

Automated Assessment of Sight Distance on Highways Using Mobile LiDAR Data

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Abstract:

One of the most important elements in highway design is the sight distance available to road users. Sight distance is the visible distance required by a driver to complete a certain maneuver (e.g. coming to a complete stop). If the available sight distance is less than design requirements, the likelihood of a driver safely completing that maneuver decreases. Current methods of measuring sight distance are very difficult, labour intensive and time consuming. Existing methods to obtain sight distance information require field visits or graphic analysis of as-built drawings. This paper proposes an algorithm to automatically extract sight distance from Light Detection and Ranging (LiDAR) data by simulating observer and target points along the virtual highway. LiDAR data is first used to create a surface model of the road. Points representing observers and targets are then created along the highway of interest. ArcGIS software is then used to create lines between the observer-target pairs and obstructions blocking the sightlines are then detected in ArcGIS. A VBA algorithm is written to compute the available sight distance along each sightline. The proposed algorithm was tested on a segment on highway 36 in Alberta. The extracted information was compared to Alberta highway design guidelines and limitations were found to both stopping and passing sight distance on existing highways. It was found that minimum stopping and passing sight distance requirements were not met in two regions. In order to analyse the impacts of sight distance limitations on safety, collision records at limited sight distance locations were assessed. Fixed object collisions and animal collisions were common in those areas, indicating that sight distance limitation could have been a factor in collision occurrence. The method developed in this study could be extremely useful in timely assessment of sight distance on highways, which could, in turn, help address limitations before safety problems arise.

1. Introduction

When designing vertical and horizontal alignments on highways an important factor which must be considered is the available sight distance. Sight distance is generally defined as the minimum distance required by a driver to complete a certain maneuver (Alberta Infrastructure 1999). Minimum stopping sight distance, for instance, is the minimum distance required by a driver to come to a complete stop before hitting an obstruction on a roadway. This includes the perception reaction time required by the driver and the breaking distance required to come to a complete stop. Similarly, passing sight distance is the distance required for a driver to complete a passing maneuver on two-way undivided highway. Whether it is stopping sight distance, passing sight distance or even intersection sight distance, highway design guides around the world require that minimum standards for those features are met when designing roads (TAC 1999, AASHTO 2004). In fact, many researchers have found that those features have significant impacts on the traffic safety and the operation efficiency on a highway (Glennon 1987, Ibrahim *et al.* 2012).

Minimum stopping sight distance is used to compute the length of vertical curves as well as determine the offset that must be provided along horizontal curves. Therefore, in theory, designing curves based on the minimum stopping sight distance requirements ensures that this distance is available at any point along the curve. Despite that, the assumptions associated with the estimation procedure and certain project constraints (financial or practical) mean that there may be locations along a highway where minimum requirements

are not met. Moreover, pavement operations such as relaying projects often affecting the original design of highways.

To that end, frequent evaluation of sight distance on highways is necessary to ensure that standards are met throughout the service life of the highway. However, despite its importance, assessment of sight distance at every point on existing highways is a time consuming process that is resource intensive and, occasionally, impractical. As a result, interest has moved towards automating the assessment process in attempts to save agencies the burden of conducting manual graphic assessments or site visits to ensure that minimum safety requirements are met.

With the increase in computing power, the use of remote sensing technology in the field of transportation engineering has gained popularity in recent years. In fact, the relative ease with which Light Detection and Ranging (LiDAR) data can be collected has enabled transportation departments to have access to detailed information about highways at a quicker rate. Various LiDAR scanner types have been employed to collect data. These scanners generate a point cloud containing millions of points depicting the roadway and surrounding features. LiDAR has proven effective in the collection of data for many transportation applications. These applications range from automated traffic sign inventory (Ai and Tsai 2014, Weng *et al.* 2016) to automated road marking extraction, edge extraction (Kumar *et al.* 2013, Guan *et al.* 2014) and the extraction of 3D road scenes (Yang *et al.* 2013).

