THAT WAS CLOSE: A VIDEO-BASED SAFETY ASSESSMENT OF SIGNALIZED TRAFFIC INTERSECTIONS ALONG A HIGH-SPEED CORRIDOR

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ABSTRACT

Intersections are critical junctures in urban traffic networks, frequently identified as hotspots for traffic-related injuries and fatalities due to their complex vehicle-to-vehicle (V2V) and pedestrian-to-vehicle (P2V) conflict points. This study presents a comprehensive case study focusing on the utilization of video analytics and artificial intelligence (AI) to enhance intersection safety in Broward County, Florida. By leveraging traffic cameras and AI-based methods, the research aims to measure and track pedestrian and vehicle movements, providing crucial insights into traffic behaviors and potential risks.

The study employs surrogate safety measures such as Time-to-Collision (TTC) and Post-Encroachment Time (PET) and uses an event filter to determine severe events (*1*). Key findings reveal significant conflict points, especially during left-turn movements, and underscore the role of driver and pedestrian behaviors in contributing to these conflicts. Specifically, along the high-speed corridor of Stirling Road in Davie, Florida, the most frequently occurring type of P2V conflict involved a northbound left vehicle. To address issues such as this, the research proposes a range of countermeasures, including the addition of standardized signage, crosswalk visibility improvements, and walk signal timing adjustments. These strategies aim to improve driver awareness and ultimately reduce the frequency of accidents at intersections.

The findings and recommendations of this study provide a data-driven foundation for traffic engineers, urban planners, and policymakers to implement effective safety measures, thereby enhancing the overall safety and performance of traffic intersections.

Keywords: Pedestrian safety, Traffic safety, Computer vision, Near miss conflicts

INTRODUCTION

Traffic intersections are major hotspots for injuries and fatal crashes, with a typical four-legged intersection comprising 32 vehicle-to-vehicle conflict points and 24 vehicle-to-pedestrian conflict points (*2*). According to the Federal Highway Administration, approximately 25% of traffic-related fatalities and 50% of traffic-related injuries occur at or near intersections each year (*3*). Despite reduced traffic movement during COVID-19, pedestrian fatalities increased from 6,075 in 2017 to 7,388 in 2021 (*4*). This underscores the urgent need for transportation professionals to develop strategies to mitigate high-risk zones at intersections. Traditional methods of monitoring and analyzing traffic patterns, such as manual observation and simple video recording, are often insufficient to capture the dynamic and multifaceted nature of intersection traffic.

One effective approach is the use of traffic cameras combined with artificial intelligence (AI) to analyze traffic and pedestrian movements at intersections. While the number of traffic cameras at intersections continues to grow (*5*), new AI-based methods for traffic safety are emerging. This paper focuses on utilizing traffic cameras at signalized intersections to automatically measure and track pedestrian and vehicle movements. By doing so, we can gain crucial insights into their behaviors, aiding in the development of safer road systems.

The use of traffic cameras necessitates addressing privacy concerns. In this study, fisheye cameras are employed due to their ability to capture a wide field of view, often covering an entire area with a single lens. These cameras are installed at elevated positions at intersections, facing down at right angles to the road. Even with a resolution such as 1280×960, they are incapable of reading license plates due to both the distance from and the angle to the road. Additionally, privacy concerns are mitigated by not storing any vehicle or personal details. Instead, only the trajectory coordinates and timestamps of movements are stored, thereby eliminating any personally identifiable information captured by the cameras.

This study evaluates potential risks and hazardous situations between pedestrians and vehicles by employing surrogate safety measures and an event filter to quantify severe events, utilizing existing metrics such as time-to-collision (TTC) and post-encroachment time (PET). Near-miss incidents, where pedestrians and vehicles come into close proximity, are characterized by deceleration and speed. Previous studies typically define proximity using a range of approximately 1.5-3.0 seconds for TTC and 1.0-1.5 seconds for PET. Thousands of near-miss events are identified using these thresholds, and the event filter further refines this set by applying advanced selection rules, such as assessing whether vehicles involved in the event properly yielded, thereby determining if it is a non-event.

This case study aids traffic operations by providing insights into potential hazardous behaviors of pedestrians and drivers at intersections, helping to make these areas safer through various interventions such as signal timing adjustments, signage installation, and, in some cases, modifying the intersection geometry. By responsibly leveraging these technological advancements, the research aims to enhance intersection safety, protect vulnerable road users, and contribute to the broader goal of creating safer roads. The study contributes to the field in the following ways:

1. Development of a specialized software tool aimed at aiding traffic engineers in analyzing traffic patterns and inherent P2V and V2V conflict issues.
2. Demonstration of the software's effectiveness through its application to heavily-utilized intersections in Florida.
3. Utilization of the study's findings to devise appropriate countermeasures for enhanc-

ing the safety and performance of traffic intersections.

The rest of the paper is organized as follows. The next section reviews related work, presenting a literature study pertinent to this research. Following that, the video processing pipeline methodology developed and utilized in this study is described. This is followed by an in-depth case study of five intersections in Broward County, Florida, and a discussion on countermeasures. The paper concludes with a discussion of the results.

RELATED WORK

The related work in this field comprises three parallel areas: surrogate safety measures, the sensors available to compute these measures, and analyzing traffic safety using video processing methods.

Surrogate safety measures

Surrogate safety measures are safety indicators that strongly correlate with traffic conflicts (*6*). The most prominent of these measures are Time-To-Collision (TTC) (*7*) and Post-Encroachment Time (PET) (*8*). Additional metrics include deceleration and the proximity of conflicting vehicles. A near-miss event is typically detected when TTC or PET measures fall below a certain threshold, such as 2 seconds (*9*). Thousands of near-miss events can be detected, making it impractical for practitioners to review them all. However, this paper leverages prior work by the same research group, which applies an event filter to retain only the most severe events among the set of near-miss incidents. The details of the event filter are presented in (*1, 10*).

Intersection sensors

Loop detectors (*11*) are traditionally installed at intersections to monitor traffic and signal states. Although these detectors are effective in identifying traffic incidents (*12*), they cannot determine the exact location of conflicts due to their underground placement. With recent advancements in technology, a variety of other sensors, such as video cameras, LiDAR cameras, and infrared (IR) cameras, are now used for intersection monitoring (*13–15*).

There are two main types of video cameras: standard cameras and fisheye cameras. Fisheye cameras can monitor an entire intersection with a single unit for smaller intersections, and two units are sufficient for slightly larger ones. In contrast, standard cameras require one camera per approach (typically four) to fully monitor an intersection.

Intersection safety analysis using video processing

Our work analyzing traffic safety using video processing methods aligns with the approach described in (*16*) by Abdel-Aty et al. Both studies employ video-based methods to monitor and analyze traffic safety, leveraging the rich data provided by video footage to extract detailed information about vehicle trajectories and classify objects in the traffic stream. While Abdel-Aty et al. focus on using CCTV cameras and advanced algorithms like Mask-RCNN and OcclusionNet to detect vehicle key points and reconstruct 3D views for safety analysis, our study emphasizes the use of fisheye cameras to cover entire intersections with fewer cameras, enhancing the cost-effectiveness and deployment ease compared to conventional cameras. Further, our study incorporates surrogate safety measures such as TTC and PET to identify near-miss events. Also, our work goes a step further by employing an event filter to retain only the most severe near-miss events, making it feasible for practitioners to focus on the most critical incidents.

Our paper is closely related to the work by Samara et al. [14], which also employs video analysis for intersection traffic analysis. However, there are several key differences between the two studies. Firstly, Samara et al.'s work does not address pedestrian-to-vehicle (P2V) conflicts, whereas our paper specifically includes this important aspect of intersection safety. Additionally, our study can identify movement trajectories, enabling us to pinpoint persistent issues with specific traffic movements. Furthermore, while Samara et al. use only PET as a safety indicator, our paper incorporates multiple surrogate safety measures, providing a more comprehensive safety analysis. We also discuss phase-based conflict hotspots, which are not covered in their work. Lastly, our paper addresses countermeasures to improve intersection safety and explores how intersection safety impacts overall intersection performance, areas that are not discussed in Samara et al.'s study.

METHODOLOGY

The methodology used to analyze an intersection's safety and performance characteristics has three distinct steps: video collection, one-time setting of intersection-specific parameters, and video processing. We explain each of these steps as follows.

Video collection

The video collection setup was established by Broward County specifically for this study, utilizing VLC media player software (previously the VideoLAN Client and commonly known as simply VLC) and a script to capture sample videos from multiple cameras installed at the traffic intersections. These videos were directly stored in a designated folder on UF OneDrive, utilizing cloud storage. It is important to note that the videos were never stored at any point in the Broward County system during the video collection process.

The duration of the video data collection was scheduled for two consecutive weeks at each intersection of this study. However, due to occasional hardware failures caused by excessive temperature in South Florida, the cumulative two weeks were achieved through the spring months of March through May, collecting whenever possible and achieving two days across all weekdays until every intersection had reached the goal.

Setting up intersection-specific parameters

After collecting videos from the intersection cameras, several essential steps are taken to prepare the video processing software for operation. These are all one-time processing tasks needed for each intersection.

1. Training Machine Learning Models: The models are trained to recognize and ignore certain physical elements of the intersection, such as signal heads, mast arms, visible equipment hardware, and tree shadows, and to identify road objects from specific angles.
2. Correcting Fisheye Distortion: Fisheye lens distortion, which causes straight lines in wide-angle photos to appear curved, is corrected using specialized software. This software maps fisheye intersection images to Google Maps, as developed by our team in previous work (*17*).
3. Delineating Lanes: The Google Maps image of the intersection is loaded into Microsoft Paint, where the lanes are delineated in terms of pixel coordinates to easily identify vehicle and pedestrian movement phases.

4. Calculating Pixels-to-Meters Ratio: To calculate vehicle speeds, the pixels-to-meters ratio is established by measuring the distance between two parallel lines in both Google Maps and the intersection image. This ratio facilitates accurate conversion of pixel-based measurements into real-world distances.
5. Determining Traffic Phases and AADT: For each intersection in the case study, the traffic phases for vehicle and pedestrian movement are determined, and the Annual Average Daily Traffic (AADT) is collected to provide a general comparison of traffic volumes and turning movement counts.

