CLEARANCE MEASUREMENT VALIDATION FOR HIGHWAY INFRASTRUCTURE WITH USE OF LIDAR POINT CLOUDS

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ABSTRACT:

This paper introduces a method to automatically estimate vertical and horizontal clearances of highway viaducts and gantries from Mobile Laser Scanner (MLS) point clouds. It is essential to have accurate data on the vertical and horizontal clearances of overhead infrastructure objects along the highway. Accurate clearance data is used for routing oversized transports, infrastructure reconstruction, maintenance and settling legal claims after incidents. The proposed method takes a point cloud of an infrastructure object as input, and as output provides the user with a concise overview of the horizontal and vertical clearances of the object. A point cloud of a highway overpass or gantry is segmented into the different clusters relevant for determining the clearances. The discrete points in these clusters will then be used to approximate their surfaces with B-splines. Subsequently the minimal clearances can be estimated. These clearances are estimated at certain pre-specified locations according to guidelines from the highway authority. The paper also includes a comparison of the inferred clearances from the point clouds with archived measurements performed by third party contractors. For this case study, a Dutch highway section containing 50 gantries and 20 viaducts is selected. Along this stretch of highway the clearances are estimated. The estimated clearances for each structure are then compared with archived in situ measurements. This will give a quantitative analysis of the quality of the estimated clearances. The estimated vertical clearances have an overestimation of 20-30 mm compared to the validation data. The horizontal clearances show a median underestimation of 20 mm.

1. INTRODUCTION

The Dutch highway network contains more than 3.000 kilometers of roads (Rijkswaterstaat, 2021). Spanning these roads are thousands of viaducts and traffic sign wielding gantries (Figure 1). It is essential to have accurate data on the vertical and horizontal clearances under these objects. This data is used when routing oversized transport, carrying out maintenance or settling legal claims after an incident with oversized transport.

Figure 1. A typical traffic sign gantry on a Dutch highway with in the background a highway viaduct. The horizontal clearance is restricted by guard rails on both sides of the road. (Source: Rijkswaterstaat, 2006)

For all overhead structures along the highway network the clearances are documented according to specifications issued by the executive organisation of the Dutch ministry of Infrastructure and Waterways: Rijkswaterstaat. These specifications (Rijkswaterstaat, 2019) describe at what locations under a structure and with what margin of error the clearances should be measured.

Traditionally these measurements are taken in the field with usage of geodetic devices such as a total station, rangefinder or laser scanner. Measurements and documentation are usually performed by a third party contractor and involve a lot of manual work. To guarantee the quality of this data the measurements need to be validated. For the validation of measurements yearly Mobile Laser Scanner (MLS) point clouds are available for the complete Dutch highway network.

This study introduces a method to automatically estimate clearances under viaducts and gantries from MLS-point clouds with a geometric approach (Figure 2). The paper is structured as follows. In the section Background information will be given on related research and guidelines for determining clearances. The section Method will show a step by step workflow for estimating the vertical and horizontal clearances. In the section Case Study and Results the method will be validated on two sections of highway in the Netherlands.

2. BACKGROUND

This section gives some insight into related researches and also provides information on the definition of a 'minimal' clearance used in this research.

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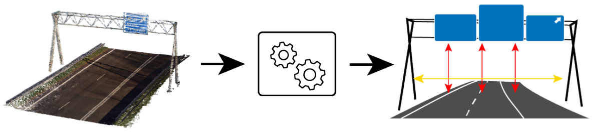

Figure 2. A simplification of the tool to be developed in this research. A point cloud of a gantry is taken as input and processed. The result is a visualization with the estimated clearances.

2.1 Related research

Gargoum et al. (2018) propose an algorithm whereby mobile LiDAR data is used to assess vertical clearance at overhead objects on highways. The algorithm detects and classifies all overhead objects on a highway segment. At each detected object the minimal clearance is determined. This research mainly focuses on vertical clearances under viaducts and power lines and does not cover gantries. The location where the vertical clearance should be determined is manually defined by the user. Differences between estimated clearances and conventional measurements were up to 15 cm.

Point clouds often contain differences in point density. This variation is expected to affect the quality of the information that is inferred from the point clouds. Gargoum and El-Basyouny (2022) investigates the impacts of point density reduction on the extraction and assessment of different geometrical features. The different geometrical features were extracted from a point cloud at varying levels of point density and on a selection of different Canadian highway segments. It was found that clearance assessments on viaducts had low sensitivity to reductions in point density. Reductions to 10% of the original data yielded comparable results to what was obtained at 100% point density. Low point density can however cause an inability to detect accurate clearances under short span overhead objects i.e. power cables or gantries.