This paper proposes an algorithm through which assessment of sight distance along a highway can be performed on a virtual LiDAR highway. The proposed algorithm makes use of ArcGIS line of sight tools to conduct the assessment between multiple observer and target points, a visual basic program is then written to analyze the outputs of ArcGIS and compute the available sight distance along the highway. The code is also written to determine whether stopping sight distance requirements are met at each point along the highway. In case of passing sight distance assessment, the process involves additional steps where the centerline of the road is extracted to identify regions where passing is permitted. Passing sight distance is then assessed at those locations only. The proposed methodology is tested on a highway segment in the Province of Alberta, Canada with results revealing obstructions to both stopping sight distance and passing sight distance on a small portion on the segment. For locations where sight distance limitations were found, collision records were analyzed to identify whether or not limitations to sight distance might have contributed to crash occurrence.

2. Previous Work

In recent years, researchers have turned to using LiDAR data in sight distance assessments. In their paper, Khattak and Shamayleh (2005) explored the feasibility of using aerial LiDAR data to assess sight distances on highways. Data collected along a short segment of Highway 1 in Iowa, US was imported into ArcGIS to create a Triangulated Irregular Network (TIN) surface. The created surface was then inspected visually and any potential problematic locations (in terms of stopping and passing sight distance) were marked. The Line of Sight tool (in ArcView) was then used to further assess sight distance at problematic locations. Moreover, field validation was also conducted to confirm

limitations in sight distance at suspect locations. Based on the results, the authors concluded that LiDAR was indeed effective in sight distance assessments.

Castro *et al.* (2011) used ArcGIS to develop a method to obtain available sight distances along highways. The method involved the creation of a Digital Terrain Model (DTM) raster, which, along with observer inputs, allows for the computation of Viewsheds. Viewsheds denote areas on the raster that are visible from the observer. All visible areas are converted into polygons and then intersected with a vehicle trajectory obtained from a GPS survey. The distance between the observer and the closest intersection is taken as the available sight distance. The sight distances obtained were compared to values given by highway design software, Trivium. Although, statistical analysis showed no significant difference between the obtained and design data, there were several locations where the design software reported shorter sight distances, as it can better detect vertical curve obstructions.

A few years later Castro *et al.* (2013) developed an automated method for sight distance detection using ArcGIS tools. The method uses aerial LiDAR data to create a DTM. The visibility of multiple target points from a single observer are then assessed using ArcGIS tools until an obstruction is detected. At that point, the available sight distance is noted as the distance between the observer point and the last visible point. The obtained sight distances are compared to those found in (Castro *et al.* 2011) using Kolmogorov-Smirnov and Wilcoxon tests which revealed no statistically significant differences.

In a different study, Castro *et al.* (2016) attempted to show differences in accuracy between DTM (bare ground) and the Digital Surface Model (DSM) also known as Triangulated Irregular Network (TIN) surfaces when extracting sight distance information. The paper uses both mobile and aerial data for two DSMs. Kolmogorov–Smirnov and Mann–Whitney–Wilcoxon tests were used to measure any differences in sight distance outputs using the two surface models. The results showed a significant difference between all three surfaces. Specifically, DSMs were found to have shorter sight distances than DTMs, which means that more obstructions can be picked up. Comparisons between the aerial and mobile DSMs showed that mobile DSMs had a greater density which allows for a higher DSM resolution, leading to a more accurate representation of the environment.

As evident from the review, not many studies have attempted using mobile LiDAR data in assessing sight distance along highways. In addition, some of the algorithms developed in previous studies require manual user input at some stages of the implementation. Finally, although there are a few algorithms that have been developed to assess stopping sight distance, to the best of our knowledge, no previous study has developed algorithms to assess passing sight distance.

3. Extraction Procedure

This study presents an automated method for sight distance extraction and assessment using LiDAR point cloud data. The method is a two-step process that employs the use of ArcGIS tools for distance assessment and a Microsoft Visual Basic algorithm for processing and analyzing the outputs obtained from ArcGIS. The next few paragraphs provide a description of the extraction procedure.

3.1 Developing Surface Model and Importing Trajectory points

The first step of the extraction procedure involves building a Digital Surface Model (DSM) raster of the roadway from the LiDAR point cloud data. The DSM raster surface is a grid of cells representing elevations. The elevation of each cell is estimated based on the average elevation of all LiDAR points that fall in that particular cell. This surface usually represents the tops of buildings, trees, and other objects, or the ground, if unobstructed. Creating a raster surface simplifies the analyses procedure since each cell in the raster surface is a representation of multiple points, hence the amount of data is reduced.

