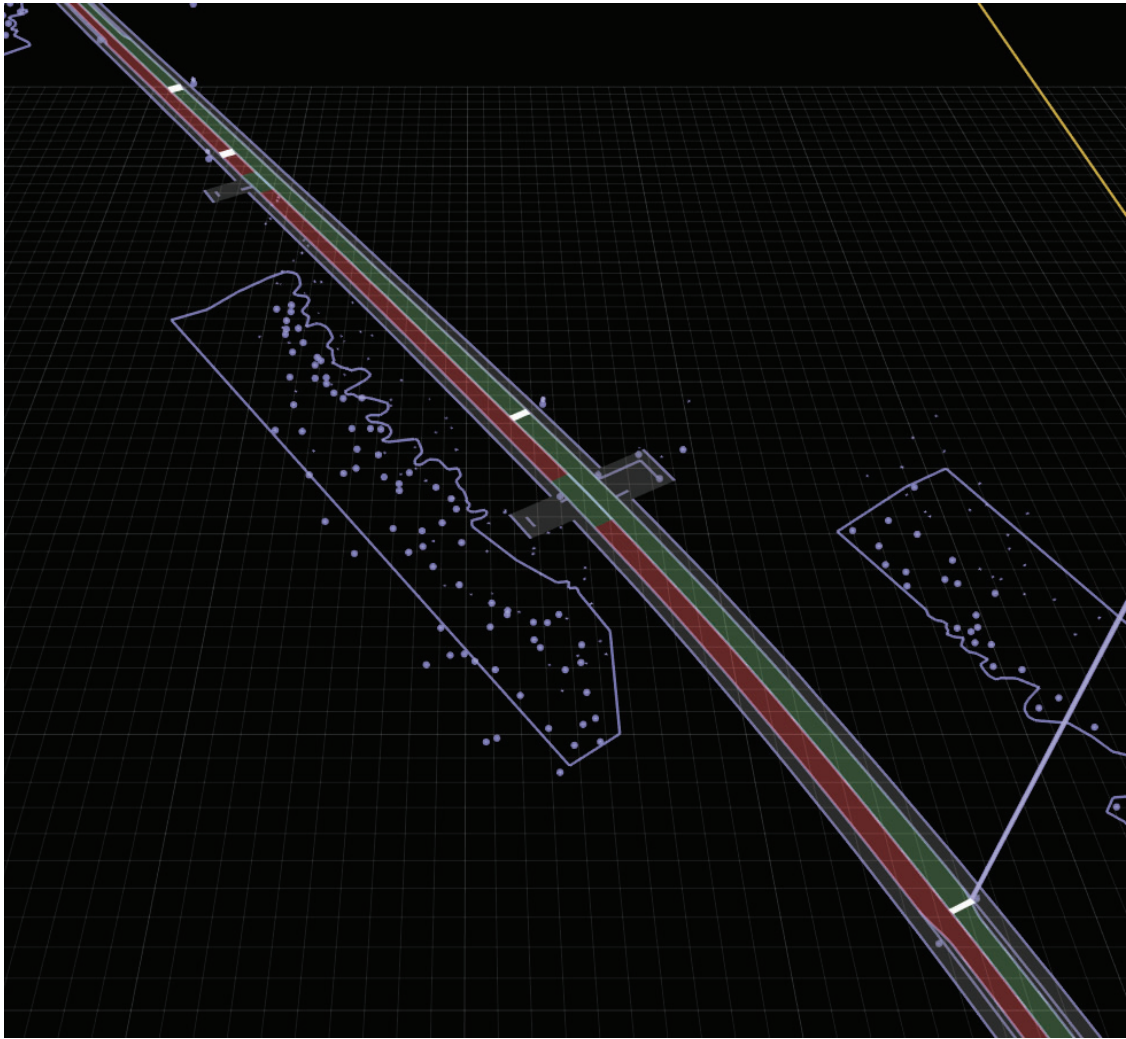


Figure 24 Roadwork Scenario 2 – No lines - no mesh

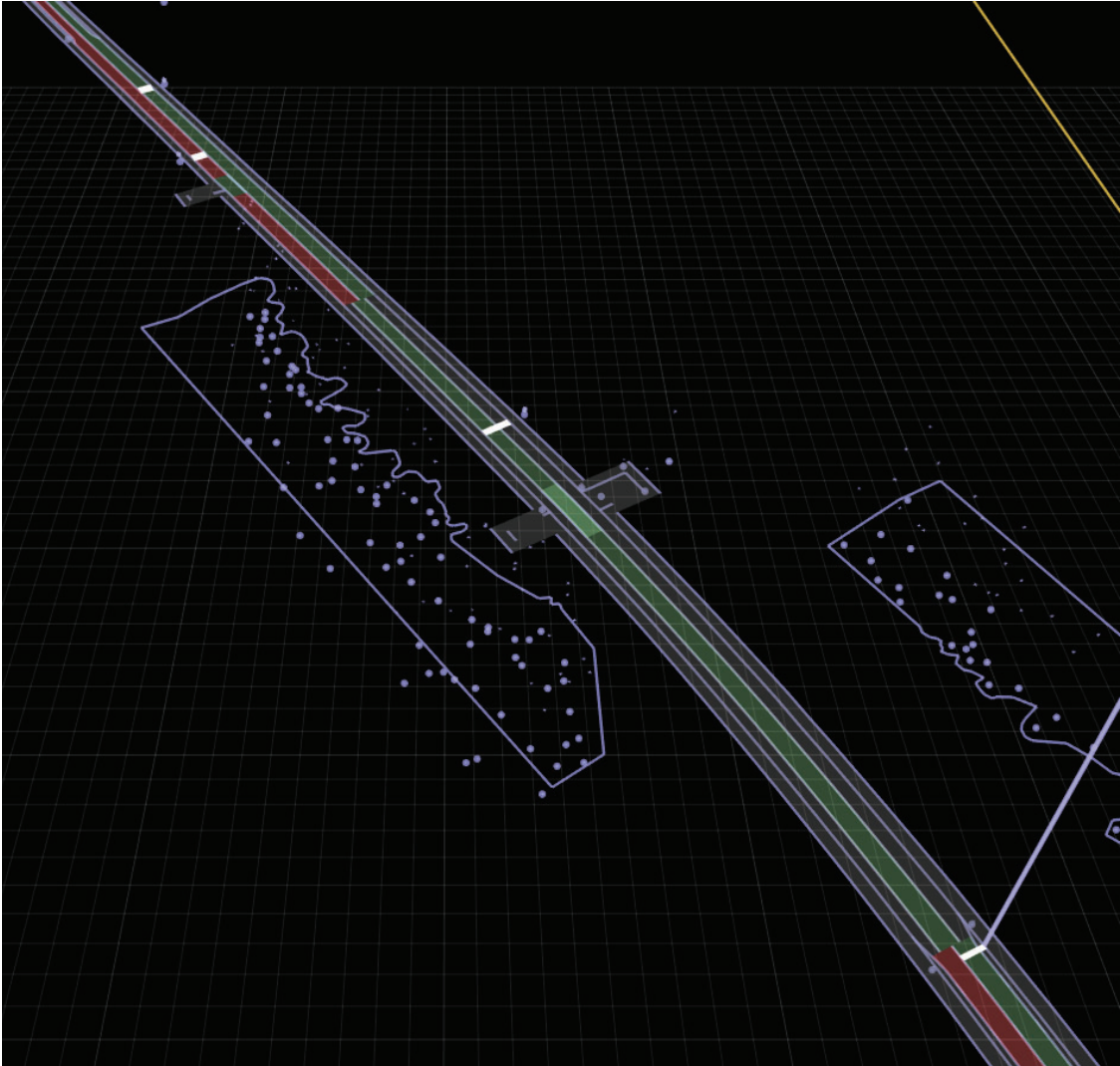


Figure 25 Roadwork Scenario 3 - Centred middle lane - no mesh

8.1.2 AstaZero OpenDRIVE validation compared to RISE measurements.

In the currently used OpenDRIVE Map, the measurements existing are from a scanned version of the test track. To improve its accuracy, RISE has performed thorough measurements of select objects on the track and this document is to compare the current OpenDRIVE map and the new RISE measurements.

RISE measured Traffic Signs, Reflectors and three types of Barriers. Traffic Sign were further divided into Rural Signs and Signs but are, for the purposes of the OpenDRIVE map, processed the same way. The sign positions RISE measured were the centre of the sign plate, which when mounted on a pole that has any degree of tilt can have a distinct difference in position to the base of the pole. Since the sign and the pole are both

represented in the OpenDRIVE format, the choice was made to compare the Signal object, which is defined in the case of a sign, as the centre of the sign.

Reflectors were measured as the Circular and Rectangular reflectors placed on either side of the pole while in the OpenDRIVE it is the centre of the pole that is included. This was solved by calculating the position in the middle between the circular and rectangular reflector as the calculated pole position from the RISE measurements.

Barriers are represented in the OpenDRIVE map by a barrier object on the track followed by a repeating object to describe a continuous line while in the RISE measurements the positions of the poles of the barriers were measured. To calculate the difference between the RISE measurement positions and the OpenDRIVE representation, The the line for the centre between each barrier object and their first repeat object and between each adjacent repeat object was extrapolated. From this line the distance between the closest line and the positions measured by RISE was calculated.

There is an uncertainty in how the barrier objects are represented in the OpenDRIVE file. For the RISE measurements the pipe barrier is measured at the pole but is centred slightly off centre towards the track, see Figure 26 taken from document 105101-9P07262-05:

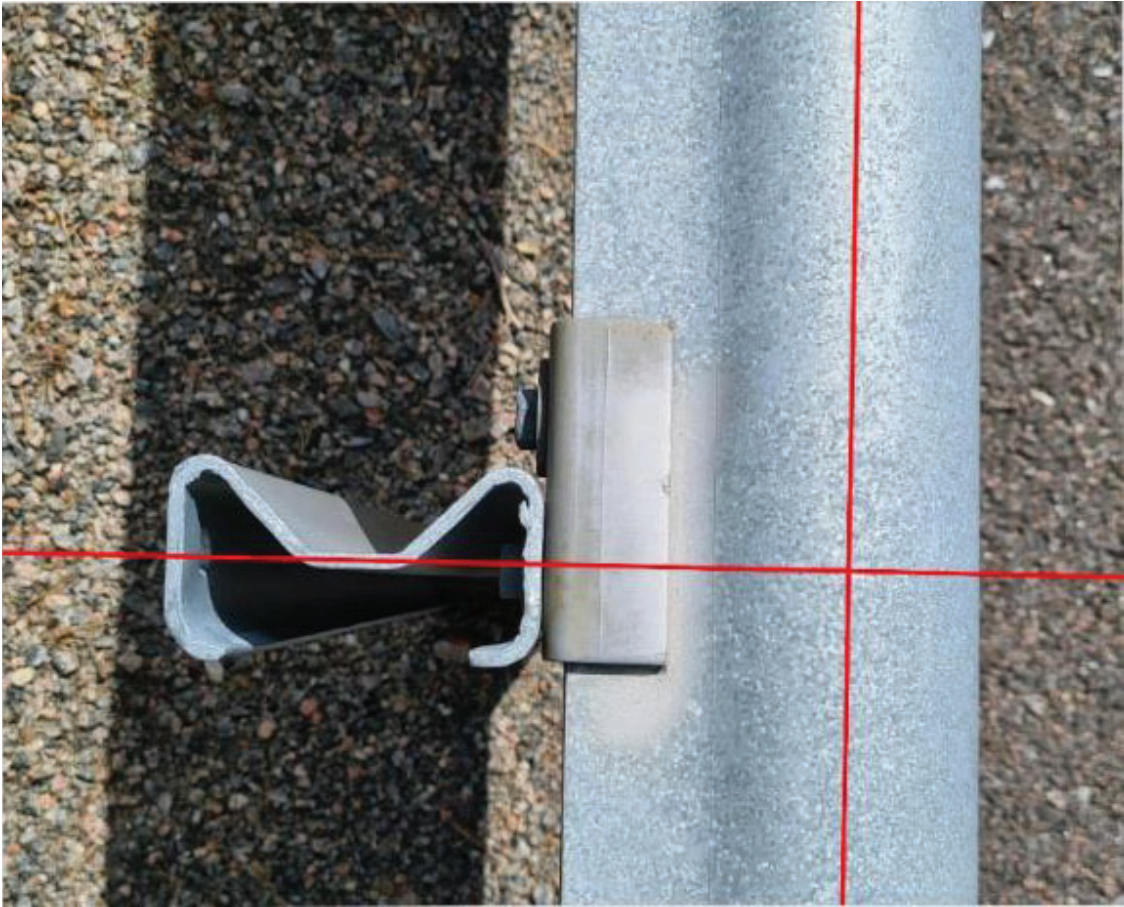


Figure 26 RISE Measurements Centre Barrier

But in the OpenDRIVE map it is unclear where it is centred, as such the exact centre of the provided values were taken as the lines used to represent the barriers.