In Zhang et al. (2013) a method is proposed to estimate vertical bridge clearances by using terrestrial laser scanners. The study introduces an approach to reduce data noise caused by nearby traffic. The locations of the vertical clearances are determined manually. No quantitative assessment was performed on the accuracy of the estimated clearances.

Railway tunnel clearance is directly related to the safe operation and freight capacity of trains. In Zhou et al. (2017) a tunnel clearance inspection approach is presented based on 3D point clouds obtained by a mobile laser scanner system. A dynamic coordinate system for railway tunnel clearances is introduced. By using a 3D linear fitting algorithm on a segmented point cloud the rail line can be extracted and is used to seamlessly connect all rail segments. Based on the rail alignment and the clearance coordinate system different types of clearance frames are introduced to perform the tunnel clearance inspection. The claimed precision reaches 0.03 m.

In a review of mobile mapping and surveying technologies, (Puente et al., 2013), an analysis is introduced on the performance of some modern mobile terrestrial laser scanning systems. The study presents an overview of the positioning, scanning and imaging devices used in these systems. A systematic comparison of the navigation and LiDAR specifications from the manufacturers is provided. Based on the accuracy requirements for a mapping or surveying project a best solution is found taking into account all scanner specifications.

2.2 Guidelines for clearances

There is not one universal method for documenting minimal clearances under viaducts and gantries. In this research the guidelines of the Dutch highway authority were used as a base (Rijkswaterstaat, 2019).

The **vertical clearance** is a measurement perpendicular to the road surface between a viaduct or traffic gantry and the underlying pavement. The minimal vertical clearance is found where this distance is the smallest. The vertical clearance measurements must meet the following requirements: The precision σ should be $\leq$1.0 cm and the measurements should be presented with 3 decimals. The locations of the clearance heights have different requirements for each type of object.

For a highway viaduct the following applies:

- The vertical clearance should be determined on each lane border road marking and on the asphalt edges.
- For each driving direction two clearance cross sections should be provided. The first one at beginning of the object and the second one at the rear of an object. The location of the front is determined based on in what direction the hectometer signs along the road are increasing in value.
- Double highway bridges less than 3 meters apart are seen as one object. When the gap in between is larger than 3 meters both bridges are seen as individual objects.

For traffic sign gantries the minimal vertical clearances should be determined for each lane including rush hour lanes, entry or exit lanes and emergency lanes. If there is no road sign or lane control sign directly above a lane the vertical clearance is determined from the pavement to the gantry's suspension structure.

The **horizontal clearance** is the minimal horizontal distance perpendicular to the driving direction between obstacles that are positioned alongside the pavement. Obstacles here are defined as guardrails, bridge columns or gantry columns.

The horizontal clearance measurements must meet the following requirements: The precision σ should be $\leq$5.0 cm and the measurements should be presented with 2 decimals. For the location of the horizontal clearance the following applies:

- The horizontal clearance must be determined at a height between 0.5 m and 1.0 m above the pavement. The height of the guardrail should fall within this range.
- In a situation where there is no guard rail on one or either side of the road, the width of the roadway cannot always be clearly defined. If the boundary of the clearance width on one or both sides of the road cannot clearly be indicated, for instance due to the absence of obstacles as stated previously, the edge of the pavement is taken as the boundary.

3. DATA

For this paper mobile mapping data two sections of highway were selected. Along these two sections the clearances will be estimated with the proposed method. In total 20 viaducts and 50 gantries will be processed. The MLS-point clouds that are used are all obtained with similar equipment and thus have similar characteristics.

The point clouds are obtained using a Velodyne HDL-32E LiDAR sensor which generates 700.000 points per second with a claimed relative accuracy of approximately 2 cm (Velodyne, n.d.). GPS combined with an Inertial Measurement Unit is used to present the xyz-coordinates in the RD-New (EPSG:28992) reference frame. The point cloud is delivered as a .laz file and for all points it contains five attributes; intensity, number of returns, return number, GPS time and RGB color. The RGB values are derived from a separate 360° panoramic image sensor.

A typical gantry contains 40.000-50.000 points. This is considerately less than a highway viaduct which contains on average 300.000-500.000 points. This is not including the asphalt.

4. METHOD

To estimate the clearances under a viaduct or gantry, the proposed method is divided into three components: (i) Vertical clearance estimation under a viaduct, (ii) vertical clearance estimation under a traffic gantry and (iii) horizontal clearance estimation. All three components require the location and orientation of the road markings, therefore the segmentation of the road surface and the road markings is the first step.

