# Categorizing High Risk Pedestrians Using LiDAR Sensor Data and Machine Learning to Support Vision Zero

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# Introduction

Vulnerable road user (VRU) refers to the road user who are unprotected by an outside shield and easily injured or killed in a car-dominated road space. They include pedestrians and cyclists (bicyclists and motorcyclists). According to the National Highway Traffic Safety Administration (NHTSA), about 2-3 pedestrians or bicyclists involved in fatal crashes at signalized intersection per day (*1*). Often, these populations are severely disadvantaged at crosswalks and intersections because they may have difficulty completing the crossing within the pre-programmed pedestrian phases. These pre-programmed pedestrian phases are designed based on geometric design at intersection and an assumed walking speed (e.g.,15th percentile walking speed (ITE, 2002), or 1.2 m/s (4 ft/s) before MUTCD 2009 edition). Manual on Uniform Traffic Control Devices (*2*) assumes a pedestrian walking speed of 0.91 m/s (3.0 ft/s) for the WALK phase and clearance interval of 1.07 m/s (3.5 ft/s) for traffic signal timing purposes. However, the state-of-the-practice does not take the types of VRU into considerations. For instance, a lower walking speed should be considered for the pedestrian clearance interval, in areas with a high number of elders pedestrians or wheelchair users.

Vision Zero can be achieved if the safety researchers leverage available data and proactively develop solutions for safety management. With the availability of innovative technologies and big data, it is time that we explored advanced approaches for detecting high-risk pedestrians attempting to cross the street at signalized intersections. The project team received processed data collected by Ouster digital LiDAR sensors and Seoul Robotics software from the MLK Smart Corridor in downtown Chattanooga, Tennessee. This output data includes LiDAR point clouds with labeled objects, including pedestrians, vehicles, and bicyclists, as well as subclassification features such as object size and velocity. For this research, we focus on one intersection (MLK and Georgia Ave) that is equipped with three Ouster OS1-128 LiDAR sensors (refer Figure 1).

# Objectives

The objective of this research is to develop a methodology to:

1. Categorize pedestrians at higher-risk;
2. Predict the time needed for each category of pedestrian to cross the street;
3. Evaluate whether the pedestrian can safely cross within the allocated pedestrian signal time.

The proposed research could aid cities and municipalities in developing data-driven solutions that bring us closer to Vision Zero goals and create a safer traffic environment for all road users.

# Literature Review

Pedestrian walking speed is important for signal timing. However, the walking speeds are affected by age and gender of the pedestrian, weather conditions and other demographic factors. For example, wheelchair users, elderly citizens, individuals pushing strollers, etc. Pedestrians belonging to such categories cannot reach their destination during the designated crossing time which is based on standard values. Before 2009, MUTCD (*2*) assumed a pedestrian walking speed of 4 ft/s (1.2 m/s) or slower in areas where slower pedestrians such as seniors or people using assistive devices (i.e., canes or walkers) are present. Zhou et al. (*3*) found that only 24.4 percent of pedestrians have a crossing speed lower than 1.2 m/s, indicating that 75.6 percent of pedestrians would be excluded with a design speed of 1.2 m/s.

The pedestrian walking speed was updated in the 2009 MUTCD in two ways: (1) when calculating pedestrian clearance times a value of 3.5 ft/s or 1.07 m/s will be used; and (2) when calculating the time required for the pedestrian to walk from one side of the traveled way to the other, the WALK phase and pedestrian clearance interval of 3.0 ft/s or 0.91 m/s will be used (*2*). Arango (*4*) conducted research on the crossing and normal walking speed of 1,792 pedestrians in Winnipeg. It was found that the changes made to the U.S. MUTCD, lowering the pedestrian walking speed to 0.91 m/s (3.0 ft/s), would decrease the excluded older pedestrians to 10 percent, and 55 percent when requiring walkers or canes. Moreover, pedestrians were found to significantly alter their walking speeds depending on where they are walking, with higher walking speeds at crossings than sidewalks.