Once the DSM is created, points representing the observer and target locations are imported onto the surface. These locations are represented using a set of points which are aligned along the trajectory of the road. Let I represent the set of all observer points and J represent the set of all target points, where:

$$I = [i, i+1, i+2 \dots n];$$

$$J = [j, j+1, j+2 \dots m];$$

where, n is the number of observer points used in the analysis and m is the number of target points.

Trajectory points are typically collected using a GNSS-mounted vehicle traveling along the highway. Alternatively, if Mobile Laser Scanning was used to collect LiDAR data, the points representing the trajectory of the vehicle could also be extracted from the LiDAR point cloud based on the scanner angle. The density of the observer and target points which are imported into ArcGIS is dependent on how frequent the assessment is to be conducted. The higher the point the density the more accurate the assessment is, however, processing times also increase as the number of observer and target points increase. Hence, while an assessment of sight distances every 30-50m is recommended, this is a decision that is left to the designer.

In addition to the spacing, the elevation of the observer and target points off the ground also needs to be defined before importing the points. Alberta Highway Design Guide recommends that for stopping sight distance assessment, an observer height of 1.05m and a target height of 0.38m are used (Alberta Infrastructure 1999), however, local values could be used if the extraction method were to be applied elsewhere. Moreover, these values could also change when assessing the passing sight distance (PSD) on a highway. For PSD the local values presented in the Alberta Highway Design Guide for observer and target height were 1.05m and 1.3m, respectively.

3.2 Sight Line Construction and Assessment

After creating the surface model and importing the observer and target points, sight lines are constructed representing the shortest distance between pairs of observers (I) and targets (J). This is done using the “Construct Sight Lines” tool in ArcGIS. For n observer points and m target points along the roads trajectory, $n \times m$ sight lines are created. After that, the “Line Of Sight” tool is used to test for the visibility of the target and the terrain from the location of each observer along each sight line. For instance, to assess sight distance from observer i the tool would assess the visibility on the sight lines connecting observer i

to all targets in set J . The tool works by testing for the intersection of the sight lines with the raster surface. Any intersection between the sight line and the surface indicates that there is an object of higher elevation than the line, indicating that the target is not visible. Despite being able to assess obstructions along the sight line, the line of sight tool does output available sight distance information. Hence, the necessity to process the outputs obtained from ArcGIS.

3.3 Sight Distance Computation

General Assessment

The output received from ArcGIS contains data for each iteration from all observers I to all targets J . To compute available sight distance information at all points along the highway, a Microsoft Visual Basic algorithm was written. The logic followed in the code is illustrated in the flowchart shown in figure 1. For each observer, the code loops through all observer-target pairs and stops when the target is no longer visible. The distance to the last visible target is then used to identify the available sight distance.

Once the available sight distance is computed the algorithm then compares available sight distance at all observer points to the minimum sight distance required on the road segment and denotes which observer does not meet distance requirements. The minimum allowable sight distance requirements can be fed into the code depending on the design standards followed in the region where the analysis is conducted and depending on the highways design speed

Passing Zone Determination

Unlike stopping sight distance where the minimum requirements must be met throughout the road segment, in case of passing sight distance, it is only necessary for those requirements to be met at locations where passing is permitted (i.e. lane markings are dashed). Therefore, it is necessary to extract lane marking information to perform the PSD assessment.

Lane markings are extracted by filtering the point cloud data twice, first the data is filtered based on scanner angle to extract the region in the middle of the road only (i.e. the centreline and its surroundings). After that, an intensity filter is applied to extract high intensity points only. Since lane markings are usually painted in highly retroreflective material, the intensity filter separates markings from the rest of the pavement as seen in figure 2.

The final stage of identifying the passing zone involves separating the portion of the centerline where passing is permitted from that where passing is not permitted. This is done in three steps. First the data is clustered based on point density and spacing to separate dashes from solid lines. The next step is to determine whether each cluster belonged to a dashed or a solid segment, this was done based on cluster length. Clusters which are longer than a certain threshold represented a solid line as illustrated in Figure 3:

$$Subsegment: \begin{cases} L_c \leq t & \text{Dashed Line} \\ L_c > t & \text{Solid Line} \end{cases}$$

where, L_c is the maximum Euclidean distance between points within a cluster and t is the user defined threshold length beyond which a cluster is not classified as a dashed line.

The start point of the set of dashed clusters is then identified and the distance to the next solid line is computed. This distance represents the region where passing is permitted.