4.1 Step 1: Surface segmentation

The workflow for extracting the road surface consists of multiple steps briefly explained below:

1. A quadtree representation (Truong-Hong and Lindenbergh, 2022) aims to reduce the complexity of the original point cloud. The quadtree is carried out to recursively subdivide the initial point cloud into increasingly smaller 2D cells. This is carried out until the termination criterion is reached i.e. when a subdivided cell contains fewer points than a predefined threshold.

2. For all cells the local surfaces are extracted. When the input point clouds contains a viaduct, the remaining cells can contain multiple horizontal surfaces; the road and the bridge superstructure. Since the surfaces are expected to be concentrated in different groups in vertical direction, a kernel density estimation (KDE) (Truong-Hong and Lindenbergh, 2022) is used to establish the location of the local surfaces. These local surfaces are assumed to be nearly horizontal.

3. In this step planes are fitted to the different surfaces in each cell. Cell-based region growing (Truong-Hong and Lindenbergh, 2022) is applied to group the planes from the different patches that belong to the same surface. Some additional patch filtering is applied to obtain appropriate surface edges.

4. Now that multiple surfaces have been extracted it is necessary to classify them with the correct class. Road and bridge surfaces are extracted from the set of surfaces derived in the previous step.

When the input point cloud contains a traffic gantry, the output of the road surface segmentation will only contain a single horizontal surface; the road surface. When the input point cloud contains a highway bridge, the surface extraction will output two surfaces; the road surface and the bottom of the bridge superstructure.

4.2 Step 2: Road marking segmentation

Segmentation of the road markings gives information on the orientation of the road and the location of the lane borders, which are useful since the vertical clearance is determined for each lane. This step distinguishes 4 types of markings: (1) dashed markings, (2) block markings, (3) continuous markings and (4) the asphalt edge. The asphalt edge is not a painted-on road marking, but it often defines the right border of an emergency lane. The workflow for segmenting the markings is as follows:

4.2.1 Dashed markings The dashed lines are very distinguishable from the dark asphalt surface in the point clouds. The white paint that is used for applying the road markings give points on these surfaces a much higher intensity value than the surrounding asphalt. Applying a simple intensity filter on the extracted road surface from step 1 and subsequently using the DBSCAN clustering algorithm (Ester et al., 1996) yields a set of clusters containing different kinds of road markings. To filter out only the dashed markings a cluster-based feature filter is used with PCA features. Several features have already been proposed by West et al. (2004) & Hackel et al. (2016). The following geometrical features are selected and give information on what type of road marking a cluster potentially belongs to:

- **Orientation:** With the assumption that all road markings are parallel (only small sections of road are considered at once) all markings should have the same orientation. The orientation is defined by the first eigenvector corresponding to the largest eigenvalue λ_1.

- **Length:** The largest eigenvalue λ_1 of a cluster gives information about the variance in the direction of the first eigenvector. Dashed lines as well as block markings have generic dimensions which should suggest that all dashed markings and all block markings should have similar characteristics.

- **Width:** Similar to the length, the second eigenvalue λ_2 gives information about the variance in the direction of the second eigenvector perpendicular to the first eigenvector.

- **Roughness/height:** The third eigenvalue λ_3 gives information about the variance in the direction of the third eigenvector. Since road markings usually correspond largely to 2D planes on the road surface, the variance in the direction of the third eigenvalue should be very small ($\lambda_3 \ll \lambda_1$).

- **Linearity:** The linearity of a cluster is a geometrical feature that can be derived from the eigenvalues. To describe the linearity of a cluster:

$$\textbf{linearity} = \frac{\lambda_1 - \lambda_2}{\lambda_1} \quad (1)$$

- **Planarity:** The planarity is a cluster is described as:

$$\textbf{planarity} = \frac{\lambda_2 - \lambda_3}{\lambda_1} \quad (2)$$

4.2.2 Block markings The segmentation of block markings has a similar approach to the segmentation of dashed markings. The PCA filters uses the same features with different thresholds for the length, width and linearity.

4.2.3 Continuous lines For continuous lines it is also possible to segment and classify them from the point cloud using a method similar to the method for dashed markings. However, an approach using a Hough transform (Hough, 1962) for detecting lines is more simple and gives more reliable results. The Hough method used here takes as input a 2D image. The point cloud itself is a collection of points in 3D space, so some pre-processing has to be done in order to obtain a 2D image of the point cloud that can be fed to the Hough algorithm.

First the 3D point cloud is converted to a 2D image from a bird's eye perspective with full and empty pixels. Some basic opening and closing morphological operations, (Vincent, 1993), are performed to remove noise and improve the visibility of the painted markings in the input image.