Video Processing

Figure 1 shows the multi-stage video pipeline employed to process and analyze intersection footage from intersections in Broward County.

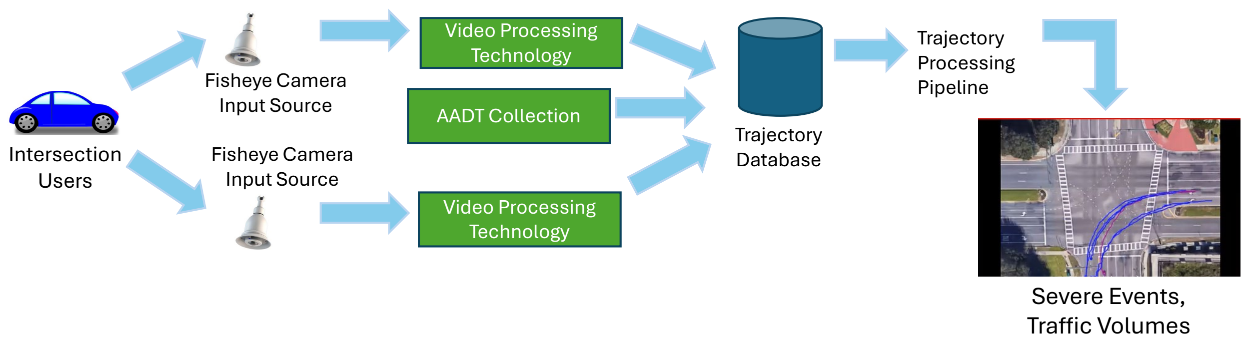


FIGURE 1: Diagram of the multi-stage video pipeline used to process and analyze intersection footage.

Object detection is a primary video processing task that involves identifying and locating objects in images or videos. It is an important part of many applications, such as self-driving cars, robotics, and video surveillance. Object tracking, on the other hand, is a method of tracking detected objects throughout frames using their spatial and temporal features. In object tracking, an initial set of detections are obtained, followed by assigning a unique ID to each of the detected objects and tracking the detected objects throughout the frames of the video feed while maintaining the assigned IDs.

The two popular algorithms for object detection and tracking are YOLO (*18, 19*) and DeepSORT (*20*), respectively, which have been used in the video processing technology. The input videos undergo processing within a deep neural network composed of convolutional layers followed by maxpool layers. The convolutional layers utilize learnable filters or kernels to extract features from the videos, while the maxpool layers downsample to reduce spatial dimensions, thereby reducing computational resource requirements and complexity.

Processing videos of moving objects frame by frame at an intersection results in a database of trajectories by recording the centroid of each identified object in a frame. Trajectories represent the paths taken by moving objects, defined by spatial coordinates and timestamps. The generated trajectories are post-processed and classified into movements and phases based on reference lines representing the cardinal directions (North, South, East, West). Using the trajectory information from the Video Processing stage, the software is able to differentiate between right turning and through vehicles in a shared used lane. This is a feature not achievable using an inductive loop detector due to the fact that right-turning and through vehicles of the same approach share a phase, even if the lanes are different. This is achieved in the software by a one-time processing step marking the North-South and East-West reference lines and computing the vehicle movement with respect to these lines, such as northbound through (NBT).

The processed trajectory data is then advanced to the third and final stage of the pipeline, Near Miss Identification. In this step, algorithms are employed to pinpoint severe events. The resulting severe events are fewer in number, and all identified severe events are manually verified. Any events deemed not serious are discarded to further refine the set of severe events. The algorithms for computing TTC and PET employed by the software are explained in detail in our recent paper (*21*).

EXPERIMENTAL RESULTS

Our video processing pipeline was applied to five intersections on Stirling Road in Broward County, Florida. In this section, the safety issues at these intersections are detailed. Two weeks of data were collected from each intersection, from 7 AM to 7 PM each day, and analyzed through the pipeline, followed by manual verification of incidents detected as severe events. For each intersection, the description includes the intersection layout, speed limits, and any special signal timing characteristics. Near-miss observations at each intersection are then described.

Intersection 1. Stirling Road and University Drive

Figure 2 shows a Google Maps image of this intersection, where north corresponds to the top edge. The approximate locations of the fisheye cameras are shown using yellow stars.

Figure 2 also illustrates the number and configuration of traffic lanes at this intersection. For example, it can be observed that there are dedicated right-turn lanes for westbound right (WBR), northbound right (NBR), and southbound right (SBR).

The timing sheet from this intersection shows that all left-turn signals are protected and given depending on the presence of vehicles in the left-turn lane. The speed limit along the minor and the major lanes is 45 mph.

Safety Evaluation - Speeds

Figure 3 illustrates the percentage of vehicles that passed through the intersection at speeds higher than the speed limit. Typically, speeding behavior increases the risks of a severe event. This figure shows that northbound through (NBT) and eastbound through (EBT) display speeding behavior, mainly over the weekend and during early morning when traffic volume is low.

Safety Evaluation - Volume distribution

Figure 4 illustrates the average pedestrian and vehicle volumes at the intersection, segmented by days of the week and hours of the day. Figure 4a displays average pedestrian counts. Notably, pedestrian traffic spikes sharply between 4 PM and 5 PM, particularly on Thursday, which shows the highest peak. Other days, such as Tuesday and Wednesday, also have significant but lower peaks during this time frame. Morning hours see minimal pedestrian activity, with counts gradually increasing from 8 AM and fluctuating through the afternoon.

Figure 4b shows the average vehicle counts. Vehicle traffic is highest during the morn-

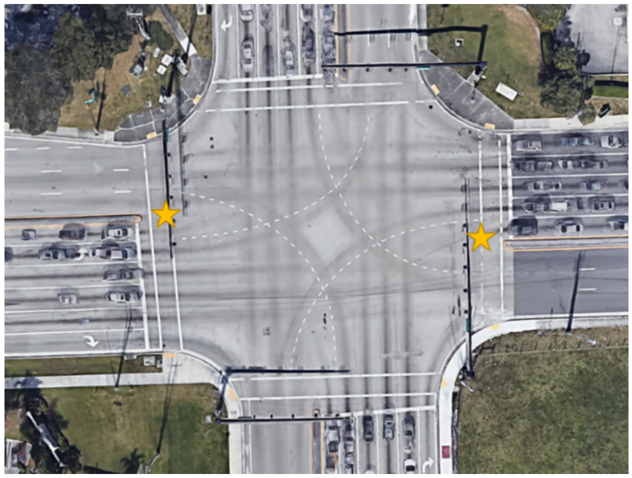
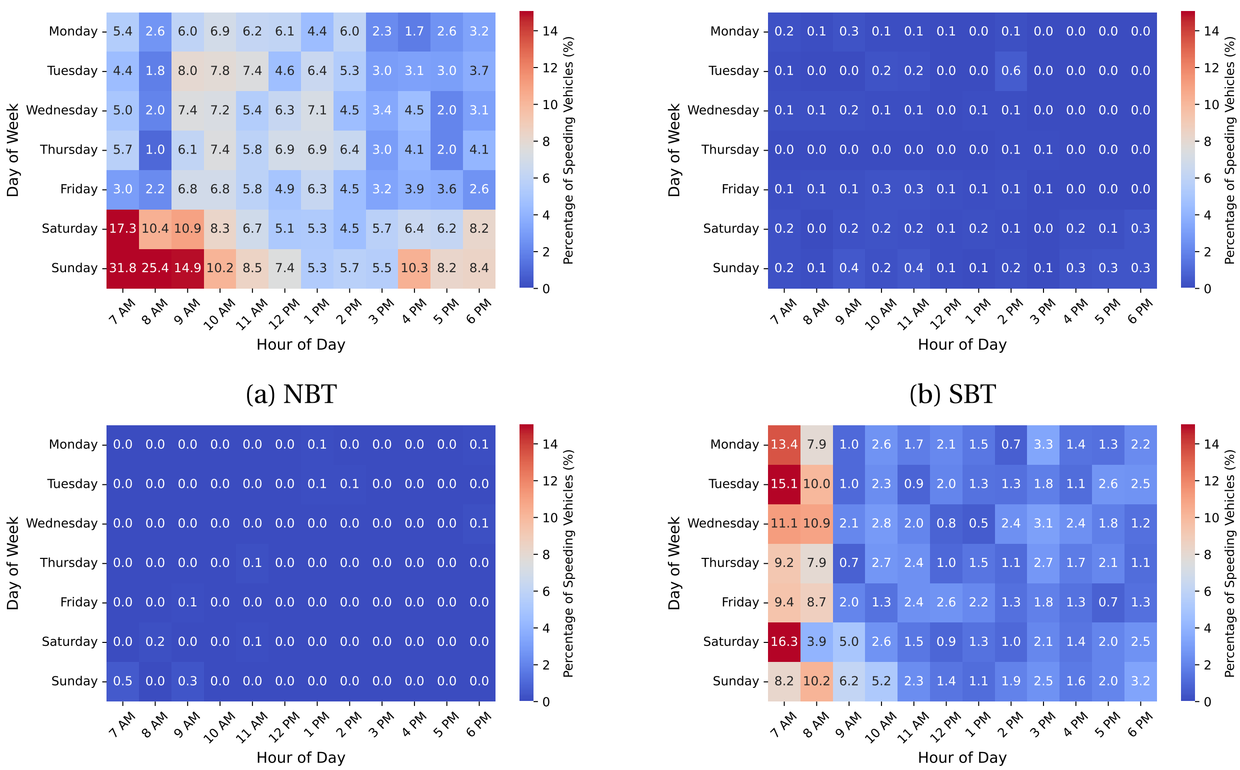


FIGURE 2: Google Maps image of the intersection on Stirling Road and University Drive where yellow stars mark the fisheye cameras' locations.