Based on MUTCD, a Canadian study on the pedestrian walking speed in 2012 recommended the inclusion of a range of pedestrian walking speeds to be included in Canadian MUTCD (*5*). It proposed the use of a range of walking speeds between 0.8 m/s and 1.0 m/s depending on the amount of older pedestrians and pedestrians requiring the use of mobility devices at the location. In areas with more than 20 percent of pedestrians requiring mobility assisting devices such as canes and walkers, a walking speed of 0.8 m/s was recommended. A walking speed of 0.9 m/s was proposed to be used for locations with 20 percent of pedestrians 65 years of age or older. At locations with less than 20 percent of pedestrians’ considered as older pedestrians, a walking speed of 1.0 m/s was proposed to accommodate the general population (*6*).

There are provisions in Canada to use a pedestrian walking speed of 0.8 m/s for special situations (e.g., high percentage of elderly pedestrians or children) at the Senior Traffic Operations Engineer’s (STOE’s) discretion. However, when a walking speed of 0.8 m/s is used, that value should be marked on the signal timing sheet.

Based on the review, it is observed that generalizing the walking speeds for pedestrian signal timing calculations may not accommodate different categories of VRUs. A robust technique is to be developed that can account for the diversity of VRUs and to improve pedestrian safety.

# Data Collection

The dataset used for this study was provided as part of the TRNSFOR22 competition. It was collected at the intersection o(refer Figure 1). Three Ouster® OS1-128 LiDAR sensors (10Hz rotation frequency) were permanently installed on light poles to capture the real-time movement of all road users, including vehicles, pedestrians, cyclists, etc. The LiDAR 2 was selected as the origin and four corners of the highlighted crossing zones are A(13.505m, 14.413m), B(9.874m, −5.121m), C(−17.368m, 4.792m), and D(−4.242m, 24.612m).

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FIGURE 1 Study Site

In addition to the point cloud data, signal performance logs (SPM) were collected from the traffic control for the duration of data collection. These provide a real-time log of traffic signal operations including phase calls, detector status and signal status. The event types and associated IDs along with the phase diagram for the intersection are included in the dataset. The attributes of LiDAR and SPM data are included in Table 1.

TABLE 1 Attributes of LiDAR and SPM Data

|  |  |  |
| --- | --- | --- |
| **Attributes** | **Unit** | **Note** |
| **Attributes of LiDAR Data** | | |
| Timestamp | millisecond | Unix timestamp of LiDAR input message |
| ID |  | The ID of the object |
| Label |  | None (0), Car (1), Pedestrian (2), Cyclist (3), Misc (4) |
| Confidence |  | Confidence of tracking quality (0.0~1.0) |
| BBox\_Position\_X | meter | Center X of bounding box |
| BBox\_Position\_Y | meter | Center Y of bounding box |
| BBox\_Size\_X | meter | Longitudinal length of the bounding box (relative to yaw) |
| BBox\_Size\_Y | meter | Lateral length of the bounding box (relative to yaw) |
| BBox\_Size\_Z | meter | Height of bounding box |
| BBox\_Yaw | rad | Heading (0.0~2.0Pi) |
| Velocity\_X | meter/second | Velocity in longitudinal direction |
| Velocity\_Y | meter | Velocity in lateral direction |
| Tracking\_Status | meter/second | None (0), Validating (1), Invalidating (2), Tracking (3), Drifting (4), Expired (5)  **Validating**: checking validity in the early stage of tracking.  **Invalidating**: short term prediction when tracking is lost in *Validating* status.  **Tracking**: stable tracking.  **Drifting**: short term prediction when tracking is lost in *Tracking* status.  **Expired**: expired tracking. |
| **Attributes of SPM Data** | | |
| Timestamp | second | Unix timestamp of event |
| Code | eventID | Event code or operator. |
| Param | eventID | Param or affected operand. (e.g., Phase, Detector, Call, etc) |

The available data was for the following times (GMT):

LiDAR Data

1) Collection 1 - Oct 8, 2021 - 2:59 PM to 3:12 PM

2) Collection 2 - Oct 8, 2021 - 3:17 PM to 3:47 PM

3) Collection 3 - Oct 8, 2021 - 4:01 PM to 4:12 PM

SPM Data

1) Collection 1 - Oct 8, 2021 - 2:00 PM to 2:59 PM

2) Collection 2 - Oct 8, 2021 - 3:00 PM to 3:59 PM

3) Collection 3 - Oct 8, 2021 - 4:00 PM to 5:00 PM

# Methodology

# SPM Log Analysis

SPMs were logged from the traffic control system at the same collection period to provide the team signal related information. Timestamp from SPM data was synchronized with the time recorded in LiDAR data to help the team to match the number of road users counted from LiDAR data to the corresponding signal cycle and to identify the available signal timing. The other attribute provided in the SPM data was ‘Message’, which is an interpretation of code and its param. For instance, 22-2 (code-param) is with “Ped Begin Clearance (Ped 2)” as message, 22-4 is with “Ped Begin Clearance (Ped 4)”.