4. Case Study

The developed algorithm was tested a highway segment in the province of Alberta. The segment was chosen so that the alignment features along the road varied. The next few paragraphs provide information about the data collection process along with some details about the highway on which the algorithm was tested.

4.1 LiDAR Data Collection

The data used to test the algorithms was collected by Alberta Transportation using Tetra Tech's PSP-7000 Multi-Function Pavement Surface Profiling vehicle. Surveys are conducted within normal traffic flows at posted speeds up to 100 km/h. Provincial surveys conducted at 90 km/h result in LiDAR point densities on the pavement surface of 150-1000 points/m² (Steel *et al.* 2014). Data collected along a given highway is saved in multiple .LAS files with each file representing a certain segment along the highway. The data considered in this paper was collected on the segment shown in Figure 4.

4.2 Test Segment

Highway 36, also known as the Veteran's Memorial Highway, is a two-lane undivided rural road which lies in the eastern part of the province of Alberta. The southmost point on the highway lies east of the city of Lethbridge while the north most point is to the east of the city of Edmonton. The algorithm proposed in this study was tested a segment of the highway which extends a length of 4 km with a .LAS point cloud file consisting of 28.9 million points. The speed limit on the road is 100 km/h and there is an at-grade stop controlled intersection at one point along the segment. Vertical alignment along the varies along the segment as seen in Figure 4. There is also a horizontal curve at one point on the segment.

5. Results and Discussion

This section discusses the results of applying the proposed sight distance assessment algorithm on the road segment on Highway 36. Figure 4 show the plan view of the segment. As evident from the figures, Segment A has high variation in the vertical elevation along the road, hence, limitations to sight distance are expected on that segment.

5.1 Stopping Sight Distance Assessment:

Figure 5 shows the available sight distance along the test segment. The x-axis represents the position of the observer along the segment and the y-axis represents the sight distance available to that observer. The horizontal line drawn across the curve on Figure 5 represents the minimum required stopping sight distance on the road segment. The figure shows that the available sight distance fluctuates as the observer is moved to different points along the segment. The sight distance on the segment ranges from a maximum of 1455 m, available 1100 m upstream the segment, to a minimum of 194 m, available 298 m upstream the segment. The reason the general trend is decreasing on figure 5 is

because the further upstream the observer is moved, the closer the observer is to the end of the LiDAR segment (i.e. the end of the point cloud file).

The horizontal line drawn across the curve on Figure 5 represents the minimum required stopping sight distance on the road segment. This is the theoretical sight distance which must be available along a highway and is a function of the design speed of the road, a driver's perception reaction time and the road's grade. In this paper, a perception reaction time of 2.5s is used and a downgrade of 3%. This combination yields a minimum SSD of 235m for the test segment. When comparing the available sight distance to the minimum stopping sight distance required it is seen that the minimum requirement was satisfied at all locations along the segment except the region between 255 m and 395 m upstream.

Figure 6 depicts the top view of a sight line where the target was not visible from the observer's location. The blue point represents the observer and the red point represents the target. As clear from the figure, the reason the target point is not visible from the observer location is because of the change in the vertical alignment between the pair of points. The sight line travels toward the target but, at one point, the line is not visible since it is overlaid by the road surface due to the change in the elevation of the surface (i.e. change in the vertical alignment). The side view, seen in Figure 7, also confirms that the sight line is obstructed by the change in vertical alignment.

In order to verify that the sight distance was limited at points where the code detected obstructions, the maps in ArcGIS were revisited and the corresponding sight lines were manually assessed. This assessment confirmed that the points were all obstructed due to changes in the vertical grade on the road. A street view image of the location where sight distance obstruction was detected is also shown in Figure 8. The figure clearly shows the limitations to sight distance caused by the downgrade which exists beyond the dashed red line.

It is worth noting that in 3R/4R projects (i.e. projects which involve resurfacing, rehabilitation and restoration of existing roads), Alberta Highway Design Guide allows for the minimum allowable sight distance on a segment to drop to that of a segment where the speed is 20 km/h lower than the current operating speed (Alberta Infrastructure 1999). In other words, if the design speed is 110 km/h only, sight distance requirements for an 89 km/h segment (165.75 m) need to be satisfied on this segment if it were analyzed as a 3R/4R project. Therefore, if this criterion were to be used in assessing the segment, stopping sight distance requirements would be satisfied for the entire segment.