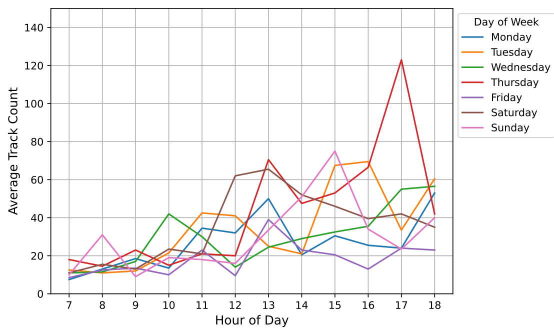


(a) NBT (b) SBT

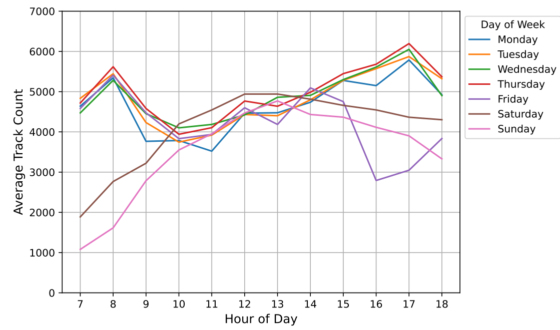
(c) WBT (d) EBT

FIGURE 3: Speeding charts as percentage of vehicles by hour of the day and the day of the week for the four approaches on Stirling Road and University Drive, with a speed limit of 45 MPH in both directions.

ing commute, peaking around 8 AM, and maintains a high volume until around 6 PM, with another peak during the evening commute around 5 PM. Monday through Thursday exhibit similar traffic patterns, with a noticeable drop in vehicle counts on the weekend particularly during the morning and evening. This data indicates a consistent pattern of vehicular traffic aligned with typical work and school schedules, whereas pedestrian traffic shows more variability, likely influenced by specific activities or events occurring mid-week.



(a) Pedestrian volume



(b) Vehicle volume

FIGURE 4: Volume plots by hour of the day and the day of the week for total volume on all four approaches on Stirling Road and University Drive.

Safety Evaluation - Conflict plots

Figure 5 shows the average P2V and V2V conflicts by the hour of the day and day of the week. Figure 5a indicates a relatively high frequency of conflicts throughout the day, with a noticeable spike around 10 AM, particularly on Wednesday, and another significant peak at 12 PM on Sunday. These peaks likely correlate with times when both pedestrian and vehicle volumes are high, increasing the probability of conflicts.

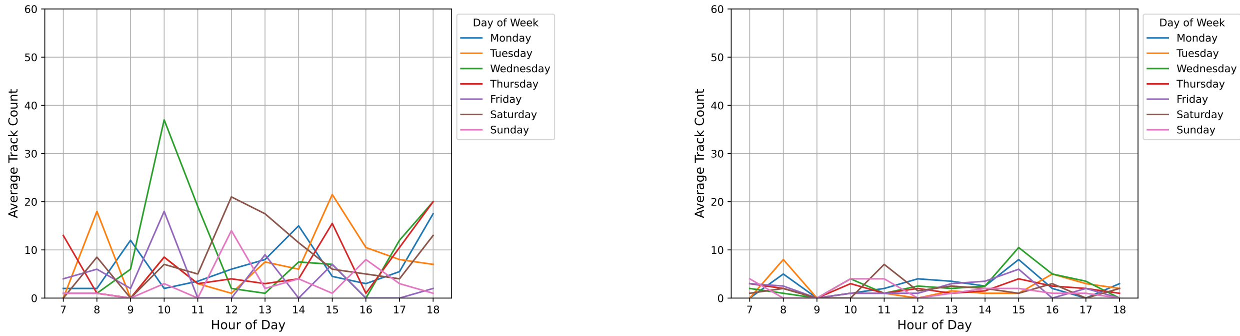
Figure 5b shows low overall conflict levels, with slight increases observed around 8 AM and 3 PM. The afternoon peak around 3 PM on Monday, Wednesday, and Thursday suggests a correlation with increased vehicle traffic during school dismissal times or early work departures. These findings highlight the importance of targeted traffic management and safety measures during specific high-risk periods.

Safety Evaluation - Pedestrian-to-vehicle conflicts

Figure 6 details the spatial nature of the conflicts. Each crosswalk can be conceptually divided into two parts: traversing the egress vehicle approach and the ingress vehicle approach. All P2V conflicts over the two weeks of processed data were aggregated for each crosswalk based on whether they involved the ingress or egress approach. Figures 6a, 6b, and 6c illustrate the conflicts with right-turning, left-turning, and through vehicles, respectively.

Figure 6a illustrates the P2V conflicts specific to right-turning vehicles. The conflicts are notably higher for WBR and NBT movements, with 71 conflicts on the ingress and 59 on the egress for these movements. This pattern indicates that vehicles are not yielding to pedestrians while making free right turns, thereby increasing the risks for pedestrians.

Figure 6b presents the conflicts arising from left-turning vehicles. A significantly higher number of conflicts are reported for the southbound left (SBL) and eastbound left (EBL) move-



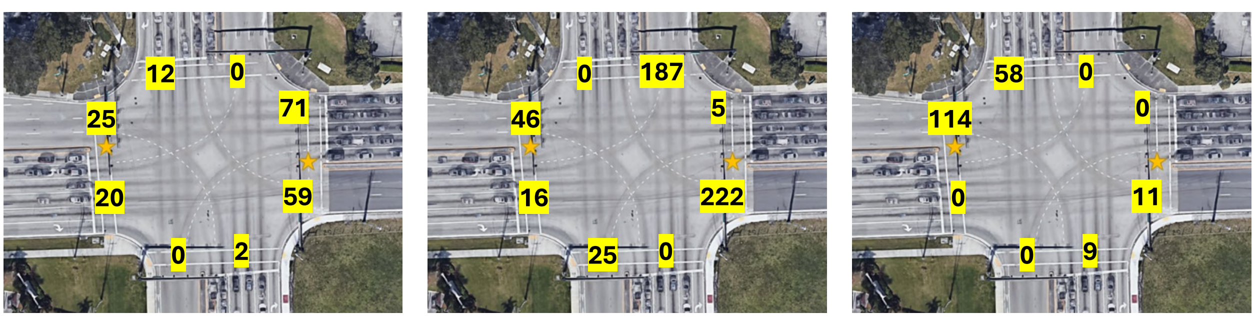
(a) P2V conflicts

(b) V2V conflicts

FIGURE 5: Average conflict plots by hour of the day and the day of the week for total conflicts on all four approaches on Stirling Road and University Drive.

ments, with 222 conflicts on the egress of SBL and 187 on the egress of EBL. Conflicts on the ingress approaches are notably lower, indicating that pedestrians face higher risks when vehicles are making left turns into the intersection. This pattern underscores critical areas where safety improvements may be necessary to protect pedestrians from left-turning vehicles.

Figure 6c displays the P2V conflicts associated with vehicles moving straight through the intersection. The conflict data reveals a significantly lower number of conflicts compared to right and left-turning vehicles. There are between 30-40 conflicts for each through movement: NBT, SBT, EBT, and WBT. This distribution suggests that through-vehicle interactions with pedestrians are less frequent. Though less frequent, these conflicts pose a higher risk in comparison to turning vehicles because through vehicles usually have higher speeds.



(a) P2V w/right-turn vehicles

(b) P2V w/left-turn vehicles

(c) P2V w/through vehicles

FIGURE 6: Total P2V conflicts on the crosswalks by vehicle movement, on Stirling Road and University Drive.

Safety Evaluation - Specific Observations

Observed P2V conflicts at this intersection include:

1. Pedestrians frequently ignoring traffic signals, leaving them in dangerous positions within the crosswalk as vehicles approach.
2. Bicyclists often violating traffic signals, proceeding through the crosswalk despite ongoing traffic.

3. Pedestrians sometimes running across the intersection while through vehicles are passing.
4. Vehicles sometimes stopping within the crosswalk, forcing pedestrians to walk outside the designated area to avoid the vehicle.
5. Heavy vehicles, such as buses and semi-trucks, taking right turns that pose a significant danger to pedestrians due to their large turning radii and limited visibility.

V2V conflicts at this intersection include:

1. Vehicles often continuing to take left turns even after the left turn signal has turned red, particularly at the northbound left (NBL) and westbound left (WBL) approaches.
2. Conflicts sometimes occurring when right-turning vehicles merge with the through stream of vehicles, leading to potential collisions.

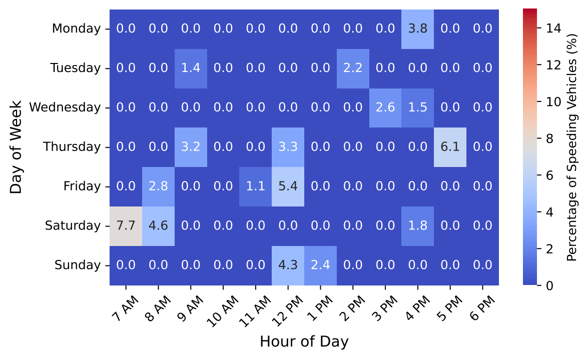
Intersection 2. Stirling Road and 61st Avenue

Figure 7 displays the image from Google Maps of the intersection; it also shows the locations of the two existing fisheye cameras. The figure also provides a visual representation of the number and configuration of traffic lanes at this intersection.

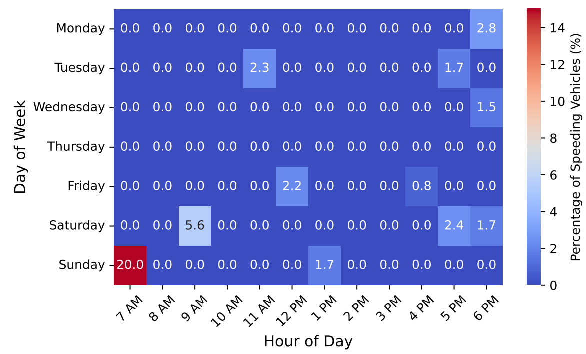
FIGURE 7: Google Maps image of the intersection on Stirling Road and 61st Avenue where yellow stars mark the fisheye cameras' locations.