4.2.4 Asphalt edge The asphalt edge is not a painted road marking but to detect it a similar approach to the continuous line detection can be used with one extra pre-processing step. After the opening and closing operations a silhouette of the asphalt remains. The edges of the asphalt need to be converted to distinct lines. With a Canny filter, (Canny, 1986), an edge detection algorithm, the asphalt silhouette is transformed into an asphalt outline. This outline is detectable by the Hough algorithm.

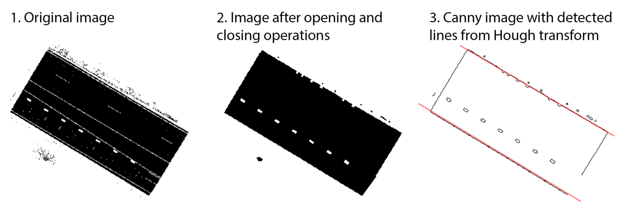

Figure 3. An overview of the pre-processing steps taken for the detection of the asphalt edges. (1) is the original 2D image obtained from the point cloud. (2) the result of a closing-opening operation. (3) the final input image for the Hough transform after applying the Canny operation overlapped with the detected Hough lines.

4.3 Viaduct vertical clearance estimation

Assuming that step 1 yielded a surface for both the road and the bottom of the bridge superstructure, it is now possible to approximate both surfaces with a 2D B-spline and infer the minimal vertical clearances for each lane from these B-splines. B-splines are suitable to represent smooth, non-planar surfaces. The goal here is to find the surface best approximating the points in the segmented surface. By taking the tensor product of two 1D sets of basis functions that describe the surface in the x and y direction, a basis for the 2D polynomial describing the 2D surface is obtained. This is also known as the 2D bi-cubic approximation method, see (De Boor, 1978).

The minimal vertical clearance is now estimated as the minimal vertical distance between the estimated bridge and road surfaces. This clearance is estimated for each traffic lane.

4.4 Traffic gantry vertical clearance estimation

A gantry has a more complex shape than the bottom of a highway bridge, which means that a 2D B-spline is not suitable to describe the bottom edge. This method will use multiple 1D B-splines to describe the irregular bottom edge of the gantry superstructure. Assuming that the road surface already has been segmented in step 1, the steps to determine the vertical clearance under a gantry are as follows:

1. A DBSCAN clustering algorithm is used to cluster the point cloud remaining after the removal of the road surface. To classify the gantry cluster correctly, PCA features are calculated for all clusters similarly to Section 4.2.1.
2. By performing a Hough transform on a top-down 2D image of the classified gantry cluster, the orientation can be determined. Its orientation should be perpendicular with the road trajectory in the xy-plane.
3. The skeleton of a gantry's superstructure can be characterized as an extruded triangle with the point facing downwards. Along the extruded edges there are steel tubes. The bottom steel tube is always present and defines the upper limit of the bottom edge. A kernel density estimation of the z-values in the remaining point cloud is used to identify the location of the bottom tube. All points above this steel tube are discarded since they are not relevant for estimating the bottom of the superstructure.
4. To identify the edge points of the remaining cluster, its alpha shape, (Edelsbrunner et al., 1983), is computed. The bottom edge of this alpha shape contains all the points needed for estimating the bottom of the gantry.
5. The remaining clusters (see Figure 4) are a collection of edges from different signs and tubes. For each edge a B-spline is computed that closely follows the points.
6. The vertical clearance is now estimated as the minimal vertical distance between the 2D road B-spline surface and the B-splines at the bottom of the gantry. The minimal vertical clearance is determined for each traffic lane.

4.5 Horizontal clearance estimation

Most often the horizontal clearance under a viaduct or gantry is restricted by guard rails on either side of the road. Hence, the workflow for finding the horizontal clearance starts with looking for guard rails. If there is no guard rail present the algorithm will look for other objects restricting the horizontal clearance. The process for finding the horizontal clearance is as follows:

4.5.1 Classification of guard rails Guard rails are predictable structures. Their height above the road surface and the horizontal distance from the asphalt edge do not vary much. A first step in segmenting the guard rails from the point cloud is by using the DBSCAN clustering algorithm. Before using the clustering algorithm a few assumptions are used:

1. Assumption 1: The guard rail is located at a height of at least 30 cm above the road surface.
2. Assumption 2: Points more than 2 m above the road surface are not considered for the horizontal clearance.
3. Assumption 3: The road surface is already classified in the lane detection step. These points can be disregarded when searching for the guard rails.