5.2 Passing Sight Distance Assessment

As already noted the assessment process was repeated to assess Passing Sight Distance (PSD). Target heights were changed to standards required to assess PSD and observers were placed at the start of the zones where passing was permitted as discussed in section 3.3.2 of this paper. The outputs of the analysis are presented in Table 1. Since passing was only permitted at two portions on the segment, only these locations were assessed.

The results show that at one of the regions where passing is permitted, the minimum PSD requirement is not met. The analysis shows that the ASD at that location is 716 m while the minimum PSD required given the design speed of 110 km/h is 740 m. At the other

region of the segment where passing was permitted, the minimum requirements were met with a ASD of 1700 m at that part of the segment.

5.3 Safety Assessment

In order to assess safety at the location of limited sight distance, collision data on the segment was analyzed. The coordinates of the collisions which occurred on the highway segment during the period from 2008 to 2012 were imported and mapped onto the segment as shown in Figure 9. The coordinates of the location with limited stopping sight distance were also mapped and the proximity of crashes to locations of limited sight distance was analyzed.

Matching the coordinates showed that, a animal object collision was recorded at a relatively close distance of the region of limited stopping sight distance. According to the records, the collision was listed as an animal collision where the vehicle struck a deer. Although this was not the only animal collision which was recorded on this segment, its proximity to the location of limited stopping sight distance (<700m) indicates that this could be a reason why the driver could not stop in time to avoid the hitting the deer. It is worth noting here that the crash also occurred during night time, hence, the limitations to sight distance could have been aggravated by the poor lighting at that time.

Although a single collision might not result in action to be taken on the segment, the assessment shows that the information obtained from the LiDAR images could be crucial when analyzing safety concerns at a particular location. In fact, the proposed assessment could assist safety auditors in performing easily and fast safety audits with more emphasis on the geometry of the prevailing sight conditions.

5.4 Challenges and Limitations

While the extraction procedure was highly successful, a few challenges were encountered when conducting the assessment. The main challenge was the processing time when dealing with a high number of observer and target points. Highway design guides require that stopping sight distance is met at every position along a highway (Alberta Infrastructure 1999). Although high point cloud density means that such an assessment is possible, increasing the number of observer and target points affects processing times. The reason here is that sight lines need to be created between each pair of lines and all combinations between those pairs must be considered. Hence, if 100 pairs are used, 9,800 sight lines need to be generated and assessed. With that being said, processing times are still reasonable even with that amount of points.

Another challenge was encountered when extracting the centerline of the highway for assessment of the passing sight distance. Since it is required that assessment of passing is performed at locations where passing is permitted, the centerline had to be extracted and assessed to automatically identify those regions. Although clustering was effective in automatically separating dashed lines from solid lines, this was not the case when dealing with regions where passing was only permitted for one travel approaches (i.e. the centerline is dashed on one side but solid on the other). Therefore, in cases where the passing zone starts at a location where passing is only permitted in one direction, locating the start of this zone cannot be done automatically.

6. Conclusions And Recommendations

This paper develops an algorithm by which sight distance along a highway segment can be automatically assessed using LiDAR point cloud data. Observer and target points are simulated along the highway and sight lines between each pair of points are constructed. The line of sight tool in ArcGIS is then used to assess whether a specific target is visible to each observer. A code was then written to estimate the sight distance available to each observer. Furthermore, the code was also used to automatically assess whether the sight distance available at a particular point on the segment exceeded the minimum sight distance required. The developed algorithm was tested on a road segment on Highway 36 in the province of Alberta, Canada. The available sight distance along the test highway is evaluated and a 150 m segment, where minimum stopping sight distance requirements are not met, is detected. The detection is verified by observing comparing the obstructed sightlines against the vertical profile of the highway and using images from the field at obstruction locations. Passing sight distance was also assessed on one of the segment and limitations to that were also identified. Finally, collision records at locations of limited sight distance were examined. A potential association between an animal-related collision and the region of limited stopping sight distance was found.

The algorithm developed in this paper is highly effective in automated assessment of sight distance on highway segments. The only challenge associated with the assessment procedure is specifying the number of observer points at which testing is required. Although a higher number of points is typically recommended, a trade-off between the number of points and the processing time exists. Another challenge, which could be considered as a limitation of this study is the inability to automatically separate regions where passing is permitted in only one direction from regions where passing was not permitted at all. In this paper this element of the assessment was done manually, hence, it could be an opportunity for future research to automate this step.