Safety Evaluation - Speeds

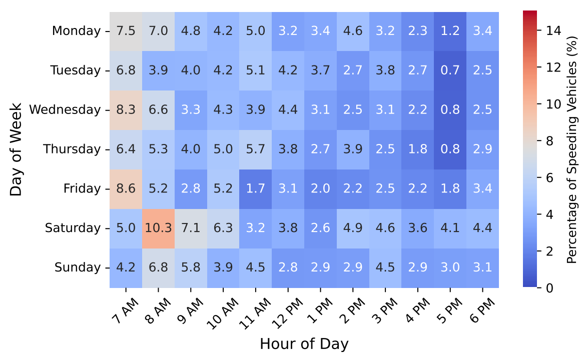
Figure 8 illustrates the percentage of vehicles that passed through the intersection at speeds higher than the speed limit. Speeding can significantly elevate the likelihood of serious accidents. According to the chart, Saturday and Sunday witness an elevated spike in the mornings; those particular days are greater than the others. However, WBT sees a slightly elevated level of around 7-8% of all motorists speeding within the early morning.



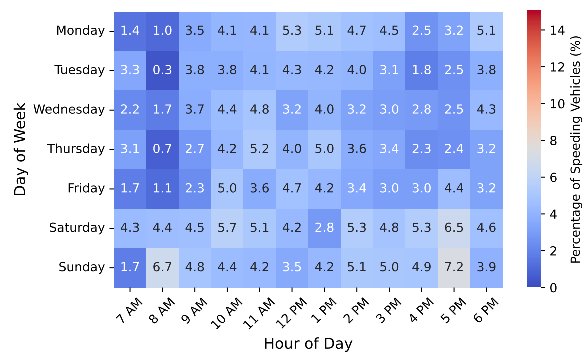
(a) NBT (Speed Limit of 30 MPH)



(b) SBT (Speed Limit of 30 MPH)



(c) WBT (Speed Limit of 45 MPH)



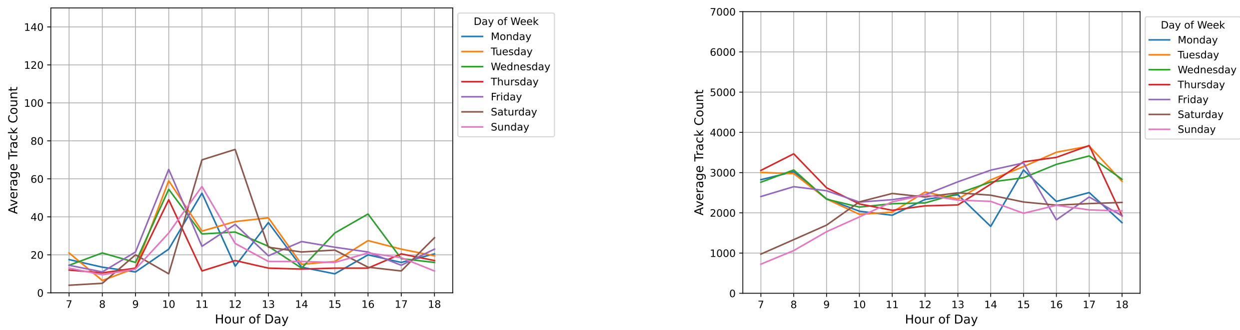
(d) EBT (Speed Limit of 45 MPH)

FIGURE 8: Speeding charts as percentage of vehicles by hour of the day and the day of the week for the four approaches on Stirling Road and 61st Ave.

Safety Evaluation - Volumes

Figure 9 demonstrates the vehicle and pedestrian volumes at the intersection of Stirling Road and 61st. Notedly, the figure highlights the intersection's peak volumes. Vehicle volume starts off high during the early hours, especially during the weekdays, averaging a track count of around 3,000. This is likely due to morning rush hour; however, it appears to average out around noon with an average track count of 2,500.

This vehicle volume is in contrast with the pedestrian volume, represented by Figure 9a, which begins low and then starts to elevate around 10 AM with the track count around 60. Saturdays, noticeably, seem to reach the highest at noon, with the track count peaking at approximately 70.



(a) Pedestrian volume

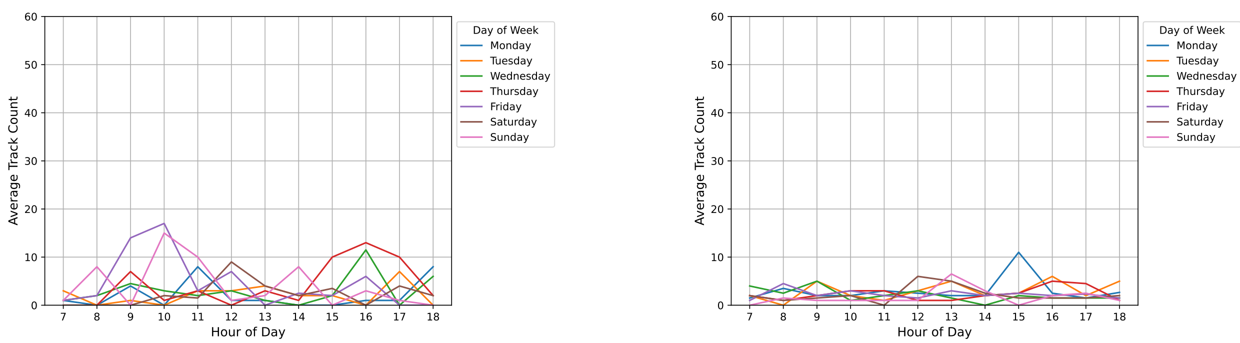
(b) Vehicle volume

FIGURE 9: Volume plots by hour of the day and the day of the week for total volume on all four approaches on Stirling Road and 61st.

Safety Evaluation - Conflict Plots

The graph depicted in Figure 10a illustrates the average P2V conflicts throughout the day, whereas Figure 10b portrays the average V2V conflicts. From the P2V conflict graph, it is evident that there is a significant peak of approximately 15 conflicts occurring at 10 AM on both Friday and Sunday. Additionally, there is a marked increase in conflicts around 4 PM on Wednesdays and Thursdays, indicating a potential period of heightened pedestrian activity or traffic interactions.

In contrast, the V2V conflict graph reveals a relatively steady pattern of conflicts throughout the day, with minimal fluctuations. However, a notable exception occurs at 3 PM on Monday, where there is a sudden rise, reaching an average track count of 10 conflicts.



(a) P2V conflicts

(b) V2V conflicts

FIGURE 10: Conflict plots by hour of the day and the day of the week for total conflicts on all the four approaches on Stirling Road and 61st.

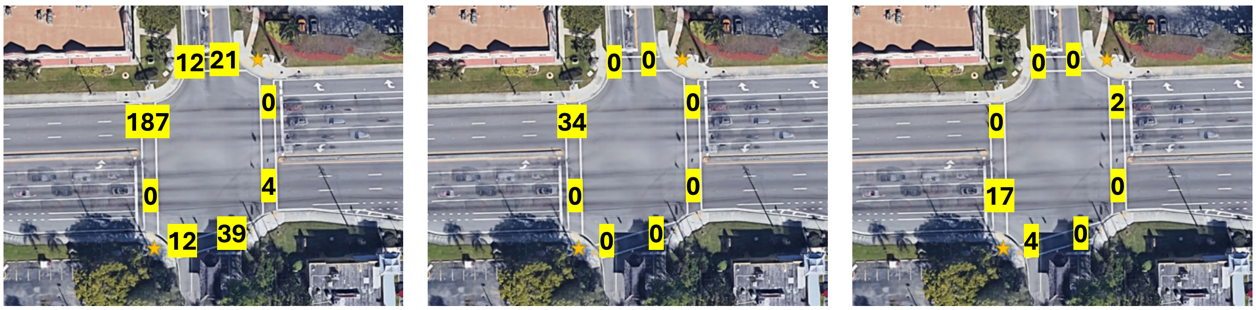
Safety Evaluation - Pedestrian-to-vehicle conflicts

Figure 11 demonstrates the total pedestrian-vehicle (P2V) conflicts on the crosswalks, categorized by vehicle movement.

Figure 11a depicts the conflicts involving left-turning vehicles. A significantly high concentration of conflicts is observed on the west leg crosswalk, with 187 recorded incidents. Additional conflicts are seen on the south leg crosswalk with 51 total incidents, the north crosswalk with 33 incidents, and the east leg crosswalk with 4 incidents.

Figure 11b represents the conflicts involving right-turn vehicles. Notably, there are 34 recorded conflicts on the west crosswalk, indicating higher interaction rate between pedestrians and vehicles turning right from this approach.

Figure 11c shows the conflicts involving through vehicles. The highest number of conflicts is recorded on the west crosswalk with 17 incidents. This is notably the lowest approach out of all the turns.



(a) P2V w/left-turn vehicles (b) P2V w/right-turn vehicles (c) P2V w/through vehicles

FIGURE 11: Total P2V conflicts on the crosswalks by vehicle movement, on Stirling Road and 61st.

Safety Evaluation - Specific Observations

Observed P2V conflicts at this intersection include:

1. Right-turning vehicles often failing to yield to pedestrians.
2. Pedestrians conflicting with left-turning vehicles.
3. Pedestrians frequently crossing directly in front of through vehicles.
4. Vehicles occupying the crosswalk, creating dangerous situations for pedestrians.

Observed V2V conflicts at this intersection include:

1. Left-turning vehicles conflicting with through vehicles due to right-of-way confusion.
2. Right-turning vehicles sometimes conflicting when merging with the through traffic stream.

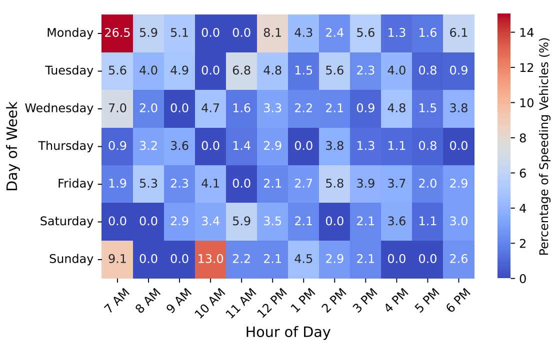
Intersection 3. Stirling Road and 68th Avenue

Figure 12 shows a Google Maps image of the intersection Stirling Road and 68th Avenue. The figure also has the approximate location of the fisheye camera and illustrates the number and configuration of traffic lanes at this intersection.