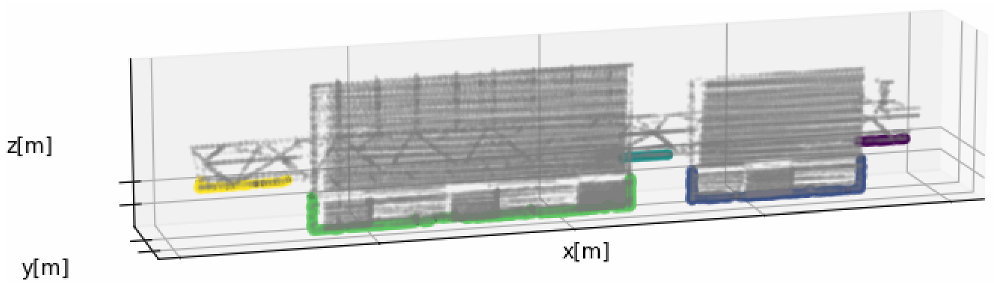

Figure 4. Each color/cluster represents part of the gantry bottom edge.

The clustering algorithm can do a good first segmentation step, but often the clusters containing the guard rails also contain a lot of grass. This is not odd since grass can easily grow high enough to make it difficult for the clustering algorithm to find a border between the guard rail and the grass. To resolve this problem some knowledge of the dimensions of standard guard rails is used.

A candidate cluster possibly containing a guard rail and possibly grass is divided into multiple sections along its main axis with a length of approximately 25 cm. For each section a kernel density estimation is performed of the z-values with a Top-hat filter (Laefer and Truong-Hong, 2017). This Top-hat filter has a total bandwidth of 30 cm. Since the height of a guard rail bumper is also 30 cm the KDE should give the highest signal on a height equal to the center of the bumper as shown in Figure 5. The information on the approximate center of the guard rail bumper can now be used to remove grass from the guard rail cluster candidates.

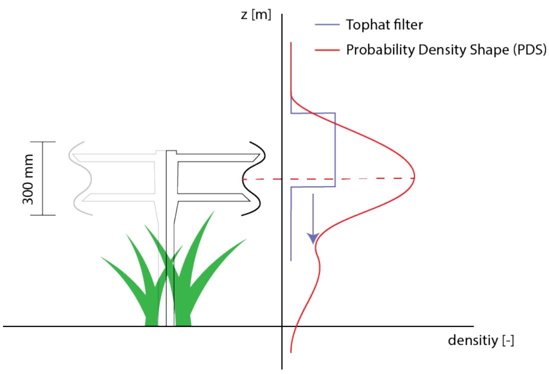

Figure 5. PDS of KDE along the z-axis with a Top-hat filter moving in the z-direction.

4.5.2 Other objects restricting the horizontal clearance

If no guard rail is present on the side of the road, the algorithm will look for other clusters of points located alongside the asphalt. Other objects restricting the horizontal clearance are bridge columns, gantry columns, concrete barriers, etc. The same assumptions from Chapter 4.5.1 are used.

4.5.3 Determining the minimal horizontal clearance

Assuming that an object restricting the horizontal clearance has been found on either side of the road, the horizontal clearance can now be estimated. The location of the estimated horizontal clearance along the road trajectory is determined by the location of the viaduct or gantry superstructure.

5. CASE STUDY AND RESULTS

The case study consists of a set of gantries and viaducts from two separate Dutch highway sections (Figure 7). These sections have been selected since they have recent (<1 year) validation data available. To analyze the accuracy of the estimated clearances, the developed method is applied to an amount of 50 traffic gantries and 20 viaducts. Each gantry yields a single horizontal clearance and for each lane 1 vertical clearance (Figure 9). A viaduct yields 2 horizontal clearances and for each lane 2 vertical clearances since the clearances are determined on both sides of the bridge as seen in Figure 8. The highway location sign on the right in green gives information on the road name, the direction ('Re' for Right and 'Li' for Left) and the location in kilometers. The white arrow on the sign indicates in what direction the kilometer value is increasing. The results for the clearance estimation errors are shown in Table 1.

Table 1. Statistics of the results [mm]

	Median Error	**MAD**
Vertical clearance gantry	-23	10
Vertical clearance viaduct	-33	7
Horizontal clearance	20	30
Vertical clearance gantry (50% subset)	0	7
Horizontal clearance ganrty (50% subset)	0	0

The median absolute deviation (MAD) is given instead of a standard deviation since the MAD is a more robust estimator of dispersion; it is not affected by outliers. The distribution of the errors is shown in Figure 10. The results in Table 1 and Figure 10 show that the proposed method overestimates the vertical clearances by 23-33 mm. However, the horizontal clearances show a median underestimation of 20 mm.