In general, SPM includes two types of messages: (1) messages per timing plan, such as “Coord Cycle Length = 80s” (i.e., cycle length is 80 seconds in a coordination plan), which are listed at the beginning of report in each of given log under the first timestamp; (2) messages per cycle, such as “Phase Begin Green (Phase 4)” (i.e., beginning timestamp of phase 4 turning green), which are listed in each cycle when relevant. To serve the purpose of this study, the team focused on the following messages and extracted their timestamps when appeared in a cycle (refer Figure 2):

* Ped Begin Walk (Ped 2)
* Ped Begin Clearance (Ped 2)
* Ped Begin Don’t Walk (Ped 2)
* Ped Begin Walk (Ped 4)
* Ped Begin Clearance (Ped 4)
* Ped Begin Don’t Walk (Ped 4)

According to SPM logs, the team considered the signal to be in a coordinated actuated control with minimal vehicular recall on phase 2 and phase 4, pedestrian recall on phase 2, and a coordinated phase 2. That is, vehicular phase 2 and phase 4 cannot be skipped during the timing plan, with phase 4 served by demand after minimal green time (i.e., tended to gap out), and phase 2 terminated by demand on phase 1 or 4 (i.e., tended to max out). The team would have a better understanding over the signal timing if more information, such as detector numbers and its corresponding detector locations, are provided. Nevertheless, the team believes to own enough knowledge over pedestrian intervals for this study.

For demonstration of interpretation of SPM log, SPM Collection. It has 45 cycles in the collection period. Each cycle has vehicular phase 2 and 4 because of their minimal recalls, and 31 cycles has phase 1 (i.e., protected left turn from the same traffic approach as phase 2). Every cycle has pedestrian intervals for phase 2 as it is the coordinated phase, but not every has those for phase 4 (i.e., only 11 cycles out of 45 have Ped 4).

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FIGURE 2 Signal Phases

Moreover, by observing the phase sequences throughout SPM log, the team considered that the collection 1 maintains a total of 4 sequence patterns: (1) phase 4, followed by phase 2 with ped 2 (refer Figure 3a below); (2) phase 4 with ped 4, followed by phase 2 with ped 2; (3) phase 4 followed by phase 1 and phase 2 with ped 2; (3) phase 4 with ped 4 followed by phase 1 and phase 2 with ped 2 (see Figure 3b below with ped 2 omitted). The first phase sequence (see Figure 3a below) is the most common one.

According to MUTCD, a walk interval (i.e., Timestamp at “Ped Begin Clearance” - Timestamp at “Ped Begin Walk”) of 7 seconds is a minimal requirement. In Collection 1, 7 seconds of walk interval is observed in phase 4. Walk interval for phase 2 varies from cycle to cycle with a value larger than 7 seconds. This is explainable by pedestrian rest. Pedestrian rest is usually observed at the coordinated phase with a pedestrian recall, which meets the case here for phase 2. Further, MUTCD requires pedestrian change interval (i.e., Timestamp at “Ped Begin Don’t Walk” - Timestamp at “Ped Begin Clearance”) with a calculated pedestrian clearance time based on the geometric distance from curb to curb with a walking speed of 3.5 fps. That is 15 seconds of pedestrian clearance time for phase 2 and 21 seconds of pedestrian clearance time for phase 4 in Collection 1.

|  |
| --- |
| Graphical user interface  Description automatically generated |
| 1. Phase sequence pattern 1 in Collection 1. |
| Graphical user interface, website  Description automatically generated |
| 1. Phase sequence pattern 4 in Collection 1 with Ped 2 omitted. |

FIGURE 3 Phase sequence pattern 1 & 4.