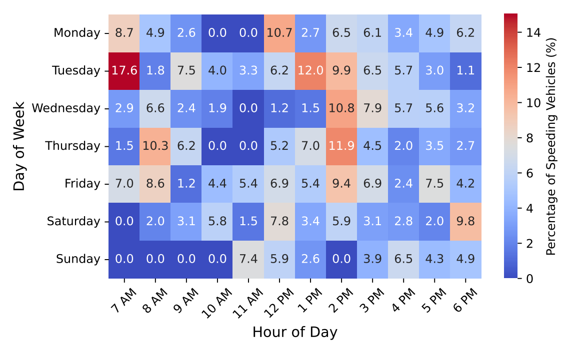
FIGURE 12: Google Maps image of the intersection on Stirling Road and 68th Avenue where a blue circle marks the fisheye camera location.

Safety Evaluation - Speeds

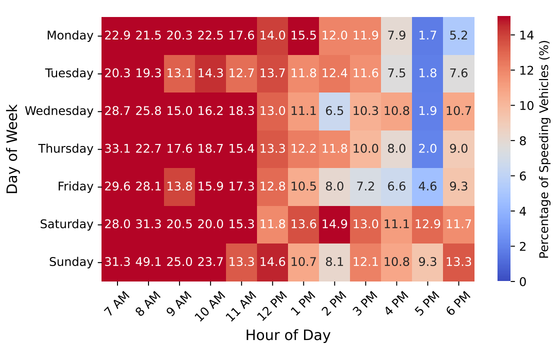
Figure 13 demonstrates the percentage of vehicles that pass through the intersection at speeds higher than the speed limit. Figure 13c and 13d reveal an elevated speeding trend for WBT and EBT. This indicates consistently high percentages of vehicles exceeding the speed limit throughout various times of the day, surpassing the levels seen in other intersections. Specifically, rates are seen in excess of 35%, such as EBT movements on Sundays at 8 AM; at those times, 49.8% of vehicles are speeding within the intersection.



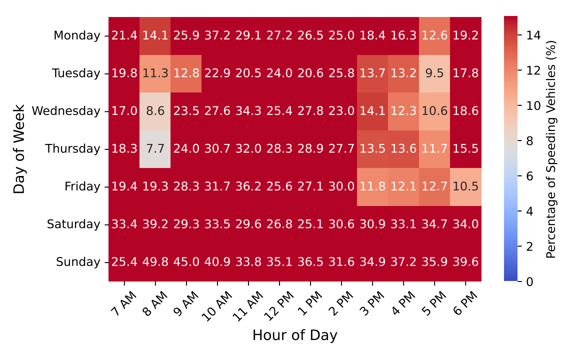
(a) NBT



(b) SBT



(c) WBT



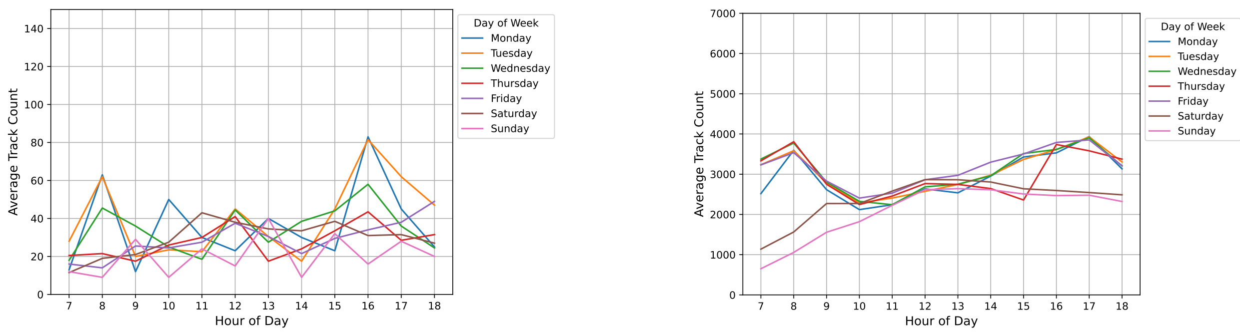
(d) EBT

FIGURE 13: Speeding charts as percentage of vehicles by hour of the day and the day of the week for the four approaches on Stirling Road and 68th.

Safety Evaluation - Volumes Distribution

Figure 14 shows the pedestrian and vehicle volumes at the intersection of Stirling Road and 68th Ave. In Figure 14a, pedestrian volumes on Monday and Tuesday mornings start at a relatively high level, peaking around 60 at 8 AM. Subsequently, the volume decreases, stabilizing around 40 for the rest of the week. Notably, pedestrian volumes on Monday and Tuesday afternoons rise again, reaching new highs around 4 PM.

Figure 14b illustrates that vehicle volumes also begin at elevated levels during the weekdays, with an average track count around 3,500 at 7:00 AM. After this initial peak, vehicle volumes generally level off and remain steady until 15:00. Vehicle volumes on Saturdays and Sundays are lower compared to the weekdays, demonstrating a different traffic pattern during the weekends.

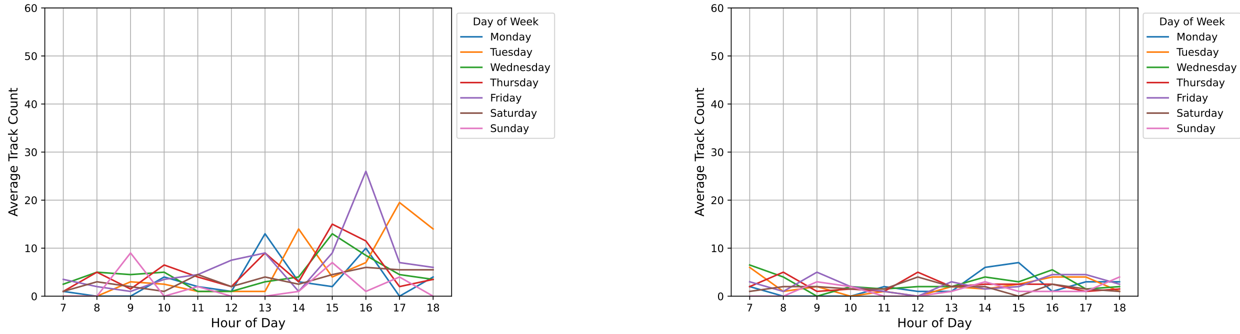


(a) Pedestrian volume (b) Vehicle volume

FIGURE 14: Volume plots by hour of the day and the day of the week for total volume on all four approaches on Stirling Road and 68th.

Safety Evaluation - Conflict Plots

Figure 15a and 15b presents the average P2V and V2V conflicts. The P2V conflict levels remain relatively stable throughout the week, with the notable exception of a significant spike on Friday at 4 PM, where the track count reaches approximately 25 conflicts. Similarly, Tuesday shows an elevated level of conflicts at 5 PM, with an average of 20 conflicts. In contrast, the number of V2V conflicts resembles a relatively stagnant pattern, with conflict levels remaining consistently low throughout the entire week.



(a) P2V conflicts (b) V2V conflicts

FIGURE 15: Conflict plots by hour of the day and the day of the week for total conflicts for all movements on Stirling Road and 68th.

Safety Evaluation - Pedestrian-to-vehicle conflicts

Figure 16 represents the total pedestrian-to-vehicle (P2V) conflicts on crosswalks, categorized by vehicle movements.

Figure 16a illustrates the P2V conflicts associated with left-turning vehicles. The most significant concentration of conflicts is observed on the lower half of the west crosswalk, with 146 incidents. This is followed by 64 incidents on the south crosswalk's left-half. Other crosswalks exhibit considerably fewer conflicts.

Figure 16b depicts the P2V conflicts involving right-turning vehicles. The south crosswalk remains the most conflict-prone with 71 incidents, and the west crosswalk contains 51 incidents, both resulting from vehicles with EBR movements.

Figure 16c presents the P2V conflicts involving through vehicles. The highest number of conflicts is again recorded on the west crosswalk, with 64 incidents.

(a) P2V w/left-turn vehicles (b) P2V w/right-turn vehicles (c) P2V w/through vehicles

FIGURE 16: Total P2V conflicts on the crosswalks by vehicle movement on Stirling Road and 68th.

Safety Evaluation - Specific Observations

Observed P2V conflicts at this intersection include:

1. Right-turning vehicles often failing to yield to pedestrians, causing near misses.

2. Pedestrians conflicting with left-turning vehicles are also common. This is particularly risky for pedestrians on the minor crosswalk, as vehicles making a permissive left turn tend to focus more on oncoming through vehicles.
3. Pedestrians frequently crossing directly in front of through vehicles.
4. Vehicles sometimes occupying the crosswalk, causing pedestrians to walk closer to traffic.

Observed V2V conflicts at this intersection include:

1. Vehicles often continuing to make left turns even after the left turn signal turns red.
2. Right-turning vehicles sometimes conflicting with the through traffic stream when merging.
3. Left-turning vehicles occasionally merging on the other side of the double yellow line, particularly when making a permissive left turn.
4. Frequent conflicts between left-turning vehicles and oncoming through vehicles.

Intersection 4. Stirling Road and 66th Avenue

Figure 17 shows a Google Maps image of the intersection Stirling Road and 66th Avenue, portraying the approximate location of the fisheye cameras with blue circles. The figure also illustrates the number and configuration of traffic lanes at this intersection.