The outliers of the vertical clearance errors in Figure 10 at -80 and 40 mm are caused by an inaccurately detected asphalt edge. If the detected asphalt edge line is not located on the asphalt but instead just outside of the paved surface, there can be a significant difference in the estimated vertical clearance. Moreover, the road surface 2D B-spline also gives inaccurate results (z-values) when evaluated outside of the road surface.

To assess the sensitivity of the method to a more sparse point cloud a single gantry point cloud is randomly sub-sampled 100 times with 50% of the data. On these subsets the clearances are determined. This shows a MAD of 0 mm for the horizontal clearances and a MAD of 7 mm for the vertical clearances.

Figure 6 shows that the bottom edge of a sign is not always accurately estimated. In this situation the MLS point cloud did not cover the complete traffic sign surface leaving gaps in between scan lines and a rough bottom edge. A possible explanation could be occlusion by a passing vehicle or because the used laser scanning device has a sparse scan line spacing. This sparse scan line spacing is also apparent on other parts of the sign since there are multiple 'empty' areas visible in the figure.

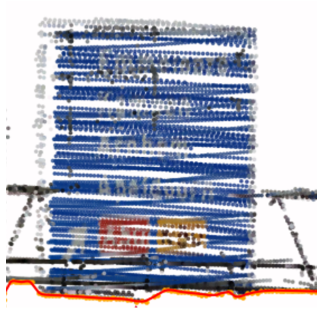

Figure 6. An inaccurately estimated sign bottom edge in red.

6. CONCLUSION AND RECOMMENDATIONS

This paper presented a method for estimating clearances under highway bridges and gantries with point clouds obtained from a Mobile Laser Scanner. The relevant surfaces and edges that determine the horizontal and vertical clearances are estimated with B-splines. The results from the case study show an apparent overestimation in the vertical clearances. This does assume that the validation data is accurate and serves as a ground truth.

The overestimation could be a consequence of the relatively sparse MLS point clouds that are used in this research. Gantries and traffic signs are slender structures and it sometimes difficult for the laser scanner to cover a bottom edge of an object that is only a centimeter thick.

The horizontal clearances is not sensitive to a significant decrease in point density. Vertical clearances however seem more sensitive. A possible explanation is that a gantry superstructure is only sparsely represented in the MLS point clouds with individual points on the bottom edge of a gantry superstructure often not covering the true bottom edge. Guard rails on the side of the road are more densely covered in points and also have a more constant profile.

There are a lot of parameters in this method that can be tuned in order to achieve a higher clearance accuracy. A sensitivity analysis on different parameters for the B-splines, DBSCAN, Hough transform and PCA could give better surface and edge estimation. This could yield better and more consistently accurate clustering results.

The point cloud data used in this research has a limited density and relative accuracy. It would be interesting to estimate and validate the clearances on point clouds with a higher density and relative accuracy. This higher relative accuracy can be reached by using a more high end laser scanner.

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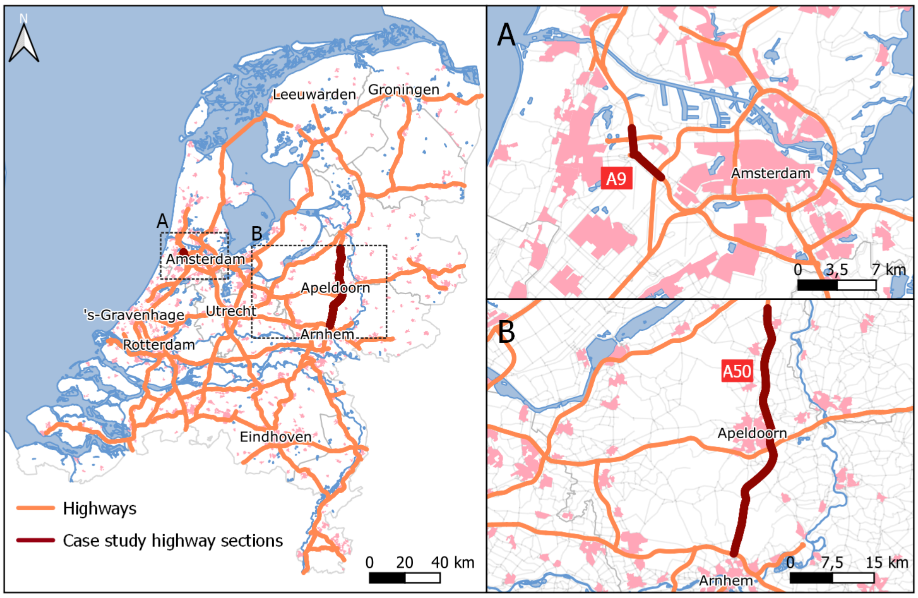

Figure 7. Overview of the selected sections for the case study.