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Table 1: Passing Sight Distance Assessment on Highway 36 Segment A

Observer ID	Available Sight Distance	Length of Passing Region	Minimum PSD Required
9	716.03m	395m	740m
22	1700.89m	500m	

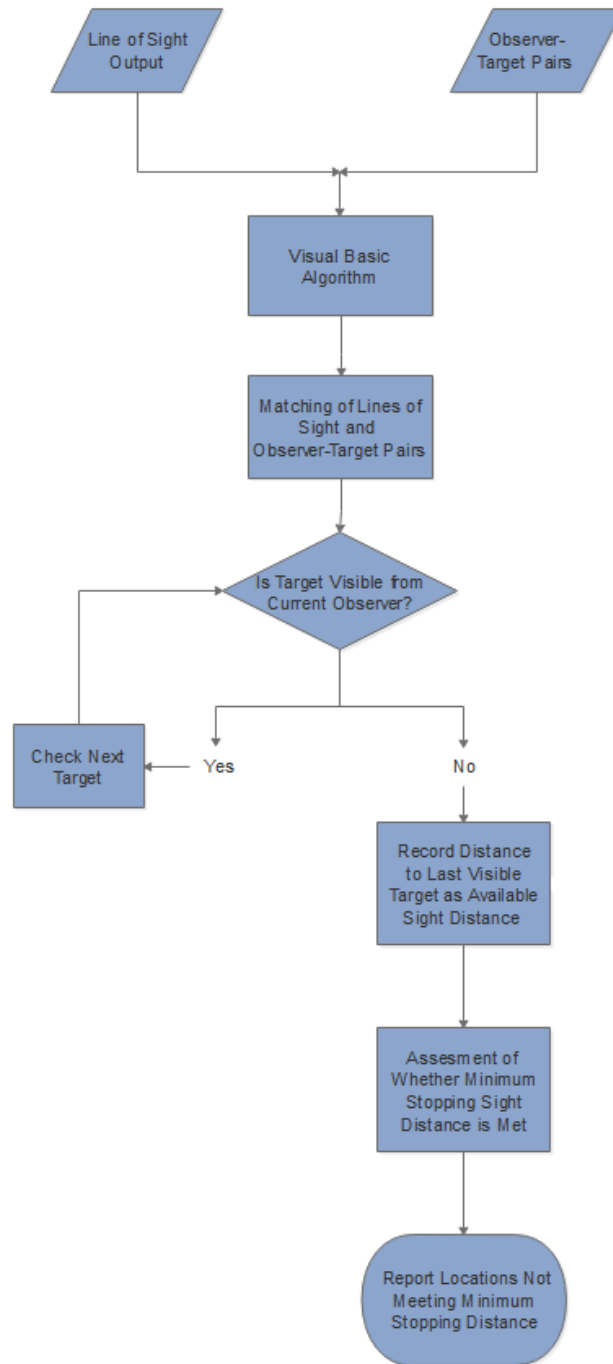


Figure 1: VBA Code Logic Used to Compute the Available Sight Distance at each Observer Point