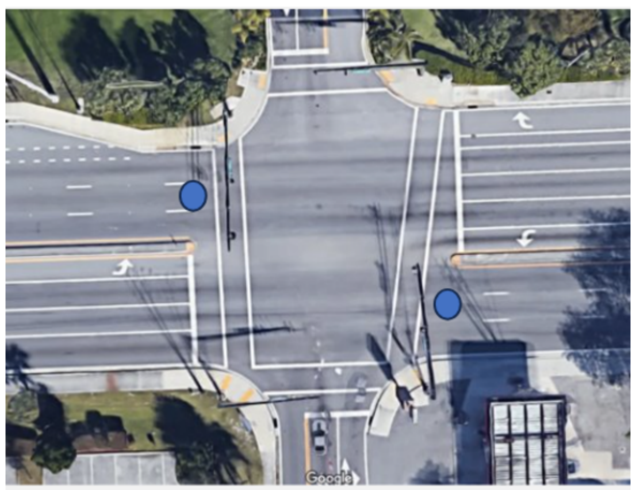
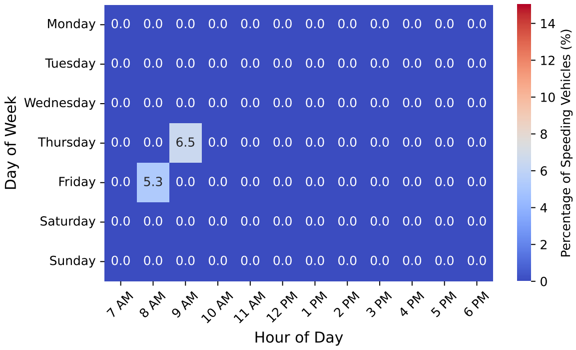


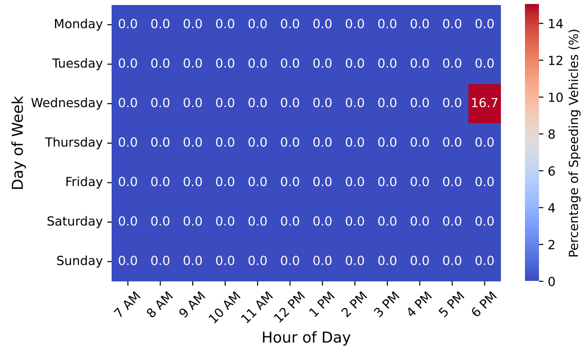
FIGURE 17: Google Maps image of the intersection on Stirling Road and 66th Avenue where blue circles mark the fisheye cameras' locations.

Safety Evaluation - Speeds

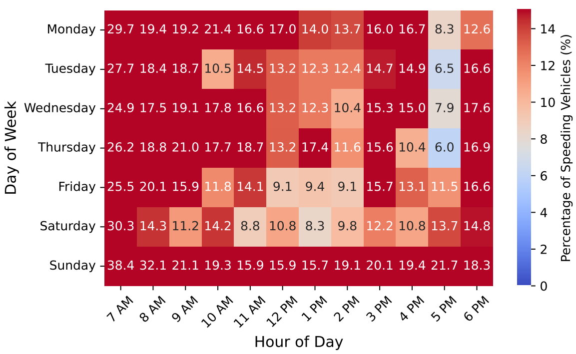
Figure 18 represents the percentage of vehicles passing through an intersection over the speed limit. It is notable that, like Intersection 3 (Stirling Road and 68th Avenue), the WBT and EBT vehicles are consistently found to be speeding through the intersection. Notably, westbound and eastbound are the directions of Stirling Road, so there may be a need for changes along that high-speed corridor to prevent and discourage speeding.



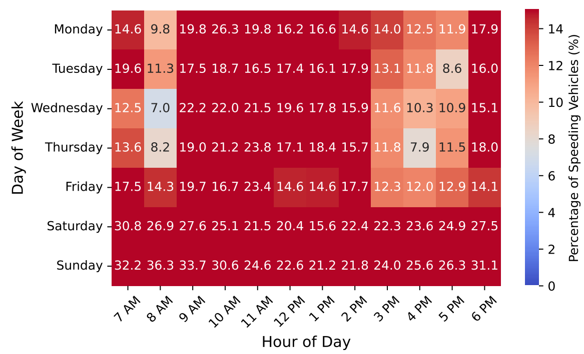
(a) NBT



(b) SBT



(c) WBT

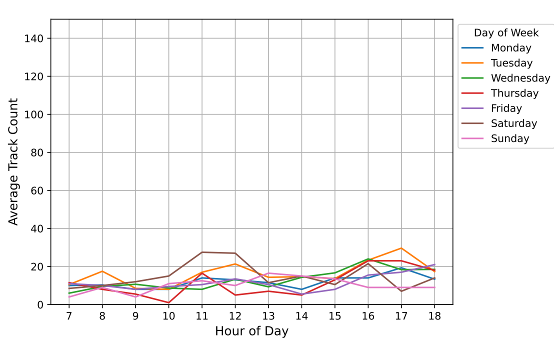


(d) EBT

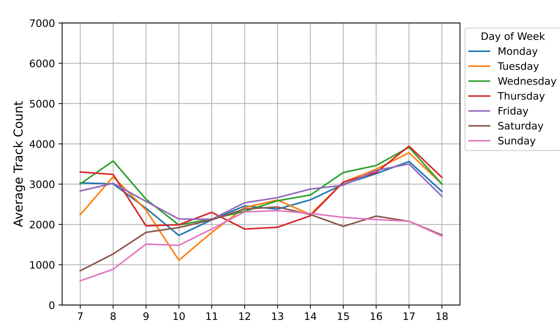
FIGURE 18: Speeding charts as percentage of vehicles by hour of day and day of week for the four approaches on Stirling Road and 66th Avenue.

Safety Evaluation - Volumes

Figure 19 illustrates the relationship between the volume of vehicles, pedestrians, and time of day. Analyzing Figure 19a shows that pedestrian traffic is relatively low and constant at this intersection, with a minor spike occurring in the early afternoon on Saturdays. Contrasting this with Figure 19b, a trend of peaking at 8 AM and 5 PM on all weekdays can be identified, aligning with typical work rush hour traffic. This is further highlighted by the relatively low, constant traffic flow on Saturdays and Sundays.



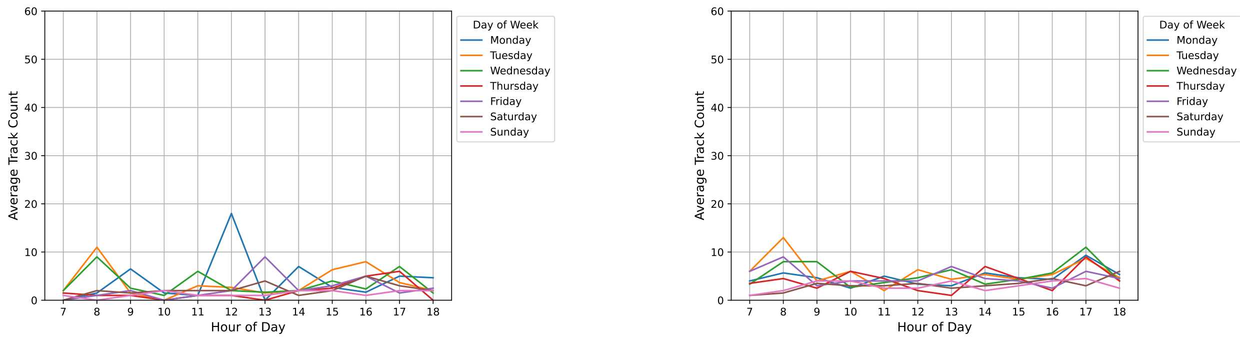
(a) Pedestrian volume



(b) Vehicle volume

FIGURE 19: Volume plots by hour of the day and the day of the week for total volume on all four approaches on Stirling Road and 66th Avenue.

Safety Evaluation - Conflict plots



(a) P2V conflicts

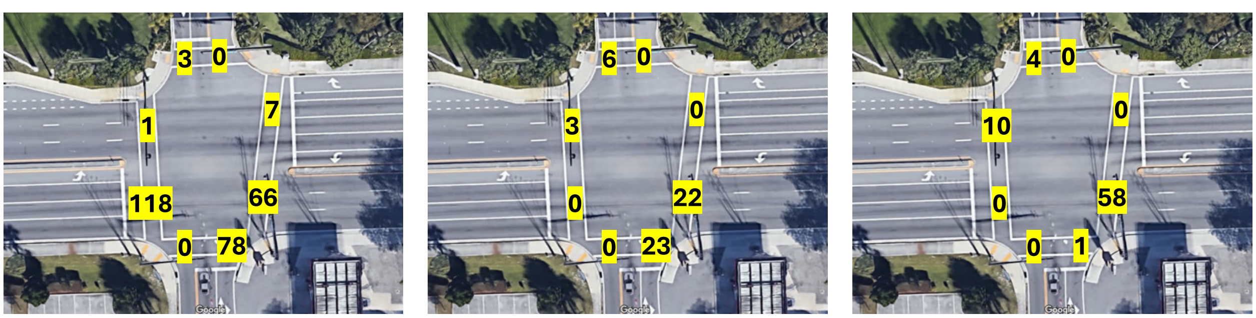
(b) V2V conflicts

FIGURE 20: Conflict plots by hour of the day and the day of the week for total conflicts on all the four approaches on Stirling Road and 66th Avenue.

Figure 20 represents the conflicts flagged by the pipeline by the hour, with Figure 20a representing conflicts between vehicles and pedestrians (P2V) and Figure 20b representing conflicts between vehicles (V2V). The data indicates a peak in P2V conflicts on Monday at noon. This is perhaps explainable by pedestrians walking to the bus stops at such time, one of which can be seen within Figure 17.

Contrasting with the sporadic pattern noted in Figure 20a, Figure 20b shows a more evenly distributed series of conflicts, with less severe peaks at 8 AM and 5 PM on weekdays, coinciding with the typical work schedule once again.

Safety Evaluation - Pedestrian-to-vehicle conflicts



(a) P2V w/left-turn vehicles (b) P2V w/right-turn vehicles (c) P2V w/through vehicles

FIGURE 21: Total P2V conflicts on the crosswalks by vehicle movement on Stirling Road and 66th.

The high volume of pedestrians conflicting with EBL vehicles in the west leg crosswalk of Figure 21a, upon further inspection, is correlated with pedestrians disobeying walk signals. Figure 21b shows a cluster of P2V conflicts in the south and east leg crosswalk conflicting with NBR vehicles. An elevated number of conflicts occurs with EBT vehicles, depicted in Figure 21c.

Safety Evaluation - Specific Observations

Observed P2V conflicts at this intersection include:

1. Pedestrians often conflicting with right-turning vehicles.
2. Pedestrians on the minor crosswalk (crossing 66th Avenue) often conflicting with left-turning vehicles.
3. An elevated number of conflicts between pedestrians and through vehicles. These are particularly severe events, as through vehicles maintain high speeds throughout the duration of their intersection crossing.