The OpenDRIVE map has an accuracy of 1-3 cm if it was measured under optimal conditions and up to 30 cm if not and the RISE measurements have an uncertainty of between 3.6 to 5.3 cm depending on what was measured except for the rural signs.

RISE 3D expanded measurement uncertainties (95%)

Lower Pipe Barriers	5.3 cm
Upper Pipe Barriers	5.0 cm
Cable Barriers	4.1 cm
Classical Barrier	3.6 cm
Reflectors(Worst)	4.9 cm
Signs	4 cm
Rural Signs	25.0 cm + 1.5m for one sign

The difference in uncertainty for Rural signs is due to them measuring the base of the poles instead of the centre of the sign which was done for the other signs. This resulted in the tilt of the pole causing a more significant uncertainty.

The following graphs, Figure 27 and Figure 28, show the positions of both the OpenDRIVE objects and the measured objects. The first is of the barriers and the second of the signs and reflectors where you can clearly see the outline of the Rural Road track.

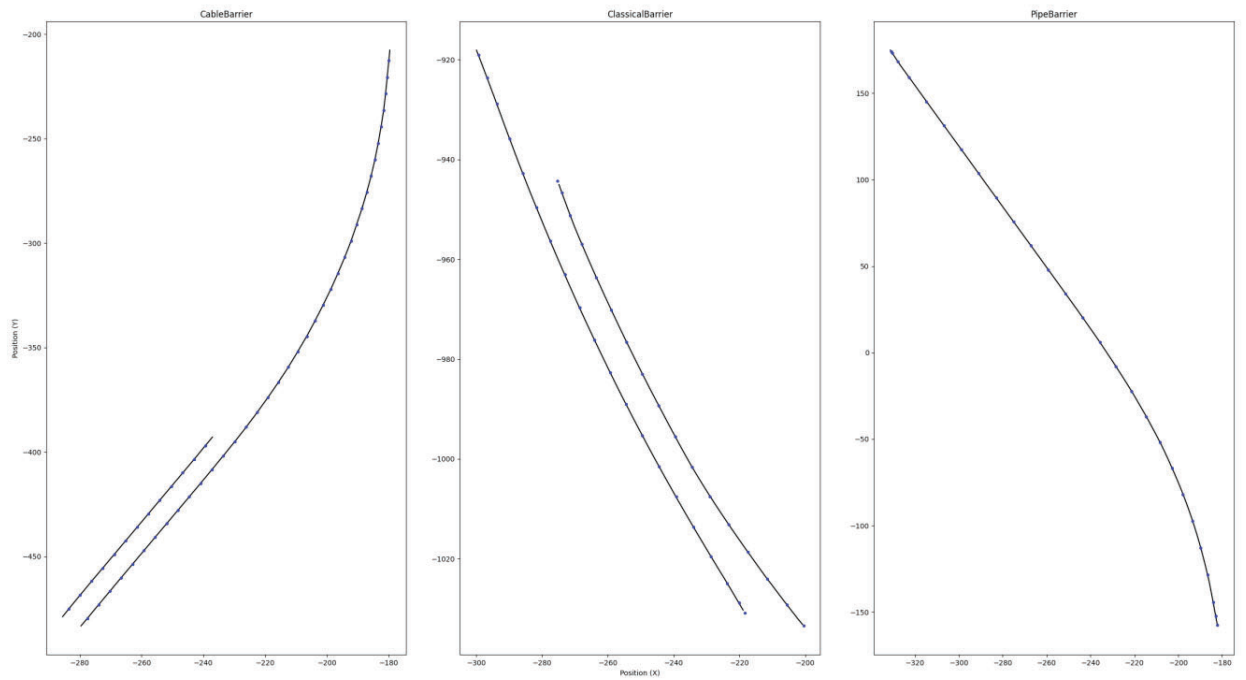


Figure 27 Barrier Positions

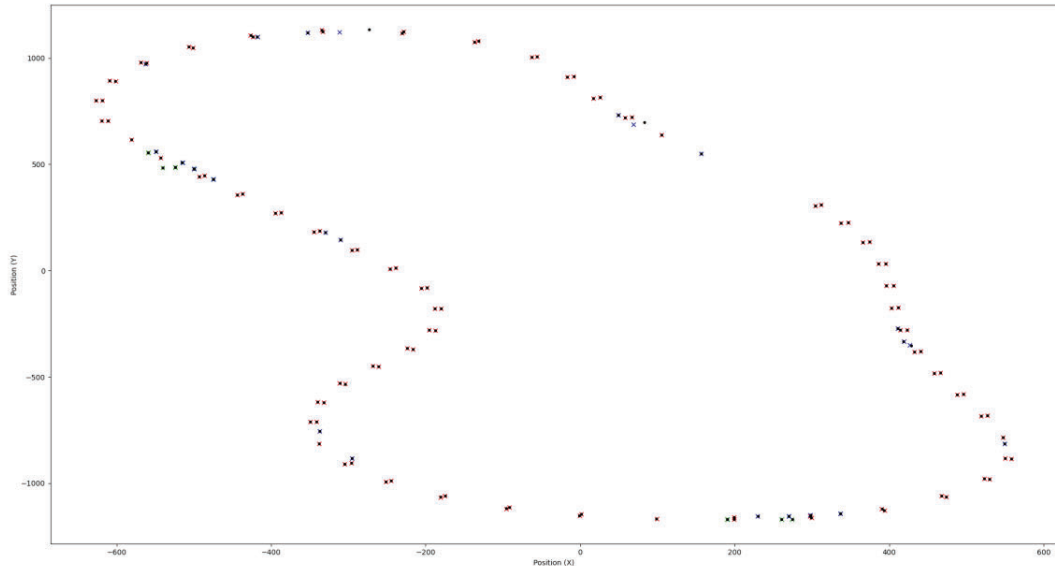


Figure 28 Reflector Pole and Sign positions

8.1.3 Results compared with RISE positions.

After calculating the deviations, the next step is updating the objects that are misaligned. Due to the aforementioned accuracy, the choice was made to keep any object with a difference to its measured counterpart less than 6 cm in its original OpenDRIVE position. 6 cm was chosen as it was deemed a significant enough difference between the measurements and the uncertainties from both sources and therefore requiring an update.

In lieu of the knowledge that some of these objects, such as, but not limited to, signposts, might be moved over time, the decision was taken to update the OpenDRIVE map in four different batches to measure the difference that time makes.

As such it was decided that the batches were divided in these timespan - First batch only included a single measurement from the 2021-03-18, as that was the earliest measurement provided and it was for cable barriers where the differences turn out to be low to the point where no changes were necessary. See Figure 35, Figure 33, Figure 36 and Figure 34 for a visualisation of the positions of the different batches.

Second batch included all measurements from then up until 2021-07, which were done on the following dates: 2021-06-11, 2021-05-03 and 2021-06-08. Third batch was a single date at 2021-10-27 and the last batch was from the measurement done in 2022-07-12, 2022-07-18 and 2022-07-25.

The first batch was a measurement of Cable barrier positions and when measuring the differences, none of the cable barriers were outside of the chosen accuracy, and as such, the first batch results in a Map identical to the original.

The second batch included reflectors, classical barriers, and pipe barriers. For reflectors there were 67 out of 103 possible that needed adjustments, while for classical barriers it was 52 out of 146 and for pipe barriers it was 28 out of 112, for a batch total of 147 out of 361 and a grand total of 147 out of 774 whereas out of those 774, more than half was due to the cable barriers that was not changed.

The third batch had only a measurement of signs, of which there were 14. 8 of which needed to be updated. Grand total: 155 / 788

The fourth, and largest, batch, included measurements of Signs, Reflectors, and Classical, pipe and cable barriers.

Classical Barriers: Out of 146 possible: 0 have been changed.
 Cable barriers: Out of 413 possible: 0 have been changed.
 Pipe Barriers: Out of 112 possible: 1 have been changed.
 Reflectors: Out of 105 possible: 7 have been changed.
 Signs: Out of 44 possible: 31 have been changed.

This brings it to a total of 1594 points that could have needed an update and a total of 185 that were: 11.6%.

What one can draw as a conclusion of this is that OpenDRIVE is mostly quite accurate, and a lot of the difference might be with how the OpenDRIVE original creation was calculating the centre point of objects compare to how the ones creating the RISE Measurements did. While the OpenDRIVE specification has as strict definition of the various object types, the way to calculate these from the different ways differ due to the approach that was taken and as such the result will vary a little. As one can see, the largest difference that is not abnormal is approximately 2 meters for a rural sign, 66 cm for reflector poles and only around 10 cm for the barriers (see appendix B). Poles are quite difficult to measure the centre of due to tilt it might have, and as one can see, reflector poles, which are generally shorter and more stable, have a smaller difference than the rural sign, and the barriers, which are even more stable, are even more accurate.

The following tables shows the statistics for how the different measurement differed between the OpenDRIVE and the RISE measurements.

Sign:

Type	Min (m)	Mean (m)	Median (m)	Max (m)
X	0.0028	0.1951	0.0718	2.0483
Y	0.0021	0.1203	0.056	1.3077
Distance (XY)	0.0064	0.2490	0.1307	2.4302

Table 3 Table of difference in measurements for Signs

Reflectors:

Type	Min (m)	Mean (m)	Median (m)	Max (m)
X	0.0001	0.0698	0.0345	0.6357
Y	0.0048	0.08802	0.0687	0.6004
Distance (XY)	0.0087	0.1227	0.0804	0.6663

Table 4 Table of differences in measurements for Reflector poles

Barriers:

Distance (XY)	Min	Mean	Median	Max
Cable Barriers	0.00003	0.0013	0.0009	0.0048
Classical Barriers	0.0004	0.0139	0.0073	0.0466
Pipe Barriers	0.0005	0.0057	0.0042	0.0170

Table 5 Table of differences in measurements for Barriers

Barrier Statistics:

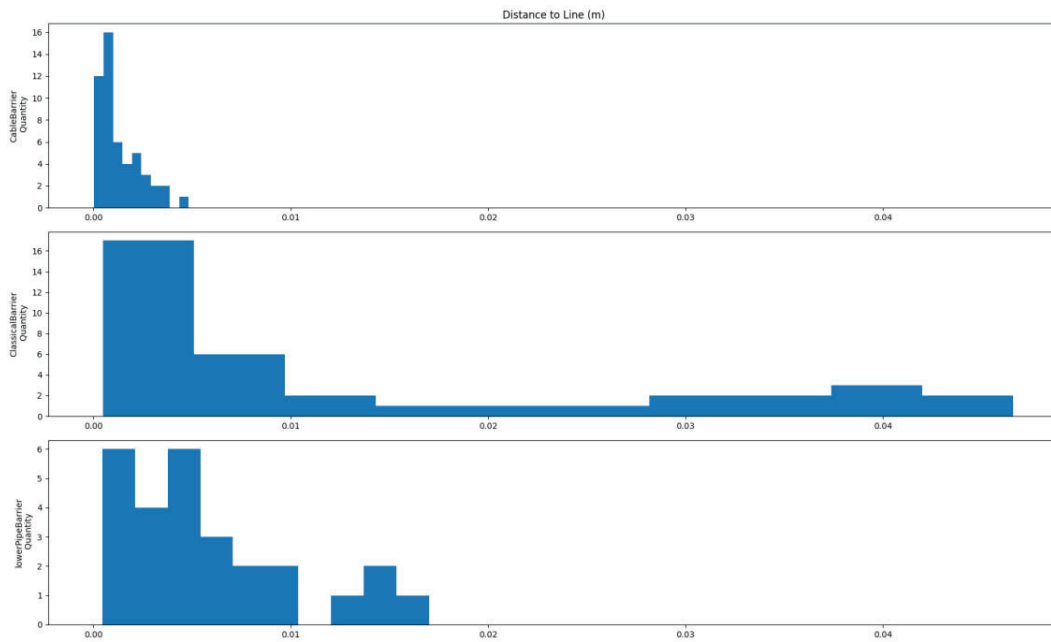


Figure 29 Barrier Differences

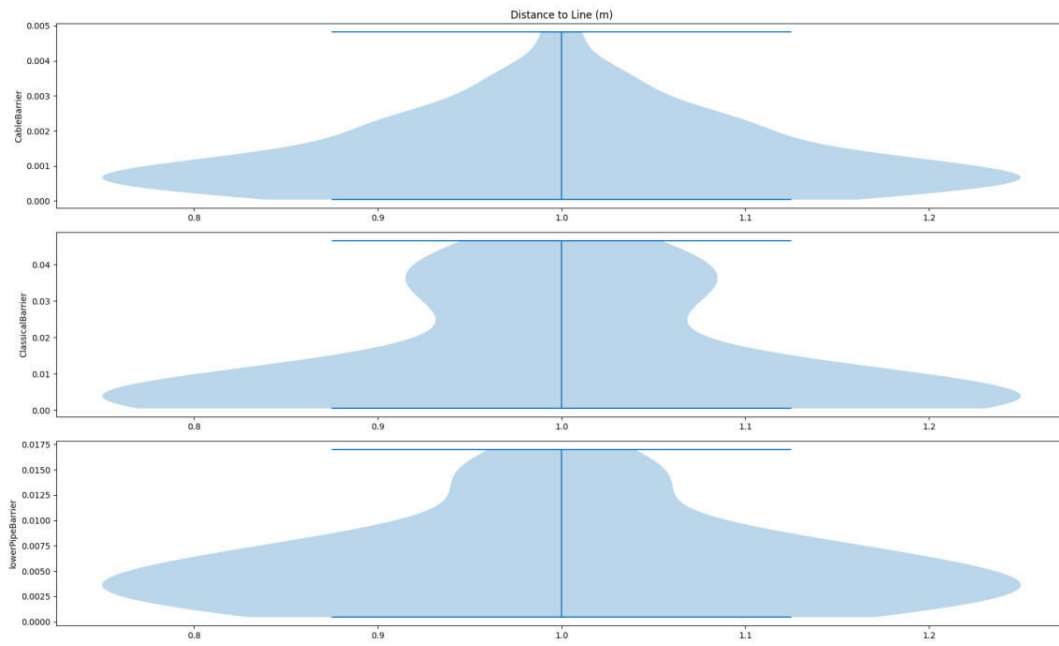


Figure 30 Barrier Differences - Violin plot

Signs and Reflectors Statistics:

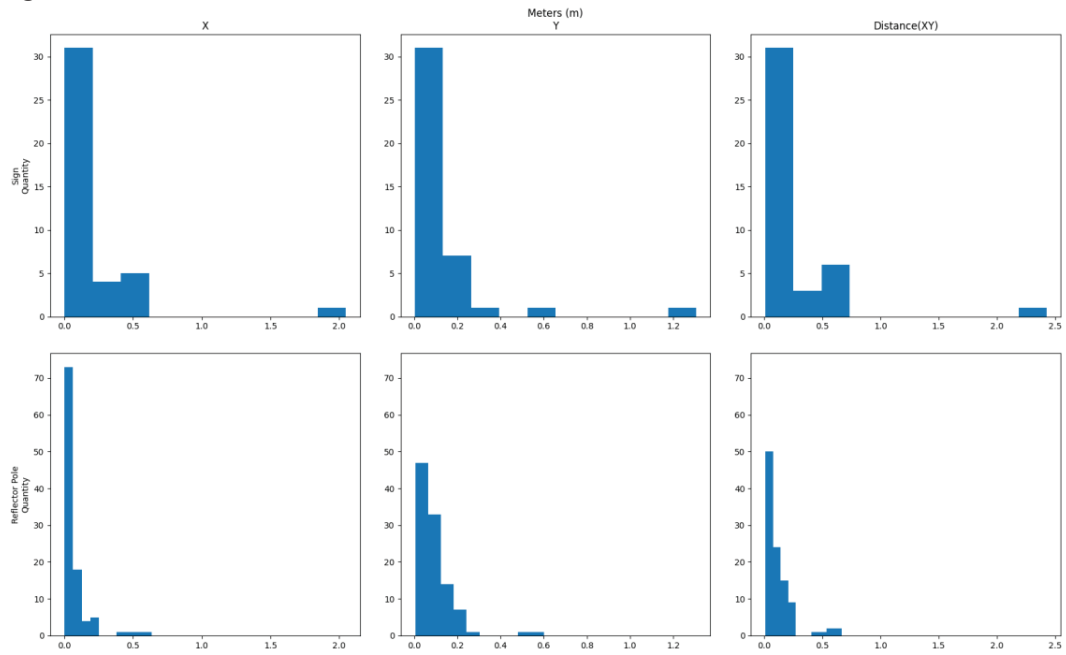


Figure 31 Sign and Reflector pole differences

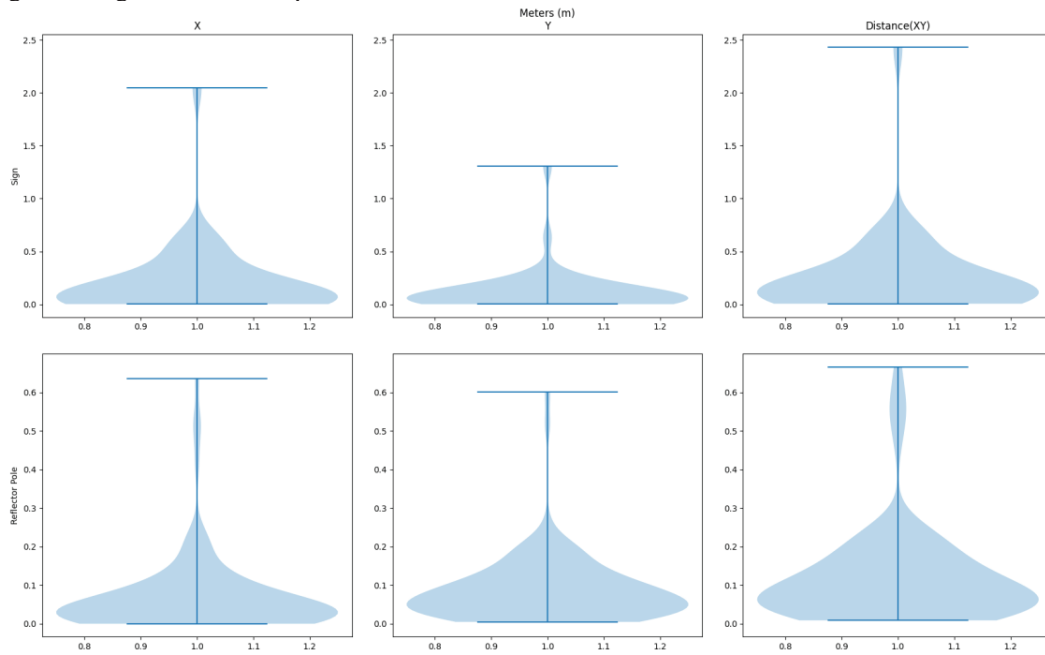


Figure 32 Sign and Reflector pole differences - Violin plot

8.1.4 How to use the library

With the library provided by AstaZero, the way to make use of it is to open the OpenDRIVE map in python and store references to all the objects that are relevant to be updated. For example, if one has accurate measurements of reflector poles that one wants to compare to the existing OpenDRIVE map, first load all the object of type pole into an array, then match the closest pole to the measurements and update the position if the difference between the position of the measurement and the position in the map is too far apart.

In the case of the measurements received from RISE, the reflector poles were provided positions of the reflectors on each side of the pole, so to be more accurate, the average position of each of the reflectors was taken and used that as the centre of the pole and compared that to the objects of type Pole. If the differences were greater than 6 cm, a distance that was higher than each of the sources of uncertainties, that pole would be updated with the new value.

A more complicated example is barriers. Barriers in OpenDRIVE are represented by a continuous object, which is a repeating structure of different values, which when compared to the RISE measurements, which are points at various intervals, it is not possible to do the same thing as for poles. In this case, it was elected to represent the RISE measurements as a line and compare each barrier continuous object to the closest point to that line. This, as one can see in the next section, proved that the barriers were clearly more stable than poles and signs, as none of the measurements diverged in any significant amount from the existing OpenDRIVE map. Should they have diverged, it was the intention to update the objects with the difference to the closest line and as such represent the objects and the repeating objects by the new measurements.

Should one want to add objects to the OpenDRIVE, it is simple. Take the new measurements and call for its corresponding add function from the helper file, for instance: for an Object, just call AddObject with the measurements as arguments.

To understand the library a bit more thoroughly, what one must do to compare the contents of the OpenDRIVE to measurements in a more classical coordinate system is to first find the local coordinates in the OpenDRIVE file. OpenDRIVE uses a road-based coordinate system where all coordinates are in relation to its distance to the road, and the road itself is defined by several geometrical shapes, such as lines, arcs and polynomials and others.

The first step is to find the local coordinates of the map, which is to take the data in the geoReference and adjust the x and y coordinates in the new measurements by adding the geoReference x and y value to them. Now that the measurements are in the local system, it can be compared to the objects and items in the map by simply comparing the measurements to the objects' coordinates by converting, according to the OpenDRIVE specification, between the local coordinates to the map coordinates.

To do that, one must find the geometry closest to the object, and using the given function for the geometry, convert between the s and t coordinates to the x and y coordinates and add the geometry x and y starting coordinates. Now that both sets of coordinates are in the same system, they can directly be compared and the distance between the two is an elementary task to perform.

Once you have found the closest object of the same type, you can evaluate if it is close enough to not warrant to be updated, or if it is too far away to realistically be the same object, in which case, one might need to add the object instead of updating an existing.

OpenDRIVE was designed to cater to the view of a vehicle on the road and so the data is presented in a way that makes it easy to be organized and accessed for that purpose. This has the consequence that some of the data is easy to convert into other coordinate systems, but not back from another coordinate system to its local, road-based view.

The cartesian coordinate system that was provided in the measurements from RISE was provided in SWEREF 99 TM. To convert it into the local distance along the road and perpendicular distance from that position (s and t), such that OpenDRIVE specifies, required a brute-force method where one moves along each geometry, for each road, to find the closest one by going through the geometries iteratively and finding the closest.

When the closest geometry is found one needs to iterate over it once more, in a more thorough manner by selecting a distance to iterate over. The chosen distance in this case was 0.0001 meters. Every 0.0001 meters, the cartesian position along the line was calculated and then compared to the actual cartesian position of the point one is comparing to, taking the distance between the two as t , the perpendicular distance from the line to the point. With this point, one can take the distance along the geometry and the distance from the line as s and t and use these to calculate the actual cartesian coordinate of that point. Then the difference between this point and the measured point is taken and if it is smaller than the previous smallest point, stored as the closest s and t values for that point.

8.1.5 How this library was used to modify the Rural Road map.

Using the techniques mentioned above, the measurements provided by RISE was used as a basis to update the AstaZero map.

By drawing a line through each of the measured positions and comparing the closest barrier objects, one finds the difference in position and, map these. For any that is further away than 6 cm, update these to be placed in the position provided by RISE. For the first batch, there were no changes to the Rural Road.

For the second batch, there was reflectors, classical and pipe barriers. These barriers were handled in the same way as the previous batch but here there were differences found. To find the differences between the reflectors, one first found the centre of the pole by taking

the average of the two measured positions of the reflectors, as they are placed on separate sides of the pole. This position was then compared to the pole in the OpenDRIVE map and if the position differed with more than 6 cm, it would be updated.

For the third batch, there were signs which are handled mostly the same as reflectors, with the key difference that they are compared to signals instead of poles and signal references need to be updated as well.

The fourth and largest batch covered signs, barriers, and reflector poles. They were handled in the same way as previous batches.

This clearly shows how little drift there are on the objects with better classification for stability, as shown in Table 2: Classifications of anchor points objects based on their estimated stability adjusted after project results from measurement campaigns.