# Categorizing VRUs Based on LiDAR Data

Among the available data, LiDAR Collection 1 is used to demonstrate the step by step

methodology to categorize VRUs. There were 41130 entries from 3774 unique users (IDs) in collection 1. Since our focus is on vulnerable users, to avoid elimination of VRU detections because of false negatives (VRUs detected as cars but at a low confidence), only entries that were detected as cars (label =1) with a confidence of 75 percent at least once were removed in the first round. This resulted in 2236 unique road users. Users with only one instance in the entire collection was then removed resulting in 405 unique users. Some of these users belonged to more that one type of label.

Cluster analysis was conducted to categorize the above 405 users. Cluster analysis groups a set of objects in such a way that objects in the same group are more similar (in some sense) to each other than to those in other groups (clusters). Two types of clustering were evaluated for their categorizing capabilities. They were Minibatch KMeans Clustering and BIRCH Clustering. The [KMeans](https://scikit-learn.org/stable/modules/generated/sklearn.cluster.KMeans.html#sklearn.cluster.KMeans) algorithm clusters data by trying to separate samples in n groups of equal variance, minimizing a criterion known as the inertia or within-cluster sum-of-squares (*7*). BIRCH is a scalable clustering method based on hierarchy clustering and only requires a one-time scan of the dataset, making it fast for working with large datasets. The attributes used for clustering were user dimensions ('BBox\_Size\_X', 'BBox\_Size\_Y', 'BBox\_size\_Z'), speed (√(Velocity\_X2+ Velocity\_Y2)) and confidence. Based on the number of clusters and the corresponding residual sum of squares error (SSE), the optimum number of clusters were four. All 405 users were categorized to four groups based on the above three clustering algorithms.

Further analysis was based on average and median speed, maximum and average confidence, number of detection instances (number of rows available for one ID), percentage of time the user was in tracking status = 3, labeling, initial and final box position, duration in the system (end time - start time) and engineering judgement. Since the existing pedestrian crossing interval is at least 15 seconds, all users with duration less than 10 seconds in the system (this might be because of problems with detection) were removed. The remaining 39 users were then matched to the crossing location.

**Location Matching**

Location matching was conducted to determine the pedestrian phases to which the user belonged to. Two methods were adopted. (1) based on location coordinates with respect to reference points at intersection corners. (2) based on buffering analysis in GIS. For both, the coordinates of the user at the start and end of detection were used. Q-GIS was used for the GIS analysis.

|  |  |
| --- | --- |
| A map of a city  Description automatically generated with medium confidence |  |
| a. Reference point based location matching | b. GIS based location matching |

FIGURE 4 Location matching of road users to intersection.

Some of the road users could not be matched to location based on the start and end locations from OD pair based on GIS analysis as well as reference point matching. This was because either both their start and end points were within the same corner. This is possible. For example, certain users can stay at one location for a longer time if they are conversing to someone else in person or phone. These users are detected for longer duration, but their movement is less. Such users were eliminated.

The remaining 20 users were categorized to 3 groups using BIRCH clustering based on size and median speed. 4 among the 15 in group 1 was labeled as cycle for at least 7 percent of the instances it was in the system. One of those 4 was excluded since it was labeled as cycle for 43 percent of the instances. For each category, the average dimensions, speed, and duration in the system are provided below:

TABLE 2 VRU Categories based on BIRCH Clustering

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Category** | **Duration** | **Median Velocity** | **Length** | **Width** | **Height** |
| Group 1 | 12.06 seconds | 1.34 m/s | 0.71 | 0.81 | 1.57 |
| Group 2 | 30.01 seconds | 0.92 m/s | 0.72 | 0.70 | 1.62 |
| Group 3 | 66.2 seconds | 0.12 m/s | 0.78 | 0.82 | 1.78 |

## Pedestrian Signal Time Calculations

For each of the above categories and directions, the extensions for pedestrian signal timing were calculated based on MUTCD. Values given in the table below were used to determine the distances used for signal timing calculations. Sample calculation for segment AB is shown below.

TABLE 3 Length of Segments for Signal Time Calculations

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Point** | **X** | **Y** | **Segment** | **Length (m) from Coordinates** | **Length from Google Earth (m)** | | | |
| **Corner 1** | **Curb to Curb** | **Corner 2** | **Sum** |
| A | 13.505 | 14.413 | AB | 19.87 | 2.4 | 12.81 | 4.75 | 19.96 |
| B | 9.87 | -5.121 | BC | 28.99 | 4.75 | 20.08 | 4.15 | 28.98 |
| C | -17.37 | 4.792 | CD | 23.77 | 4.15 | 17.78 | 1.75 | 23.68 |
| D | -4.242 | 24.612 | AD | 20.47 | 2.4 | 16.35 | 1.75 | 20.5 |

**Georgia Ave (Segment AB, Zone 1, Phase 2)**

Group 1 VRUs

The average median velocity is 4.4 fps. MUTCD uses 3.5 fps. Therefore, no change in signal timing was required for Group 1 VRUs.