Observed V2V conflicts at this intersection include:

1. In regards to left turns,
   (a) Especially in westbound traffic, vehicles continue taking left turns even after the left turn signal turns red. This results in a rise in conflicts with oncoming eastbound through traffic.
   (b) Many westbound left-turning vehicles cut left turns too sharp, crossing over the double-striped yellow line for the north/southbound lanes, resulting in near collisions with idle traffic.
   (c) Left turns from 66th Ave (north and southbound) are signaled together; however, the intersection is too narrow to allow safe multi-directional left turns.
2. In regards to right turns,
   (a) Northbound right turns fail to yield for oncoming southbound left turns.
   (b) Vehicles waiting to turn on red occupy the 66th Ave crosswalk.
   (c) Vehicles making right turns from 66th Ave onto Stirling Rd fail to keep in the far right lane, resulting in many conflicts.

Intersection 5. Stirling Road and State Road 7

Figure 22 shows a Google Maps image of the intersection Stirling Road and SR7, showing the approximate locations of the fisheye cameras with yellow stars. The figure also illustrates the number and configuration of traffic lanes at this intersection.

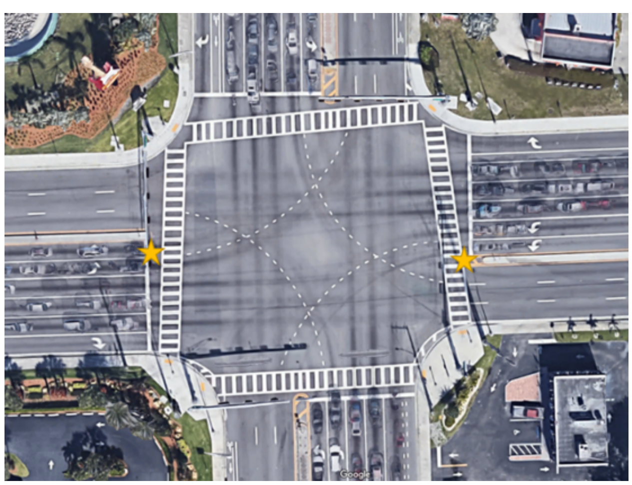
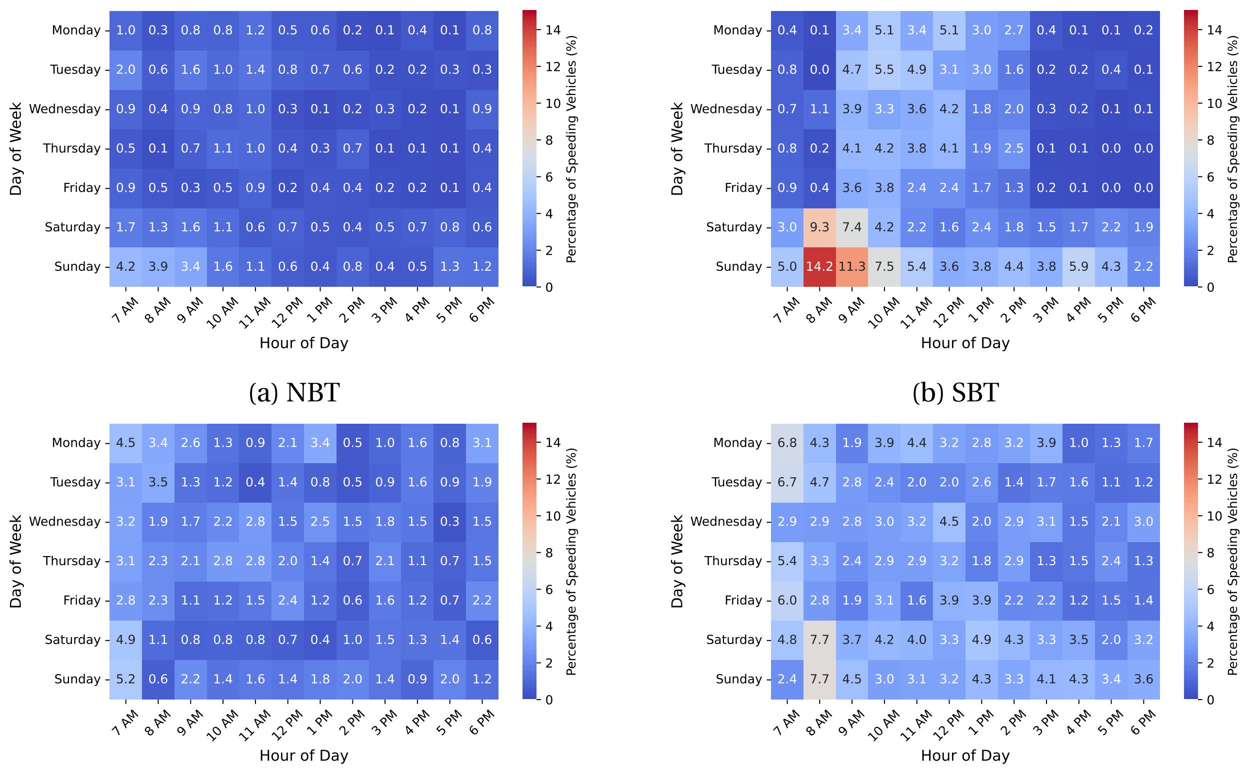


FIGURE 22: Google Maps image of the intersection on Stirling Road and State Road 7 where yellow stars mark the fisheye cameras' locations.

Safety Evaluation - Speeds



(a) NBT (b) SBT (c) WBT (d) EBT

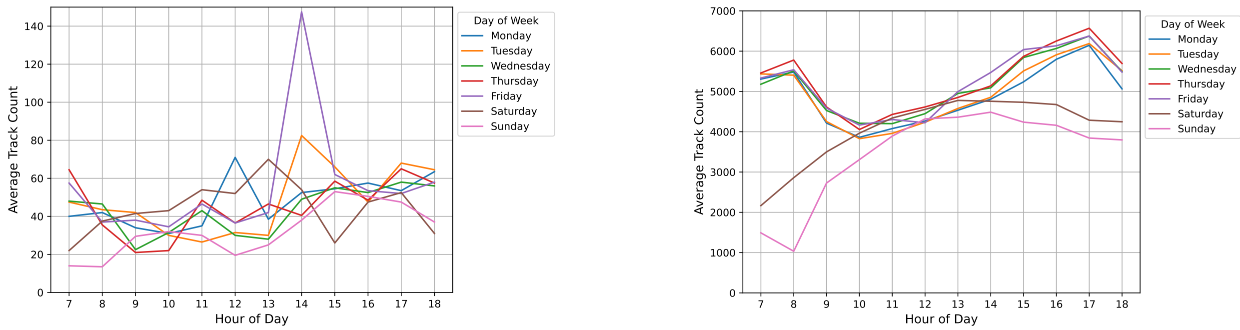
FIGURE 23: Speeding charts as percentage of vehicles by hour of the day and the day of the week for the four approaches on Stirling Road and SR7.

Figure 23 illustrates the percentage of vehicles passing through this intersection at a speed greater than that of the posted speed limit, and their correlation between the direction, day, and time of day. The vehicles at this intersection mostly conform to speed limits. Notably, the only defined peak of speeding incidents at this intersection is seen in Figure 23b, occurring on Sunday, from 8 AM to 9 AM for SBT traffic.

Safety Evaluation - Volumes

Rivaling Stirling Rd and University Drive, this intersection is one of the busiest of this study via both pedestrian traffic volume, as seen in Figure 24a, and in terms of vehicle traffic volume, as noted in Figure 24b. Focusing on Figure 24a, pedestrian traffic is seen to increase later in the day, with peaks occurring from 12 PM to 3 PM, and sustained high levels of foot-traffic thereafter. In particular, a very high level of pedestrian traffic occurs on Fridays at 2 PM, with over 100 pedestrians identified moving through this intersection.

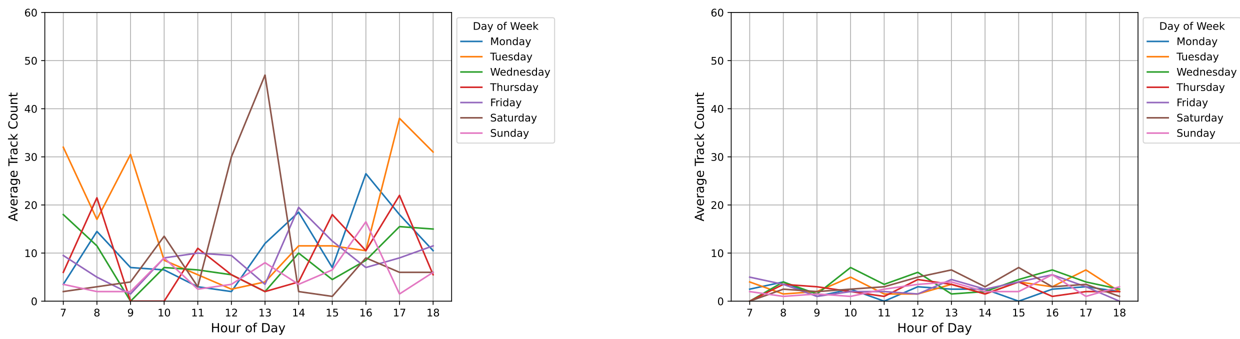
With high volumes of vehicle traffic detected through this intersection, a detailed picture of the level and habits of traffic moving through this intersection may be made. It is first seen that high traffic levels peak from 7 AM to 8 AM during week days, and drop off in a substantial way during the early afternoon (10 AM to 12 PM). The afternoon rush hour surge then begins at around 2 PM and continues until 6 PM, reaching levels higher than the morning rush at approximately 5 PM.



(a) Pedestrian volume (b) Vehicle volume

FIGURE 24: Volume plots by hour of the day and the day of the week for total volume on all four approaches on Stirling Road and State Road 7 (SR7).