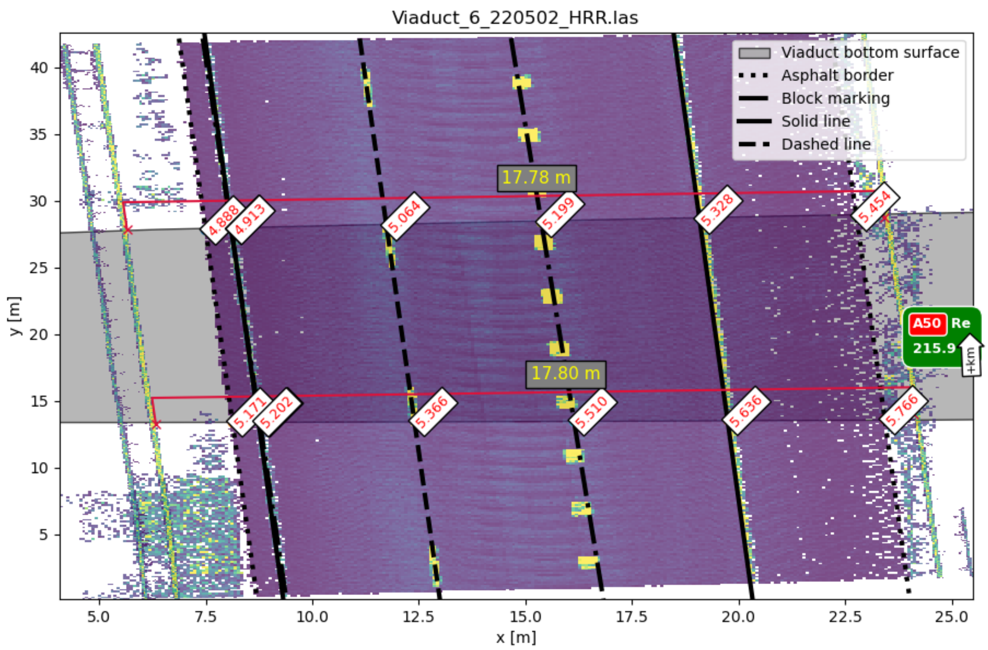

Figure 8. Example of the estimated clearances under a viaduct. The vertical clearances are shown in red and the horizontal clearances in yellow.