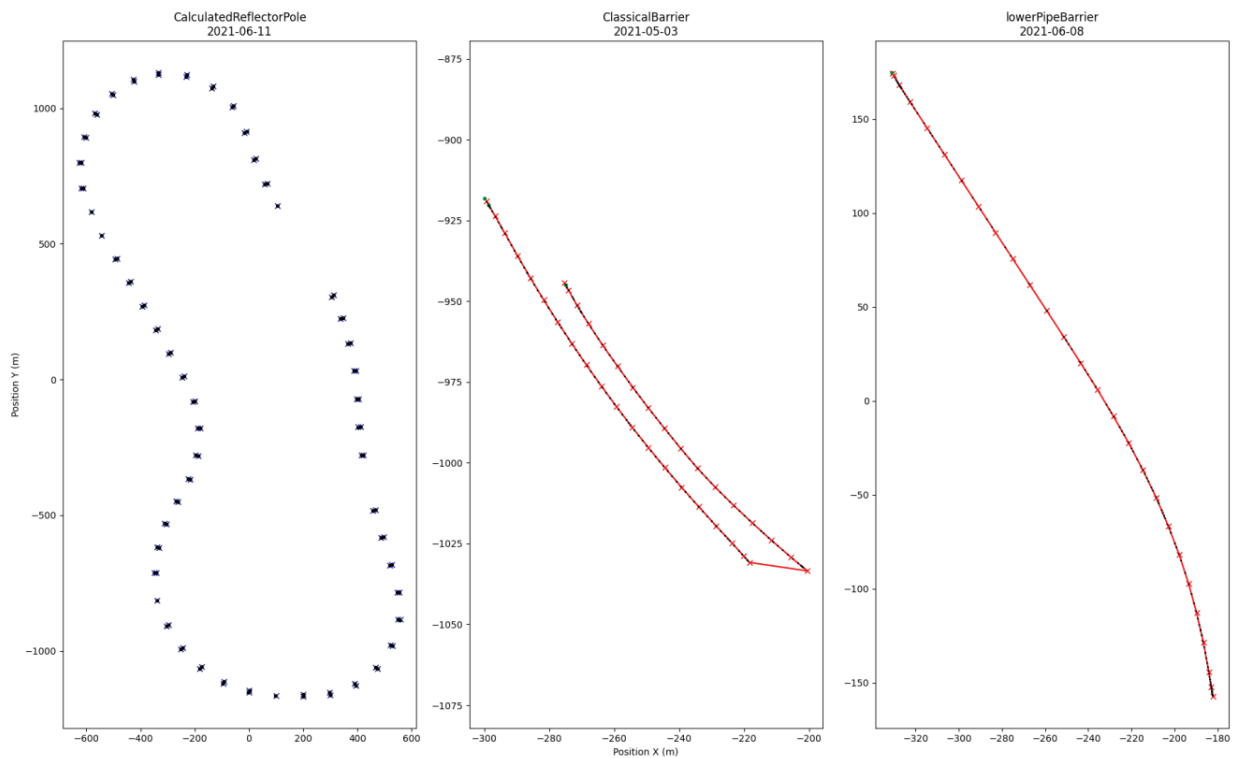


Figure 33 Second Batch Measured Position vs OpenDRIVE positions

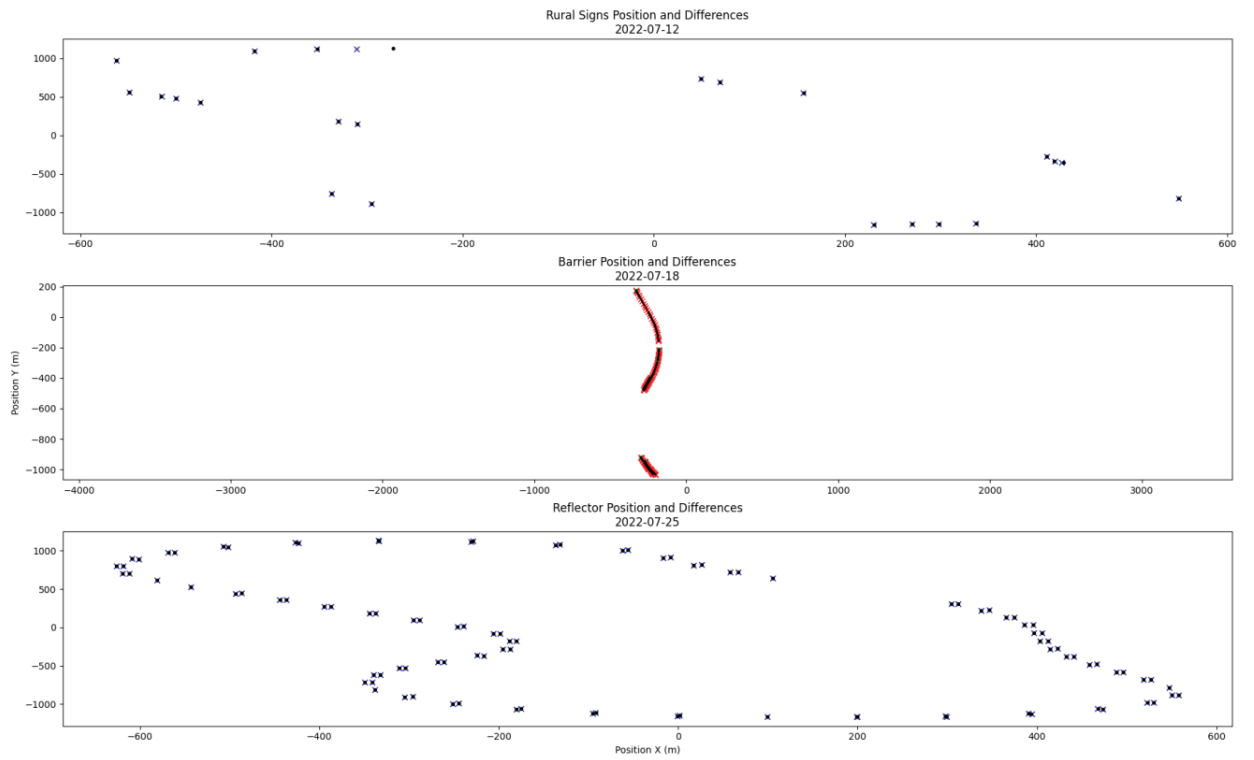


Figure 34 Fourth Batch Measured position vs OpenDRIVE positions

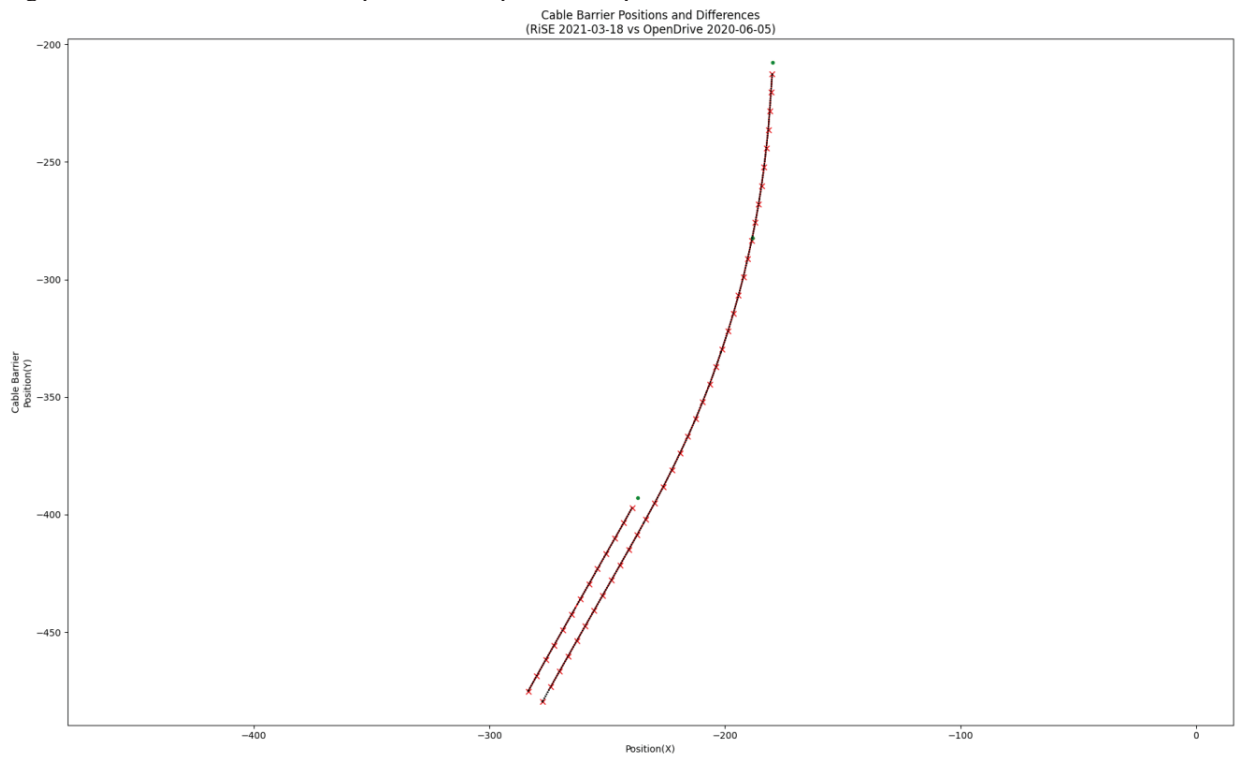


Figure 35 First Batch Measure Positions vs OpenDRIVE positions

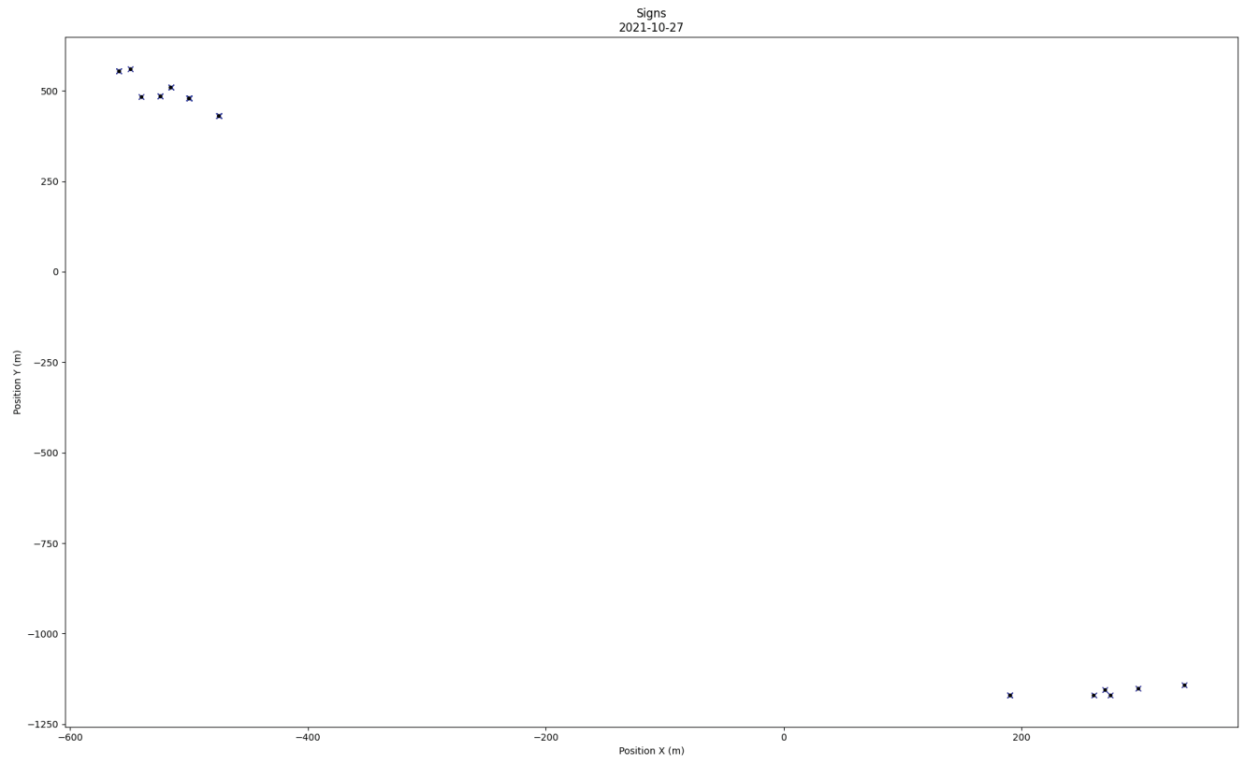


Figure 36 Third Batch Measured Positions vs OpenDRIVE positions

8.1.6 Where you can find OpenDRIVE parser.

AstaZero has created a code library that can provide aid in opening and modifying an existing OpenDRIVE map in the python programming language. It is not a complete library, but it does provide sufficient help in modifying the provided OpenDRIVE map for the intended purposes in this report.