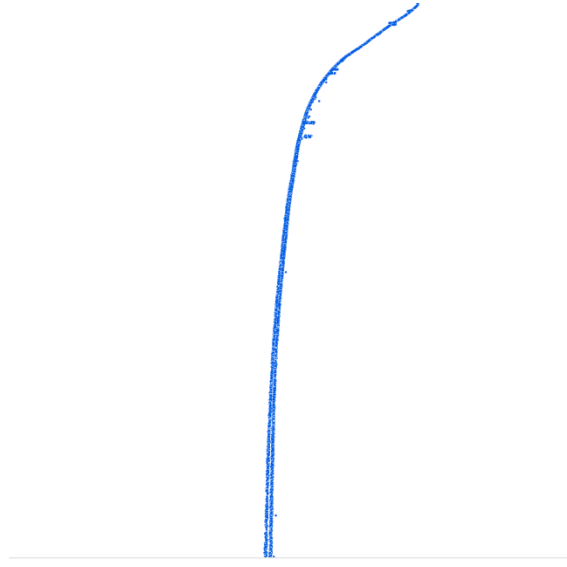


Figure 2: Filtered Centreline Markings



Figure 3: Centerline Clustering



Figure 4: Point Cloud Data at Highways 36 Segment A

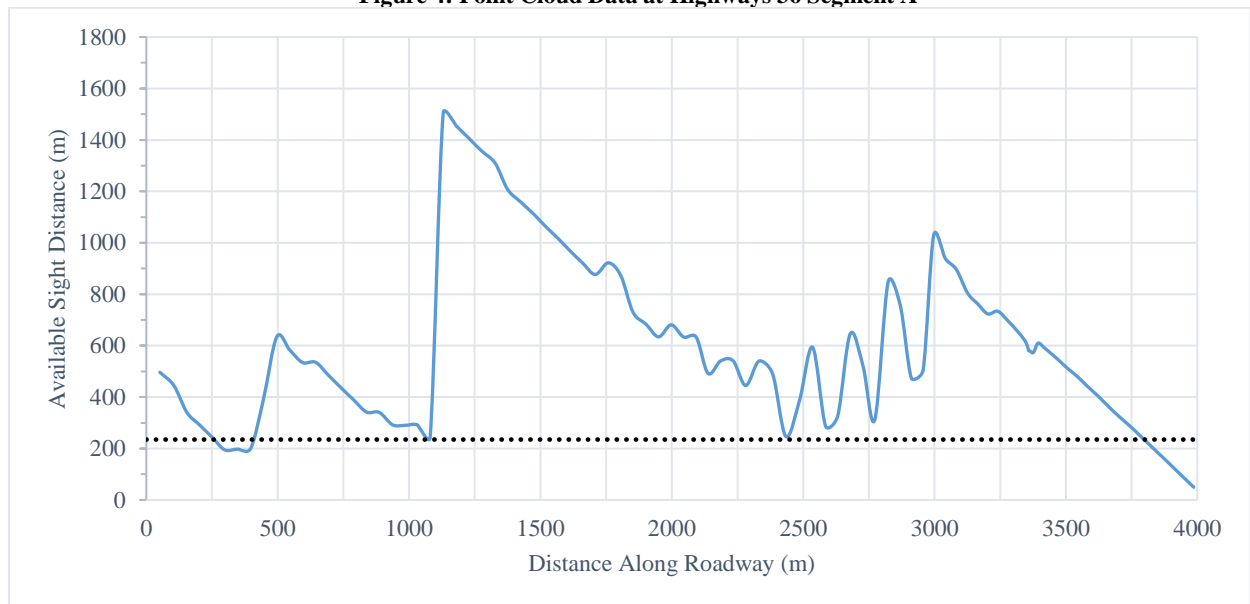


Figure 5: Available Sight Distance Along Highway 36 Segment A

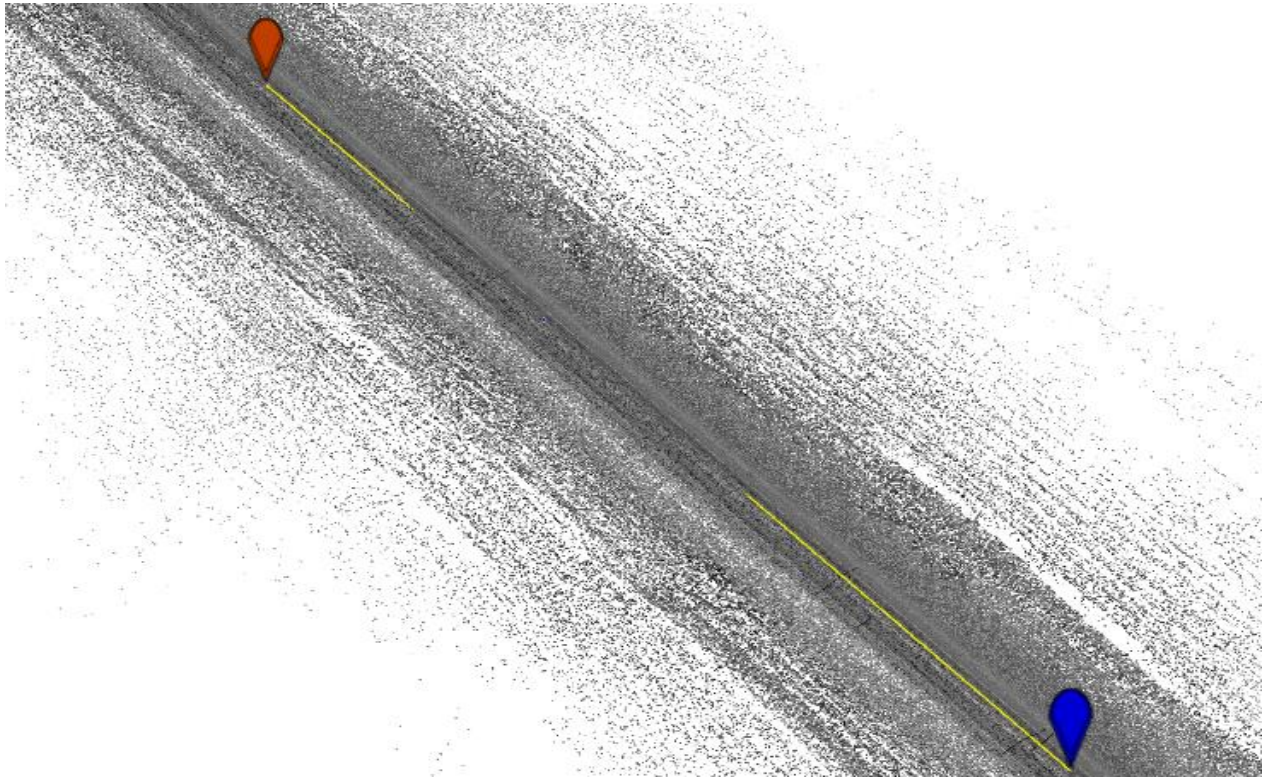


Figure 6: Observer and Target Points at Location of Limited Sight Distance (Plan View)