Group 2 VRUs

Considering 12.8 meter as curb to curb distance

PCT = 42ft / 3 = 14 sec

Walkmin + PCT = 7 + 14 = 21 sec

Distance AB = 19.87m, that is 65.2 ft

Total =  (65.2) /3 = 21.7 sec = Walk + PCT

Among Total and Walkmin + PCT, Total is longer, use total for timing plan

Set Buffer =  Y+ AR (from timing plan, SPM log) = 4+1 = 5 sec

PCI = PCT – Buffer =  14 – 5 = 9 sec = FDW

Walk = Total – PCT = 21.7 – 14 = 7.7 sec

Final = Walk + PCI + buffer = 7.7 + 9 + 5 = 21.7 sec. Approximately 22 seconds

Current = 15 + more than 7 seconds = 22 sec

**No addition of time required.**

Group 3 VRUs

Adding 5 seconds to the pedestrian phase will account for 67 percent of peds crossing AB. Based on the above categorization, group 3 velocity seems too small. That would require the pedestrian phase to be too large and unrealistic. Presence of group 3 category might be a result of variability in the confidence of detections (the confidence ranged from 0.3 to 0.82). Since the pedestrian phase is required to terminate at the same time as its corresponding vehicular phase, the pedestrian phase extensions cannot be “forever”. Thus, it is hard to compromise different categories of VRUs by just extension. It is time that we think about other provisions for such road users. Similar calculations were conducted for segment CD. Based on segments AB and CD (Zone 1 and 3), it is recommended to add 5 seconds to the pedestrian phase 2, which will account for 92 percent of pedestrians.

**MLK Blvd (Segment BC and AD, Phase 4)**

For the directions, **AD and BC (Zone 2 and 4), it is recommended to add 4 seconds to the pedestrian phase 4 based on signal timing calculations. If AD is taken individually, there is no need of an extension since the current pedestrian clearance time is 21 seconds. However, from Google Earth and GIS analysis, it is seen that pedestrians flock at corner B and that contributes the additional distance and slower speeds. Just extending the phase 4 would not solve the problem in this case. There should be a study to address the increased pedestrian traffic at corner B.**

Another point to note is that all pedestrians receive 4 additional seconds (buffer interval) before ‘All Red’ as the ‘Ped don’t walk’ appears the same time when vehicular phase turns yellow. For actuated vehicle detectors, the extension is 2 seconds per vehicle. However, the buffer interval is not safe even though it allows pedestrians to cross. We recommend an addition of 4 seconds to both phases by accounting for the buffer interval.

# Transferability and Adaptability

Using collection 1, the team demonstrates the constructability of the new approach to improve road use for VRUs. Different machine learning based clustering methods were evaluated and the best one was selected for second round categorization. GIS based location referencing helped in determining the specific issues (example, increased walking distance along BC due to congestion at corner B. An analysis combining all the LiDAR data was not taken up so that the transferability of proposed methodology could be evaluated further. The clustering models might require optimization for data from other times which is not time consuming. Therefore, the project team believes that the new approach has transferability and adaptability, which the conventional approaches lack.

**Conclusions**

This project made use of LiDAR data and SPM data to find different categories of VRUs. The results from the models were then used to calculated extensions for pedestrian phases – a new approach and compared to the MUTCD procedures that assume a standard walking speed for all road users. The safety improvement and accessibility impact of the suggested measures shows the need for data driven solutions. Certain aspects of safety and accessibility projects such as gap analysis and economic appraisal (e.g., cost-benefit analysis), are not included in this project due to time and budget constraints. However, the project has successfully introduced and presented the new approach that cements the need of categorization of VRUs. Moreover, the methodology seems to have good transferability and adaptability for new sites. Therefore, a machine learning approach combined with engineering judgement (which can be automated and updated with minimal effort) can be considered as a better and proactive solution.

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