There are alternatives to the AstaZero repository, such as the esmini repository (esmini, u.d.) or the pyoscx repository (pyoscx, u.d.) that does similar things, though they are mainly built for other purposes that may or may not be more suitable for other cases:

9 WP4 Data Collection and Distribution

First is the WP4 description described in the application after that is the work performed during the project and the dataset description.

WP4	Data Collection and Distribution
Leader (role and responsibility)	<p>Zenseact: Access to test vehicles equipped with the appropriate sensor set (Lidar, video, GPS etc). Collecting the sensor data at AstaZero test track (primarily Rural Road track) needed to create the dataset.</p>
Other participants (roles and responsibilities)	<p>AI Sweden: Responsible for distributing the dataset. They will also help spread knowledge about the dataset to their partners within academy, public sector and industry.</p> <p>AstaZero: Assist in getting access to the test track. Possibly, it should involve a driver from AstaZero in order to be able to react quickly to bad weather conditions.</p>
Description of contents	<p>This WP main purpose is to collect data for the dataset when driving around at AstaZero’s test track Rural Road. There are some different data collection parts.</p> <p>First there is Baseline data acquisition. Which is collecting of “normal” data described in method.</p> <p>Second there is change detection data collection which implies that you have changed some road objects position or removed them described more in method.</p> <p>Thirdly there is the different weather and unusual condition collection. Where we use AstaZero personal to collect bad weather and poor lighting conditions.</p>
Method/approach (when relevant)	<p>Baseline data collection: Collection of data from LIDAR, reference camera video and GPS from Zenseact development vehicle. The baseline collection refers to collecting data from Rural Road without any modifications on road geometry, at daytime, and in weather conditions which are considered as normal, i.e. sunny or overcast, possibly with light rain or snow, but no heavy rain or snow.</p> <p>Change detection data collection: Road objects will be moved and/or changed intentionally, and data will be collected. Road objects are lane markers, traffic signs and guard rails. The idea is to be able to demonstrate in</p>

	<p>the map validation and building step that these changes are identified. These change scenarios will also be used to investigate the robustness of the onboard localization algorithms. Some of the changed road objects will be measured in by RISE using the methodology of WP2. Physically changing the road objects will be done by AstaZero.</p> <p>Some data collections in poor illumination conditions can be part of the baseline data collection but the different weather and unusual condition needs to be planned with a Zenseact development car standing on hold at AstaZero for this dedicated collection.</p> <p>AI Innovation of Sweden will contribute with knowledge sharing and feedback by arranging a workshop with interested partners.</p>
Delivery	<p>5.1: Initial Baseline dataset, which will start as soon as possible after project start during autumn 2019.</p> <p>5.2: Extended baseline dataset which will continue throughout the entire project, with scheduled collection runs at least one day per month.</p> <p>5.3: Change detection dataset.</p> <p>5.4: Bad weather dataset.</p>

9.1 Motivation

Open datasets are crucial for research, product development, and generally advancing the field of autonomous driving. Open datasets fuel innovation by enabling researchers and developers to access a wide array of information for their algorithms to learn from, or benchmark. Autonomous driving relies heavily on machine learning models, which in turn require vast amounts of data to perform effectively. Within the context of autonomous driving, these datasets can include information from diverse environments, weather conditions, and different traffic scenarios. A good example of this is the Waymo open dataset, which features high resolution sensor data collected over different time of day, traffic densities, and weather conditions (Sun, o.a., 2020). Even though these types of datasets are of importance, there is a motivation to collect data in full controlled environments with well-defined objects, and access to their positions through HD-maps, which is within the aim of the project.

The role of open datasets extends to fostering of collaboration and standardizing benchmarks. Open datasets enable researchers from various institutions and companies

around the world to work on similar problems, which in turn accelerate innovation. Moreover, it promotes fairness and transparency by providing standardized benchmarks against which algorithms can be objectively compared. Standardization facilitates peer reviews and helps with experiment reproducibility. The aim of the data collection within the project is to enable the usage of our controlled dataset for similar purposes.

Open datasets can help democratize the field of autonomous driving. By making high quality data available to everyone, independent researchers, small companies, academic institutions that might not have the resources to gather such data can still participate in cutting-edge research. This broad access enables competition, which in turn will drive the industry forward. An example on which our data collection intends to have an impact is around HD-Maps, since several of them will be available along with the vehicle-collected data. Hence, the dataset has a direct impact towards map validation/creation innovative ideas.

9.2 Data description

The data contains a variety of scenarios in a controlled environment, namely the rural road in AstaZero's test site. The rural road is approximately 5.7 kilometers long. Half of it is designed to handle 70 km/h while the other half 90 km/h. The test road includes two T-junctions and a crossroads (AstaZero, 2023). Signage and temporal lane markers along the route and customizable to requirements.



Figure 37: Rural Road at AstaZero's testing ground (AstaZero, 2023).

Some details about the dataset. The data amounts to a total of 4 hours and 11 minutes of driving; this translates into 2 terabytes of data. The data has been collected during several seasons and weather conditions throughout the year, including rain, sun, clouds and snow.

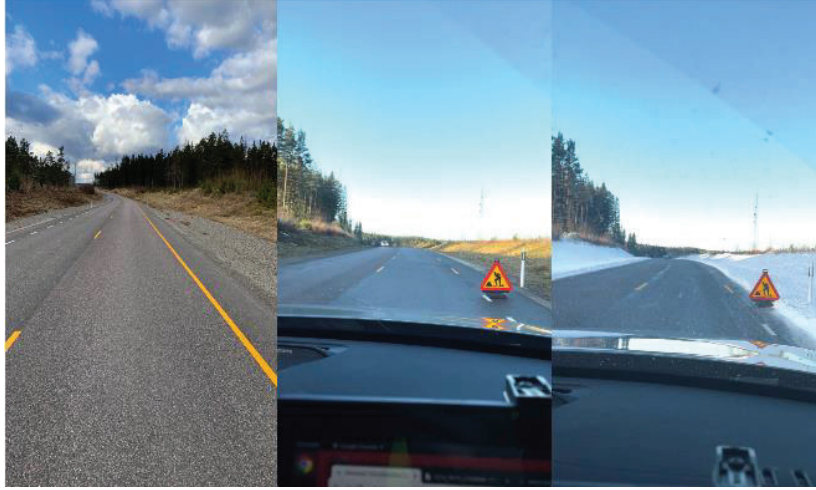


Figure 38: Examples of scenarios and diverse weather conditions within the dataset.

One of the major contributions along with the collected dataset includes 6 HD-Maps corresponding with the different driving scenarios within the data collection.

9.3 HD-Maps

HD-Maps are digital maps specifically crafted for autonomous vehicles and advanced driver-assistance systems (ADAS). They offer granular details, often to a few centimeters, about the road environment, such as lanes, traffic lights, and signs. Incorporating 3D modeling and multiple informational layers, these maps are continuously updated in real-time to reflect road changes. Designed to complement vehicle sensors like LIDAR and cameras, they enhance vehicle localization and offer redundancy for safety. Crucial for both autonomous driving and enhancing ADAS features, HD-Maps are foundational in navigating vehicles through intricate environments.

The HD-maps provided in the dataset is described more in detail in section 8. The HD-maps are provided in the OpenDRIVE format. They are updated with the RISE measurement after their measurement campaign and the different scenarios are also described in the OpenDRIVE map. Each OpenDRIVE HD-map have a date in it that describes the day the measurement where made these should be compared to the date the sensor data was collected.

9.4 Licensing

The dataset is licensed under CC BY-SA 4.0 (creativecommons), similar as the Zenseact Open Dataset (Zenseact, 2023).

9.5 Sensor suite

The data collection has been conducted with the use of several vehicles. All vehicles were equipped with an identical sensor layout. The vehicles have been equipped with a high-resolution camera, front and side looking LiDARs, and high precision GNSS/IMU sensors. The sensor placement on the vehicle is exemplified in Figure 39 (Zenseact, 2023).

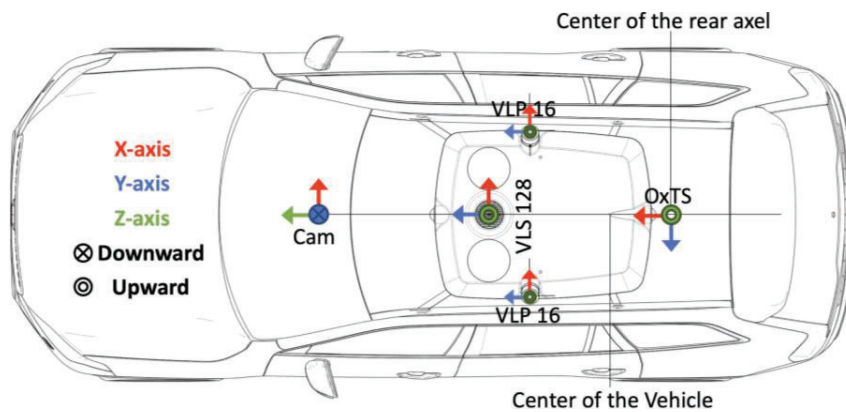


Figure 39: Sensor placement and their coordinate systems (Zenseact, 2023).

9.5.1 LiDAR data

The LiDAR point clouds are recorded at a frequency of 10 Hz and each scan is stored in a conventional binary file format (.npy). Every file comprises data from the three LiDAR sensors, depicted as a 6-dimensional vector inclusive of the timestamp, 3D coordinates (x , y , and z), intensity, and diode index. The intensity indicates the reflection magnitude, whereas the diode index identifies the specific emitter responsible for generating the point (Zenseact, 2023).

9.5.2 High precision GNSS/IMU

High precision GNSS/IMU data is collected at a frequency of 100 Hz and stored in HDF5 file format. The files comprise an array of information such as UTC timestamp, geographic coordinates under the WGS 84 (Lantmäteriet, u.d.) (latitude, longitude, height), WGS 84 (x,y,z), ECEF Cartesian coordinates, heading, pitch, roll, velocities, and accelerations (Zenseact, 2023).

9.5.3 Camera data

The camera data is recorded using high-definition 8 MP wide-angle fish-eye lenses. The raw collected data undergoes a conversion process to RGB images using an internal production-grade image signal processor. The RGB camera images, taken at a rate of 10 Hz, are stored as JPG files. In addition, images are also available in a lossless PNG format (Zenseact, 2023).

9.5.4 Vehicle data

A variety of vehicle data, when available, is made accessible. These data include vehicle control indicators such as steering wheel position, ratio of acceleration/brake pedal, status of the turn signal, along with consumer-grade IMU and GNSS data. GNSS, IMU and vehicle control indicator data are logged at 1 Hz, 50 Hz and 100 Hz, respectively (Zenseact, 2023).

9.5.5 Calibration and coordinate systems

Sensors are synchronized and calibrated regularly to ensure stability and ensure alignment of the different data types. Calibration is in accordance with the ISO-8855 reference coordinate system. Origin of reference coordinate system is a fixed point relative to the vehicle chassis, located at center of rear axle. Calibration information is provided based on date (Zenseact, 2023).

A technical summary of the sensor suite is included in Table 6.

Table 6: Technical summary of sensor suite.

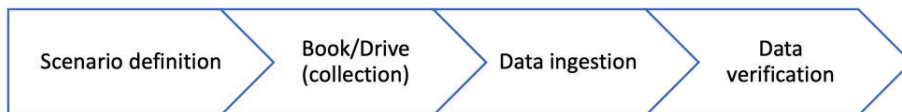
Sensors	Details
LiDARs	<ul style="list-style-type: none">• 1xVelodyne VLS128 rotating 3D laser scanner.<ul style="list-style-type: none">○ Horizontal field of view: 360°.○ Vertical field of view: 40° [-25°, +15°].○ Horizontal resolution: 0.1° to 0.4°.○ Vertical resolution: 0.11.○ Channels: 128.○ Wavelength: 903 nm.○ Range: up to 245 m.○ Frame rate: 10 Hz.• 2xVelodyne VLP16.<ul style="list-style-type: none">○ Horizontal field of view: 360°.○ Vertical field of view: 30°.○ Horizontal resolution: 0.1° to 0.4°.○ Vertical resolution: 2°.○ Channels: 16.