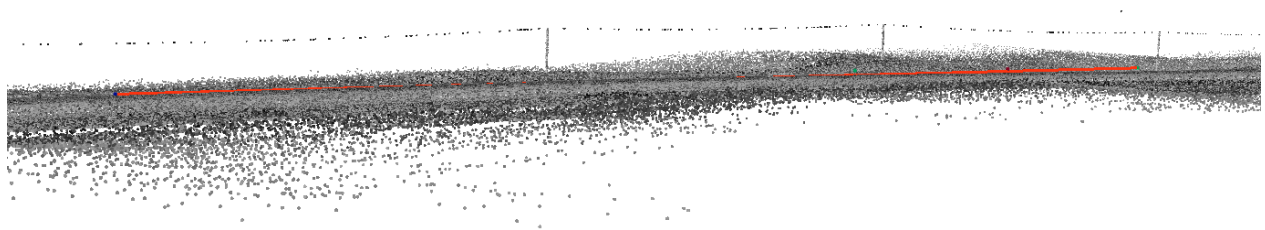


Figure 7: Sight Line Clearly Obstructed by Vertical Alignment of the Road (Profile View)



Figure 8: Limited Sight Distance Beyond Dashed Line (Google Street View)

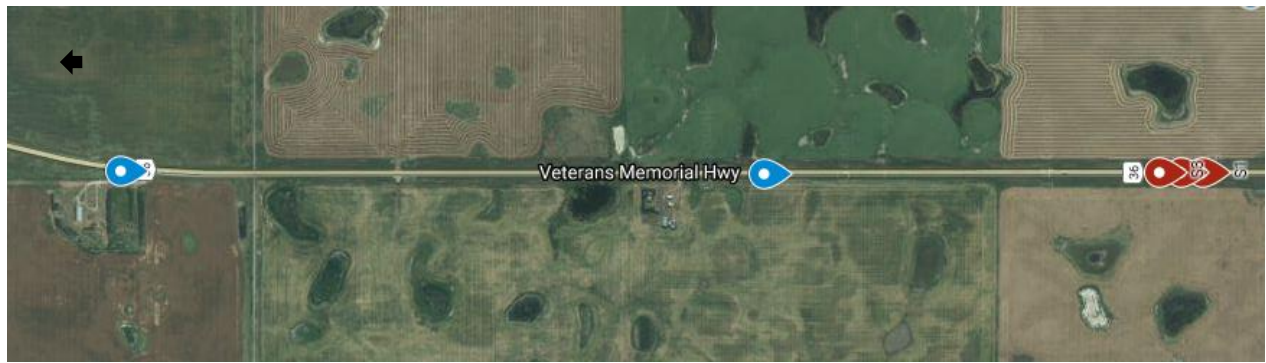


Figure 9: Location of Limited Stopping Sight Distance (Red) and Collisions (Blue)