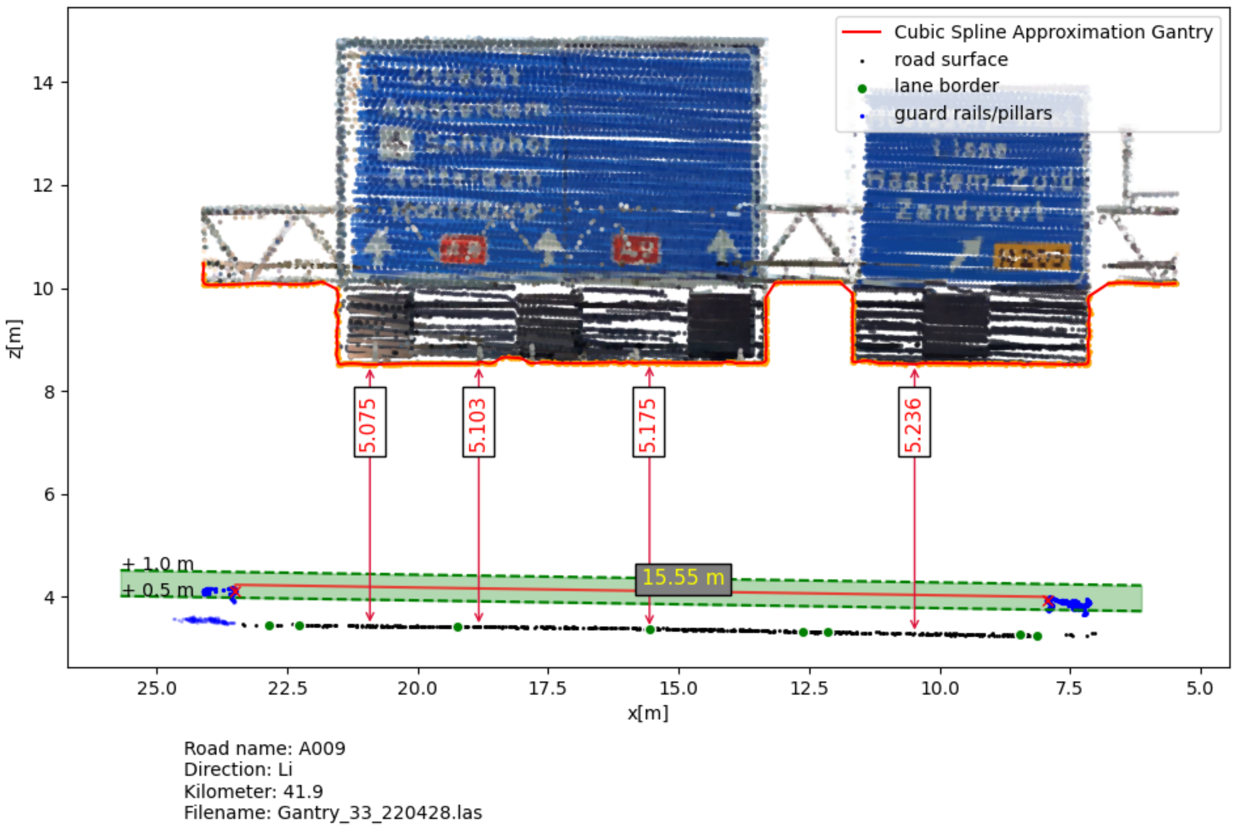

Figure 9. Example of the estimated clearances on a single gantry. The measurements are given in meters.

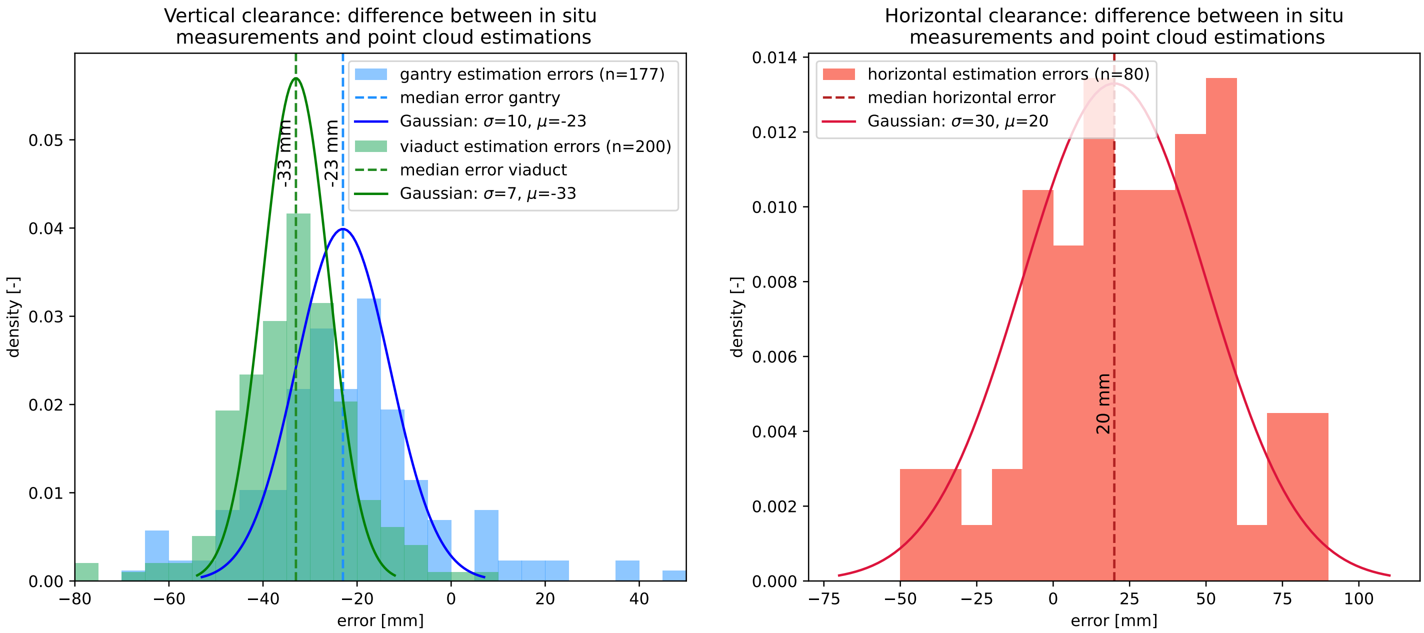

Figure 10. Histogram of errors of the estimated clearances.