	<ul style="list-style-type: none"> ○ Wavelength: 905 nm. ○ Range: up to 100 m. ○ Frame rate: 10 Hz.
High precision GNSS/IMU	<ul style="list-style-type: none"> ● 1xOxTS RT3000 inertial and GNSS navigation system <ul style="list-style-type: none"> ○ Number of axes: 6 ○ L1/L2 RTK ○ Frame rate: 100 Hz. ○ Position accuracy: 0.01 m. ○ Pitch/roll: 0.03°. ○ Heading accuracy: 0.1°.
Camera	<ul style="list-style-type: none"> ● 1xRGB front-looking camera <ul style="list-style-type: none"> ○ Horizontal field of view: 120°. ○ Vertical field of view: 67°. ○ Resolution: 3848x2168 (8MP).

9.6 Data collection and preparation

As its name implies, the data collection/preparation process encompasses two steps: (i) data collection; and (ii) data preparation. Each of these steps further subdivides into multiple substeps as depicted in Figure 40. The data collection steps are from scenario definition through to data ingestion and subsequent verification. Upon successful verification of the data, the process transitions to the data preparation step, which must be completed prior to data distribution. Detailed descriptions of these steps and their associated substeps are provided in the subsequent sections of this report.

Data collection



Data Preparation

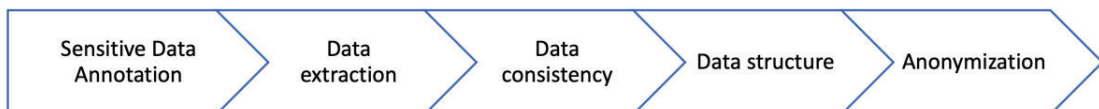


Figure 40: Data collection and preparation steps and corresponding substeps.

9.6.1 Data collection

Broadly speaking, the data collection process refers to the systematic capture, ingestion and verification of raw information from the wide array of fitted vehicle sensors, which have been previously described. The information details different aspects of environmental conditions, objects in the vehicle's path, vehicle's internal state, etc...

The data collection process consists of 4 substeps: (i) scenario definition; (ii) book/drive; (iii) data ingestion; and (iv) data verification.

Scenario definition

The first substep involves scenario definition and planning. Diverse scenarios related to map validation, such as traffic sign mapping and hazard classification were carefully planned and agreed among the partners. This involved different object placing such as traffic signs and temporal lane markers.

Book/Drive

The second substep consists of the actual physical driving. Diverse team members have been involved in the driving while making sure continuous communication regarding bookings in advance has been made together with AstaZero's testing ground. The latter involved managing availability and last-minute issues with hardware, software and human unexpected situations.

Data ingestion

Once the data has been collected and logged, the vehicle was driven to Zenseact's data ingestion center, where data is uploaded and decoded into human readable form. The decoders and pipelines used for data ingestion are used within all company and in certain periods, decoding time will vary depending on their availability.

Data verification

Finally, once data has been decoded the data is verified by team members. Verification involves file checks, videos, and in some cases graphical representations of the data, e.g., traffic signs, lane markers, etc.

9.6.2 Data preparation

Once data has been verified, data preparation is needed to enable sharing of the data. Data preparation consists of 5 substeps: (i) sensitive data annotation; (ii) data extraction; (iii) data consistency; (iv) data structure; and (v) anonymization.

Sensitive data annotation

Data collection in a controlled environment does not exempt the potential existence of sensitive data. Sensitive data can include people, faces, and other vehicles in the test track. Hence, a manual annotation of the sensitive data using internal Zenseact visualization tooling was performed to annotate all potential people, faces, vehicles and license plates. Depending on the type of annotations and the respective sensitive data, two different approaches to ensure privacy protection were taken: (i) remove data from specific time intervals i.e., for vehicles sharing the testing ground contemporaneously; (ii) anonymize images that contain personal identifiable information, i.e., vehicle license plates and human faces.

Data extraction

Once the sensitive data has been annotated and the approaches to ensure privacy protection were chosen for each of the annotations data extraction was performed. Data extraction refers to the process of retrieving and isolate the specific time intervals of interest for the collected data along with removing any proprietary information and data. The extracted data is then stored in a separate disk for consistency verification.

Data consistency

Consistency verification is performed once data has been extracted. The aim of consistency verification is to ensure data completeness for all time intervals of interest, i.e., verify that all sensor suite data is available at all time intervals intended to be shared in the dataset. If data was found to be incomplete, all data for the specific time interval was removed. This substep ensures data completeness.

Data structure

Data structuring refers to the substep where data is structured to comply with previous open datasets. Specifically, the data structure aims to comply with same structures as the Zenseact Open Dataset (ZOD) (Zenseact, 2023). This data structuring facilitates the usage, accessibility, sharing and anonymization.

Anonymization

To comply with privacy regulations such as the European Union's General Data Protection regulation (GDPR) (Voigt & Von dem Bussche, 2017), anonymization was performed through third party services (Brighter AI, 2023). The process anonymizes objects in the images that contain personal identifiable information, i.e., human faces and vehicle license plates. Since the data collection was performed in a controlled environment, the number of images is rather limited. However, anonymization is till necessary.

9.7 Hosting/Availability

The final step is the data transfer and hosting. Data is hosted and accessible to AI Sweden partners (AI Sweden, 2023); a brief description of the data is included in the reference, along with access instructions.

10 WP5 Validation of map and localization performance

First is the WP5 description described in the application after that is the work performed during the project.

WP5	Validation of map and localization performance
Leader (role and responsibility)	Zenseact
Other participants (roles and responsibilities)	RISE: Going to do some validation and analyzation of OpenDRIVE map and dataset.
Description of contents	Development of software for backend map validation and in-car localization in the map of AstaZero.
Method/approach (when relevant)	<p>Validation of the map is done both in backend map validation process (offline) and by assessing the performance of the in-car (online) localization software.</p> <p>The offline map validation is typically done using connected vehicles with sparse data, forward looking camera object data (lane tracker and traffic signs), consumer grade GNSS data, and in-car IMU data (speed and accelerometer). Online localization is continuously done in the autonomous vehicle, and depending on map accuracy and richness of features, the accuracy of the localization will differ.</p> <p>Zenseact will also need to develop software modules for import and compilation of the AstaZero map for access through the Zenseact Map interface. Zenseact Map interface is used in all Zenseact features, including in backend algorithms for map validation and in car software for localization.</p>
Delivery	6.1. Map Compiler for OpenDRIVE format suitable for the AstaZero map content ready Q1 2020.

	<p>6.2 Demonstration of workflow and preliminary results for backend map validation using standard sensors in car. Q3 2020</p> <p>6.3. Demonstration of preliminary localization performance. Q4 2020</p> <p>6.4. Demonstration of final results in map validation and localization performance. Q2 2021</p>
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HD-maps are indispensable tools for autonomous driving, playing an instrumental role in ensuring the safety and reliability of autonomous vehicles. HD-maps offer intricate details about the roadway, including lane markings, crosswalks, traffic signals, signs, among others. This level of detail is crucial for vehicles to make informed decisions about their surroundings and rely on the maps as information for diverse algorithms and features. Specifically, in terms of safety, HD-maps offer a 'ground truth' that allows vehicles to verify their sensor data and consequently, ensure accurate positioning and localization. This acts as a safeguard against sensor errors or blind spots, minimizing the risk of mishaps and reinforcing safety. The depth of information provided by HD-maps also aids in predictive and long-range planning, helping vehicles to anticipate and prepare for upcoming maneuvers and obstacles (Liu, Wang, & Zhang, High Definition Map for Automated Driving: Overview and Analysis, 2019; Liu, Jinling, & Bingqi, High definition map for automated driving: Overview and analysis, 2020).

Keeping HD-maps updated and validated is a prerequisite to their utility in autonomous driving. Given the dynamic nature of roadways with constantly changing environments, construction, new signs or signals, and a variety of other potential alterations, outdated maps can result in miscalculations or erroneous decisions, potentially compromising safety (Shladover, 2018). Thus, it is essential to continuously update HD-maps using techniques like crowdsourcing from connected vehicles. A clear example is traffic sign mapping, to ensure traffic vehicle-detected signs are present in the HD-map, while the data can potentially be shared with potential traffic authorities for inventory and maintenance purposes.

Furthermore, HD-maps can contain extra layers of information related to safety. These layers can include (but are not limited to) hazards such as roadworks. These type of safety related layers can aid autonomous driving related features. A simple example is by having operational design domains for each feature, depending on whether they the vehicle is driving (or not) within a hazardous area.

Hence, in this project we aimed in tackling both the mapping and validation through two specific use cases: (i) traffic sign mapping and (ii) hazard classification, while adding one more concept in the mix: connected vehicles. The concept of connected vehicles is essential to advancing the field of autonomous driving. Connected vehicles, enabled through various communication technologies allow autonomous vehicles to "communicate" with cloud

components. This not only broadens their awareness beyond their immediate sensor range but also allows them to anticipate situations like traffic congestion, road construction, or unexpected hazards that are not within their line of sight. As such, the information shared by connected vehicles can enhance the decision-making capabilities of autonomous driving systems, significantly improving safety, efficiency, and traffic flow. Furthermore, in a connected vehicle ecosystem, updates such as HD-map revisions or software enhancements can be rapidly disseminated, ensuring the continuous improvement of autonomous driving capabilities.

Specific system components to enable connected car-to-cloud-to-car use cases were designed and proof of concept for both cases were developed. In the next section we briefly outline and describe the developed system components.

10.1 System Components

The main common components can be categorized as in-vehicle or cloud components. The in-vehicle components include: (i) Probe data collection; (ii) Feature (de)activation; while the cloud components include: (i) HD-map compiler; (ii) probe data decoding/distribution (iii) HD-map distribution; and (iv) data pipelines/aggregation, i.e., hazard classification and traffic sign mapping. A general representation of these components is depicted in Figure 41. A brief description of each of the components is presented below.

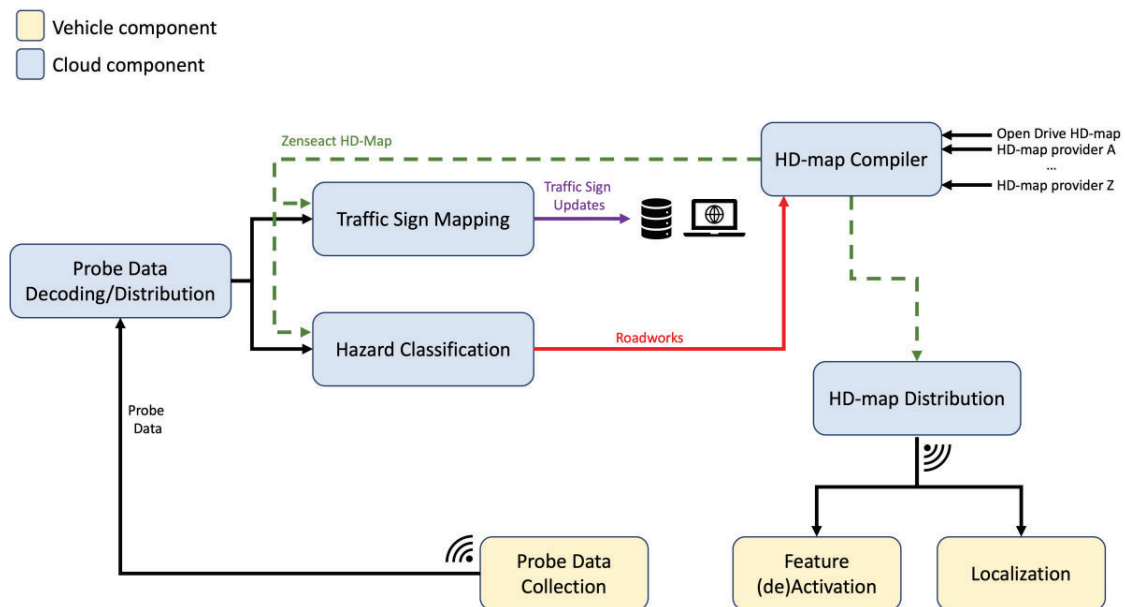


Figure 41: System components.

10.1.1 In-vehicle components

Probe data collection

The probe data collection component acts as the heart of data gathering and transmission for the vehicles. The vehicle produces processed sensor data and events which serve as input to the cloud/data Processing Pipelines. The functions include (i) in-vehicle signal collection; (ii) data encoding/encryption for transmission; and (iii) relay data in real time to centralized cloud-based infrastructure for processing and trend discovery.

Feature (de)Activation and Localization

The feature activation and localization components consume the HD-map data along with the hazard layer. The localization components make use of the HD-map as an extra sensor for localization purposes, while the hazard layer is used by the feature activation component to allow activation or deactivation of specific vehicle features depending on the hazard layer status.

10.1.2 Cloud Components

HD-map compiler

The goal of the map compiler is to produce vendor agnostic baseline maps to be used in the cloud data pipelines as well as in car for different purposes, ranging from localization to data processing. Moreover, the compilation enables the addition of supporting dynamic layers, such as hazard layers, which relate vehicle fleet processed data to HD-map elements for several reasons such as safety-related.

Probe data decoding/distribution

Probe data decoding and distribution is a cloud component/service that focuses on receiving, decoding data into suitable objects for input to the data processing pipelines.

HD-Map distribution

The goal of the HD-Map/Layer distribution block is to distribute the vendor agnostic HD-map and its corresponding dynamic layers to vehicles as needed. Moreover, the component/service also makes HD-maps available for usage within the data processing pipelines. This allows map synchronization usage among vehicles and cloud, and also make use of previous map versions if required.

Hazard Classification

The hazard classification component takes as input probe data and outputs classification decisions on a road level on whether a hazard exists or not around the roads where the fleet is navigating. Hence, the goal of the pipeline, is to find and classify roadwork related scenarios and add them to the corresponding HD-Map layer to be distributed to the vehicle(s).

Traffic Sign Mapping

The traffic sign component takes as input probe data and outputs an aggregated map of traffic signs recognized by vehicles vision components. This traffic sign map is stored in an accessible database for validation, and potential map validation and verification purposes, as well as for potential data sharing with third parties, i.e., traffic authorities. Hence, the goal of the pipeline, is to create a traffic sign base map based on the crowdsourced data from vehicles.

10.2 Hazard Classification

The principal objective of the hazard classification component is to facilitate a holistic and operational proof of concept for the car-to-cloud-to-car system, rather than merely focusing on establishing a high-performance classifier. The inputs for this component comprise probe data, including, but is not limited to, radar detections, lane marking detections, traffic sign detections, vehicle data, i.e., inertial measurement unit outputs, commercial grade GNSS position, dynamic objects, i.e., pedestrians, other vehicles. The output of this component is primarily characterized by hazard/no hazard decisions, which are intrinsically linked to HD-map objects like roads and lanes. This output is then integrated as a dynamic layer within the pre-existing Zenseact HD-Map. This enhanced map is subsequently made available to the entirety of the fleet and other cloud components, thus promoting a more robust and comprehensive navigational and operational ecosystem. A high-level overview of the cloud subcomponents is depicted in Figure 42.

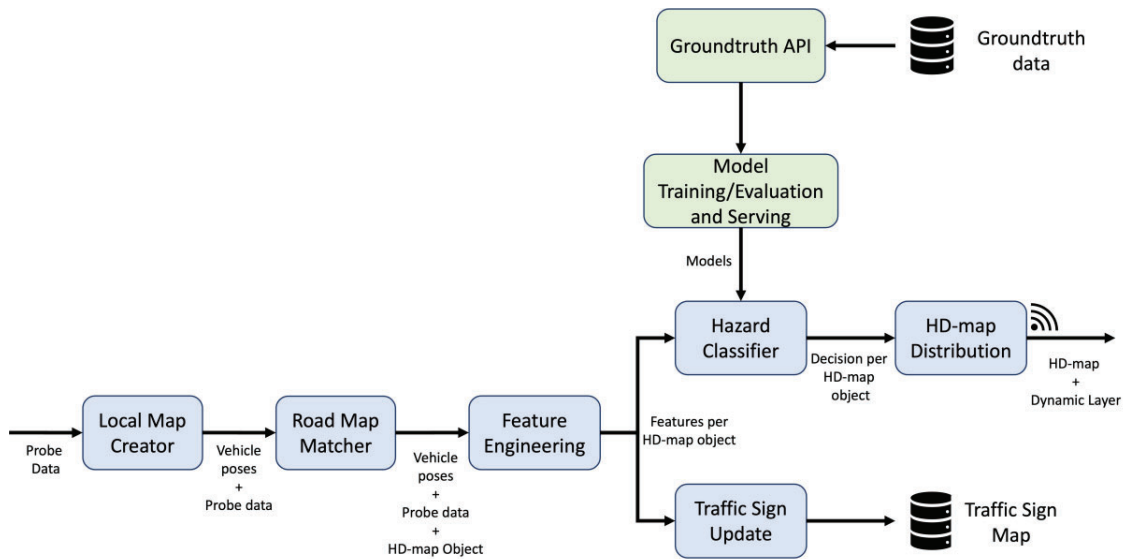


Figure 42: Cloud subcomponents/services for hazard classification and traffic sign mapping.

The process of hazard classification involves a series of sequential steps. Initially, the local map creator component transforms the probe data into what are termed "local maps." These are simplified local representations of probe data associated with each vehicle pose. If a vehicle pose does not exist at the time of a specific detection (probe data), vehicle poses are interpolated through various algorithms that incorporate vehicle data, e.g., inertial measurement unit information. Subsequently, the road map matcher associates each vehicle pose with HD-map objects, specifically lanes and roads, which are essentially sets of lanes.

Upon the relation of probe data to HD-map objects, a process known as feature engineering is initiated. This involves the transformation of data into usable features that are valuable for training, evaluation, and classification, among other functions. Feature engineering is conducted both in real-time and offline to fine-tune features instrumental for classification.

The final step entails hazard classification, which is executed using models trained offline. The resultant decisions are then integrated as a dynamic layer into the existing HD-map. This enhanced version of the map is subsequently distributed to the entire vehicle fleet, augmenting their awareness and operational capabilities.

10.2.1 Scenarios

Hazard-related scenarios in a controlled environment involves the use of specific scenario. The diverse scenarios were designed by Zenseact and executed together with AstaZero. Moreover, RISE aided with specific location information related to the different scenarios, e.g., traffic signs, temporal lane markings. Different examples are depicted in Figure 43, Figure 44 and Figure 45, along with photo examples in AstaZero's rural road in Figure 46 and Figure 47.

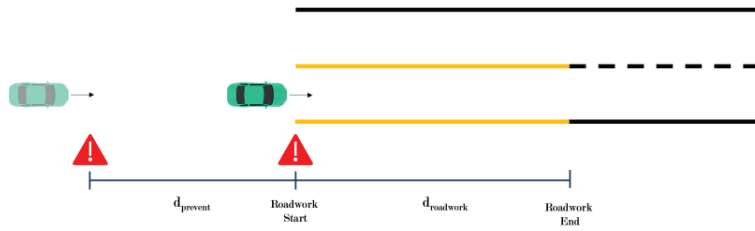


Figure 43: Scenario example. Yellow lane markers on driving lane.

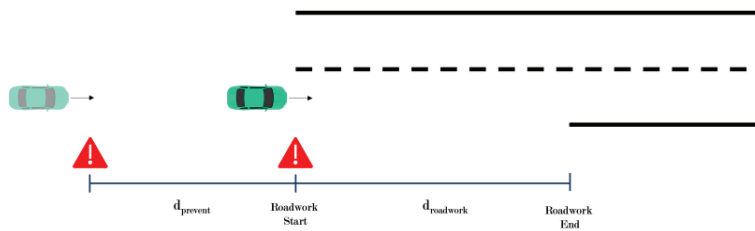


Figure 44: Scenario example. Non-existing lane marker in driving lane.

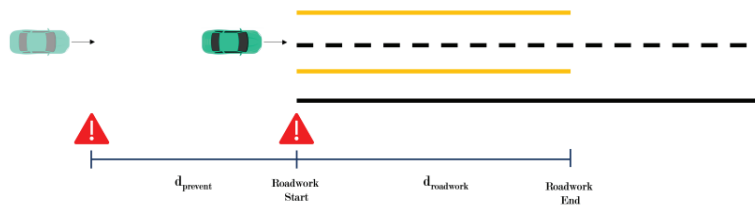


Figure 45: Scenario example. Lane reduction with temporary yellow lane makers.

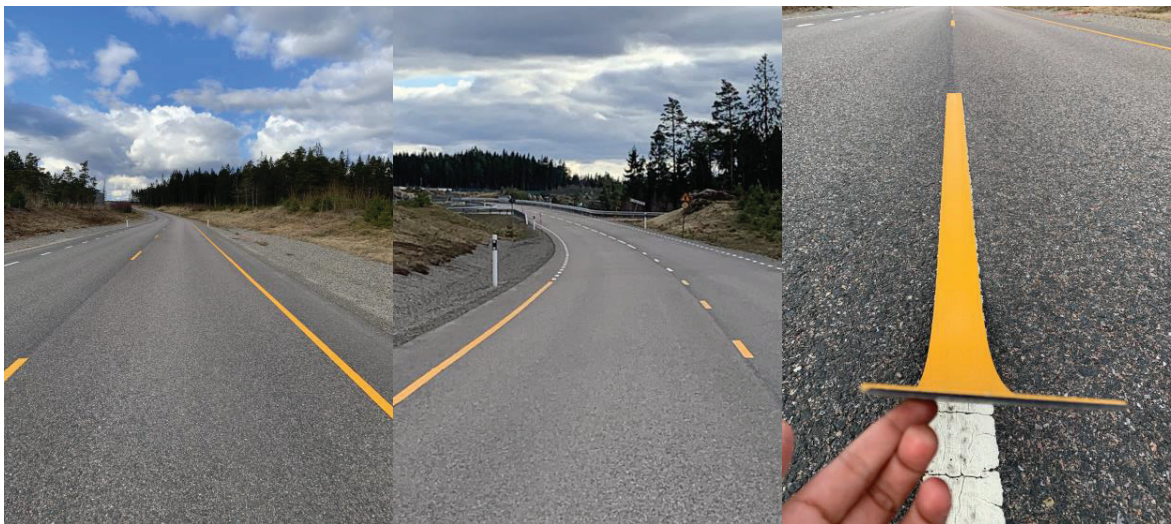


Figure 46: Scenario examples in AstaZero's rural road. Temporal lane marking examples.



Figure 47: Scenario examples in AstaZero's rural road. Temporal traffic sign examples.

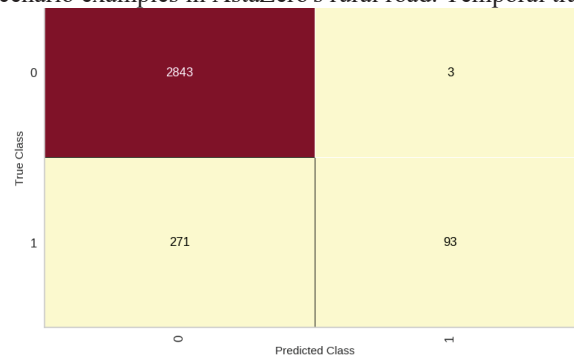


Figure 48: Confusion matrix where class 0, and class 1 represent normal and hazard, respectively.

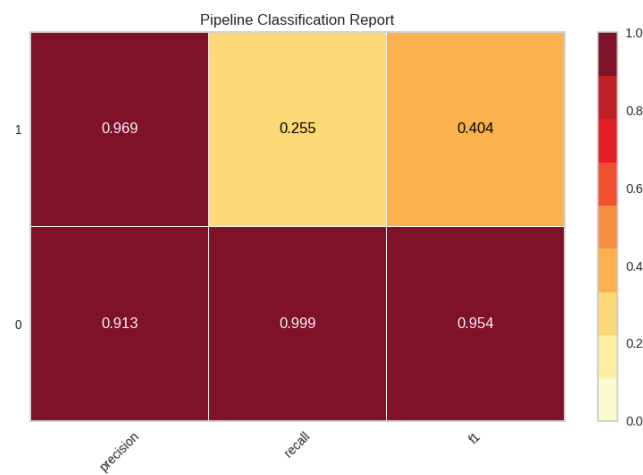


Figure 49: Class report with diverse metrics are available depending on the aim of the classifier.

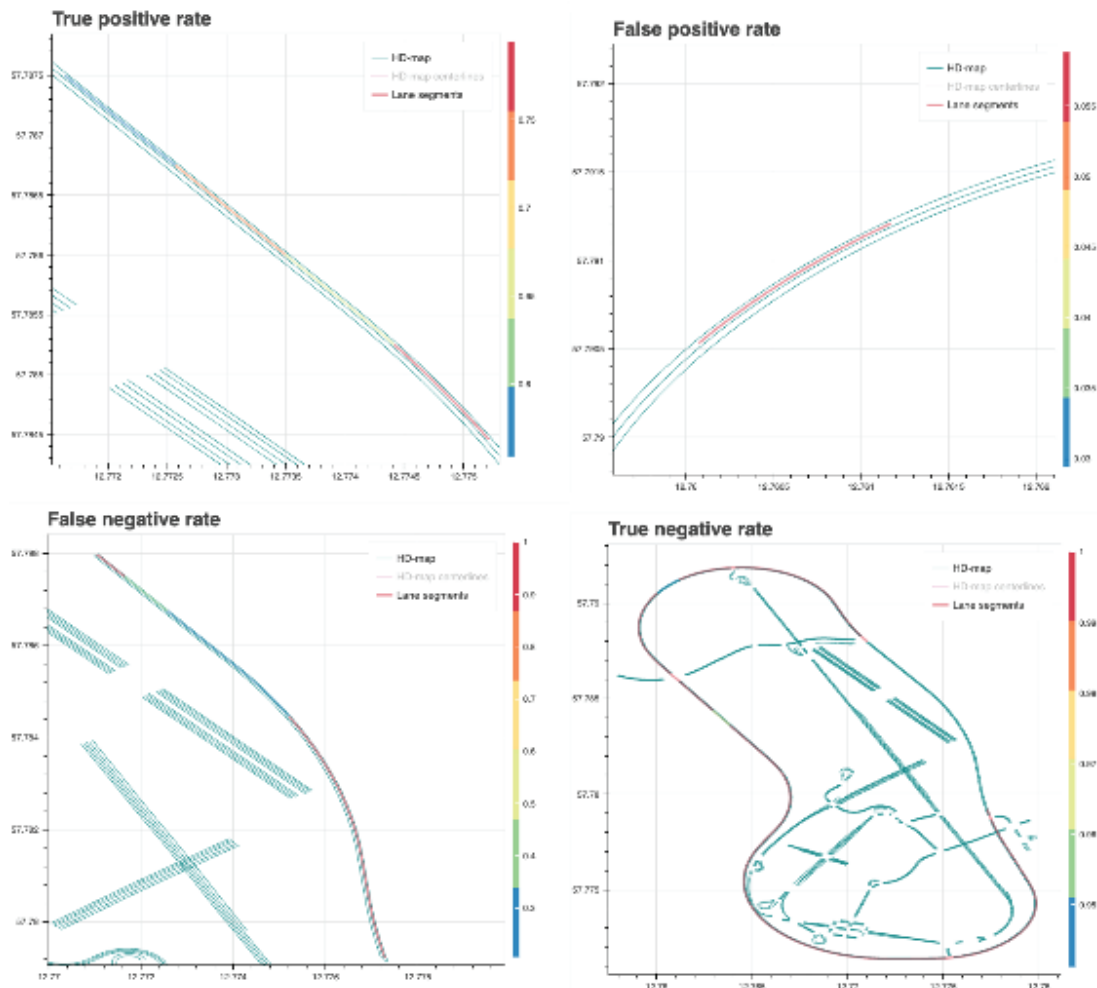


Figure 50: Images of interactive html rates with HD-map example.

10.3 Traffic Sign Mapping

The aim of this component is to enable the use of crowdsourced information from vehicles for traffic sign mapping. Contrasting with traditional mapping systems, which may be outdated or overlook certain updates, crowdsourced data from a multitude of vehicles assure a persistently updated and enriched archive of traffic sign data (Wang, Zhang, Wang, & Sheng, 2016). This crowdsourcing approach proves beneficial in detecting new, temporary, or modified signs, which might otherwise be overlooked. Furthermore, it bolsters the cross-verification of traffic sign data, as any discrepancies can be identified when information from distinct vehicles diverges and allows for cross-verification with HD-maps available in cloud and vehicles. Thus, crowdsourced traffic sign mapping

strengthens the reliability and safety of autonomous driving systems, substantially contributing to overall road safety.

The inputs for this components area probe data, mainly vehicle poses, inertial measurement unit outputs and traffic signal detections, which include information such as the sign type, position with respect to vehicle, and its respective uncertainties. The output of this component are updated and aggregated positions of traffic signs which are stored in an accessible database. A high-level overview of the cloud subcomponents is depicted in Figure 42.

10.3.1 Example Results

Traffic sign mapping was performed throughout the different data collection drives. The traffic sign map was then compared with the ground truth map, where reference traffic sign positions were calculated by RISE as explained in WP2.

Example results for one of the drive collections is shown in Table 7, while in Figure 41 we exemplify the location and uncertainties of a traffic sign. In this example, 21 traffic sings have been included, including “unknown” types, i.e., traffic signs that were not recognized by the vehicle but can still be mapped. The example results for this drive show that 75 % of all mapped signs are within 2.5 meters of their ground truth position.

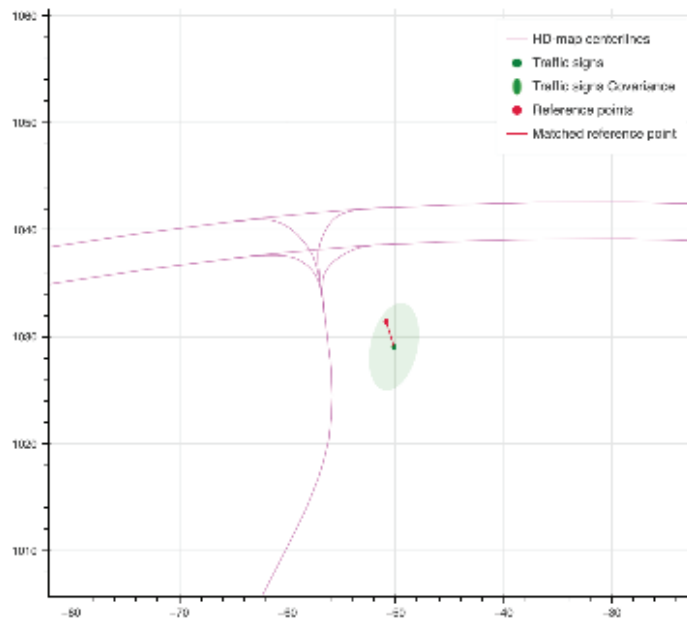


Figure 51: Example of mapped traffic sign and 2 sigmas confidence ellipse.

Table 7: Example traffic sign mapping results form a data collection drive.

	Error Distance	Longitudinal distance	Lateral distance	Number of drives	Number of detections
std	0.899046	1.283280	1.561297	17.199806	527.810031
min	0.302332	-2.033287	-3.257676	10.000000	118.000000
mean	1.787935	-0.187495	-0.203450	23.666667	712.142857
max	3.260228	2.857324	2.026500	70.000000	1920.000000
75%	2.471771	0.415814	0.548195	38.000000	1011.000000
50%	1.693845	-0.759526	0.187518	15.000000	566.000000
25%	1.014209	-0.979547	-1.048731	13.000000	382.000000

11 Dissemination and publications

11.1 Dissemination

The project and the results have been presented both at internal meetings within each partner's organization and at the following external forums and conferences.

- 2021-11-09 MOVE Conference, London.
- 2021-12-02 Organised student day for Chalmers students studying GNSS.
- 2022-03-24 SAFER Webinar, Ascetism & VAMLAV
- 2023-04-04 VAMLAV final presentation on Lindholmen.
- 2023-09-05 Part of RISE public lunch-seminar on "Measurement technology for automated transports."

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	This has increased AstaZeros knowledge within mapping and its possibilities. And the usage and need for data and open data.
Be passed on to other advanced technological development projects	X	AstaZero hope the knowledge here will be continued in future research project that are submitted. Also, the knowledge here is used in existing FFI project at AstaZero for HD-map creation and simulation.
Be passed on to product development projects		
Introduced on the market		
Used in investigations / regulatory / licensing / political decisions		

11.2 Publications

No publication was planned within the project, there was however a possibility of a publication tied to the AOREFM1 anchor point as a reference object. Delays in production, installation and Covid-19 meant this was not achieved within the project. RISE still plans to publish a joint journal article with partners after the end of the project.

RISE employed one master thesis student working within WP2, whose work focused on the stability of the anchor points (Gunashekara, 2022).

The dataset gathered during the project is public at AI Sweden and the possibility to use it for new publications exist.

12 Conclusions and future research

12.1 Conclusions

- When measuring objects with different sensors and/or at different measurement points need to consider an increased measurement uncertainty and/or correct for any offset that arises. Otherwise, there is a risk of underestimating the positioning uncertainty of the object when introducing it in a HD-map, causing other vehicles to trust incorrect information.
- The significance of open datasets in the autonomous driving domain is truly paramount. They serve as the backbone for innovation, supplying the essential information required to train, test, and refine the machine learning models and algorithms that steer these complex systems. By enabling collaboration, standardization, and transparency, these datasets nurture an inclusive research ecosystem, inviting participation from a wide range of stakeholders. As we progress towards a future intertwined with autonomous vehicles, it's vital to ensure that the data propelling this evolution remains open, diverse, and representative of the real-world complexities these vehicles will face, fostering a safer and more equitable autonomous future.
- For the scope of this project, the implementation of traffic sign mapping and hazard classification proofs of concept utilizing connected vehicles has been successfully executed. These components are specifically designed to address the issue of map validation from a connected vehicle and crowdsourcing viewpoint. The implementation of these proofs of concept has accentuated the necessity for disparate in-vehicle and cloud components. These components are vital to the evolution of connected vehicle services, with a primary objective of enhancing safety in the realm of autonomous driving.
- Our project has effectively demonstrated the value that connected vehicles and the associated data can bring to such initiatives. They can serve as critical catalysts towards the development of a fully scalable connected solution. Our success in demonstrating this lays the groundwork for further research and development in this rapidly evolving field.
- The need for HD-maps and the validation of them is paramount for (AV) autonomous vehicles to perform accurate and cost-efficient localization and mapping. They also open the possibility for more simulation within the AV domain. The Proving ground is one such domain that needs to keep up within this topic to help deploy AV. Due to most of AV will be deployed at first in a controlled environment such as a proving ground.

12.2 Future work

Below is a list of topics identified within the project but that were either outside the project scope or possible expansions that were excluded for resource reasons. They are listed below as they are of interest of the partners and that needs further research and development.

- More research within the field of HD-map creation, validation, crowdsourcing, and localization. This project only scratched the surface of the amount of work that will be required for AV to be released.
- This project focused most on deploying the dataset and use it for inhouse research within HD-map creation and validation in the different companies. Next step is to apply it for publication work.
- Additional work on creation of reference object which make sense both for vehicles and within metrology is needed. References should be stable, well defined, and useful in evaluating both single sensors and multi-modal systems. In the case of the anchor point created in this project (A0REFM1) future additions could be modular spherical objects as well as rectangular plates with known reflectivity and dimensions for use in LIDAR validation.
- Infrastructure references for verifying that vehicle systems are working as intended needs to be investigated and developed. It is in the best interest of both manufacturers and consumers that irregularities in AD/ADAS features can be detected without visiting a dedicated workshop or having access to specialised references or hardware.
- The data layers that HD-map way of thinking provides, makes it easier to associate this information layer with an Operative Design Domain (ODD). Where you map the vehicles intended domain with what it perceives by continuously probing its environment and comparing it to the pre-requisite provided by the design, which can be nested within a HD-map structure and thereby help vehicles to know the ODD and if the vehicle is within it's ODD. This is a area that can be very interesting for future research.

13 Participating parties and contact persons

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Zenseact AB	Per Lofter, Gabriel Garcia Jaime
RISE AB	Helena Björk, Carl-Henrik Hanquist, Erik Lindvall
AI Sweden	Beatrice Comoli

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