Safety Evaluation - Conflicts



(a) P2V conflicts (b) V2V conflicts

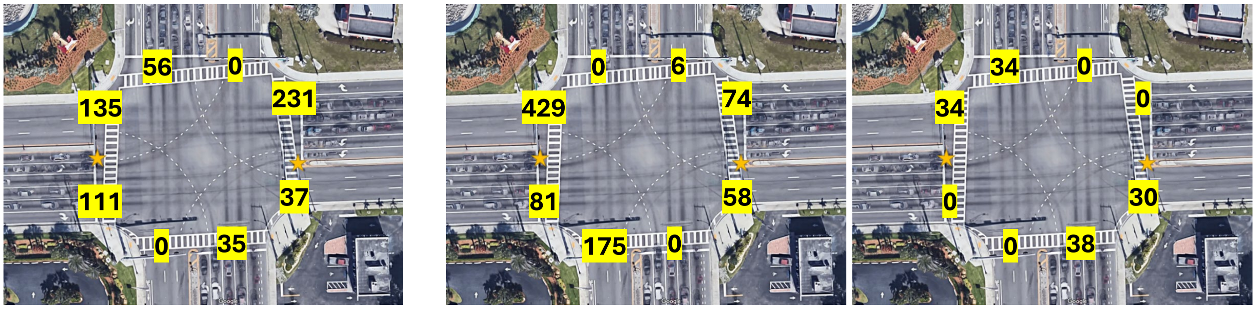
FIGURE 25: Conflict plots by hour of the day and the day of the week for total conflicts on all the four approaches on Stirling Road and State Road 7 (SR7).

Figure 25a illustrates the number of P2V conflicts, which notably occur in high volumes on Tuesday mornings between 7 AM and 9 AM, as well as Tuesday evenings between 4 PM and 6 PM. There is also a spike from 11 AM to 1 PM on Saturdays, most likely caused by pedestrians walking to popular events and activities at the nearby Hard Rock Hotel & Casino.

Vehicle conflicts (V2V), represented in Figure 25b, are less prevalent for this intersection, with no substantial spikes. This is remarkable given the volume of traffic moving through this intersection.

Safety Evaluation - Pedestrian-to-vehicle conflicts

As seen in Figure 26a, many of the P2V conflicts which occur at this intersection are seen during right-turn maneuvers. Figure 26b indicates a high number of conflicts occurring during left turns, particularly with NBL vehicles. The through traffic P2V conflicts, illustrated in Figure 26c, are relatively low for the amount of traffic this intersection supports.



(a) P2V w/right-turn vehicles (b) P2V w/left-turn vehicles (c) P2V w/through vehicles

FIGURE 26: Total P2V conflicts on the crosswalks by vehicle movement, on Stirling Road and State Road 7 (SR7).

Safety Evaluation - Specific Observations

Observed P2V conflicts at this intersection include:

1. Many pedestrians and bicyclists disobeying traffic signals, putting themselves in precarious positions within the crosswalk and creating potential safety hazards as they are exposed to moving vehicles.
2. Some pedestrians choosing to run across the intersection while through vehicles are passing, leading to dangerous near-miss situations and potential accidents.
3. Vehicles sometimes stopping in the crosswalk, forcing pedestrians to walk outside the designated crosswalk area to avoid the vehicle, which increases the risk of pedestrian accidents.
4. Heavy vehicles, such as buses and semi-trucks, taking a right turn and posing a significant danger to pedestrians due to their large turning radius and limited visibility.

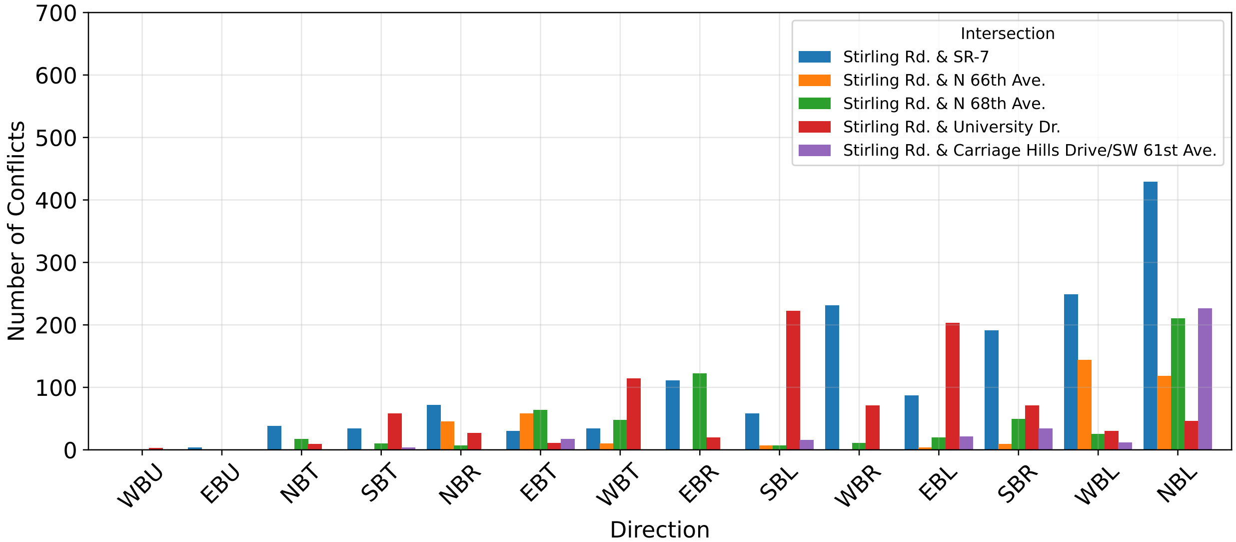
Observed V2V conflicts at this intersection include:

1. Vehicles often continuing to make left turns even after the left turn signal turns red, particularly at northbound left (NBL) and westbound left (WBL) turns. This leads to conflicts with oncoming traffic.
2. Right-turning vehicles sometimes entering conflicts when merging with the through stream of vehicles. This can result in sudden stops or swerves, potentially causing accidents and disrupting traffic flow.

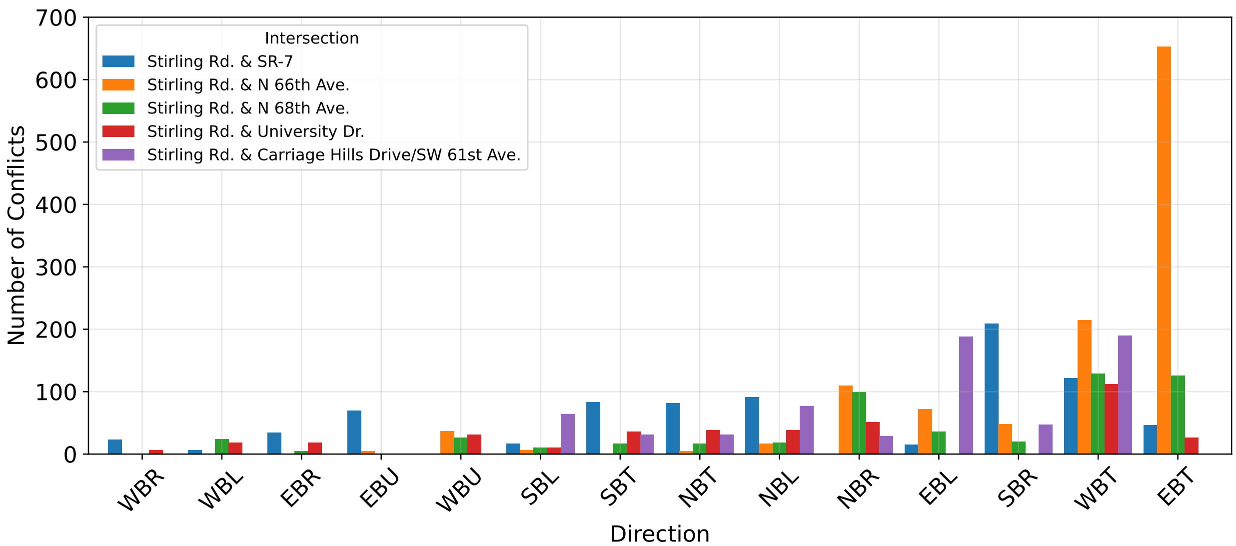
RECOMMENDATIONS FOR CONFLICT MITIGATION

Figure 27 shows the distribution of all vehicle movements that are involved either in a P2V or a V2V conflict. More specifically, Figure 28 shows an aggregation of all P2V conflicts by vehicle movement (right, left, or through) as well as V2V conflicts by Left Opposing Through (LOT), Right Merging Through (RMT), and ROL (Right Opposing Left).

Adjustments to the intersection in the environment may decrease the rate of near-misses. For instance, according to Figure 27b, the highest conflict rates on 61st Avenue occur between WBT and EBL vehicles, where there is confusion between which vehicle has the right of way. A "left turn yield on green" sign can resolve this issue, as shown in Figure 29a. The Stirling Road & 61st Avenue intersection may benefit from the addition of such a sign.

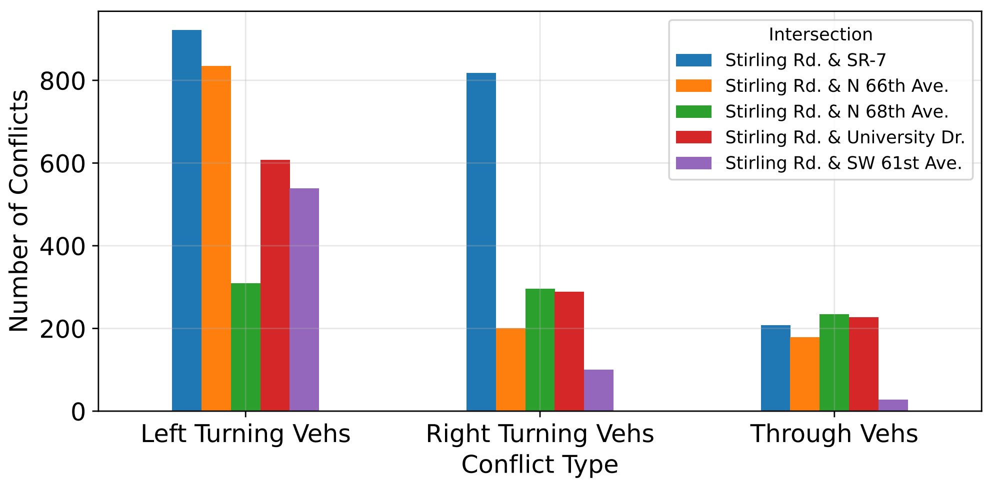


(a) P2V Conflicts by Directionality

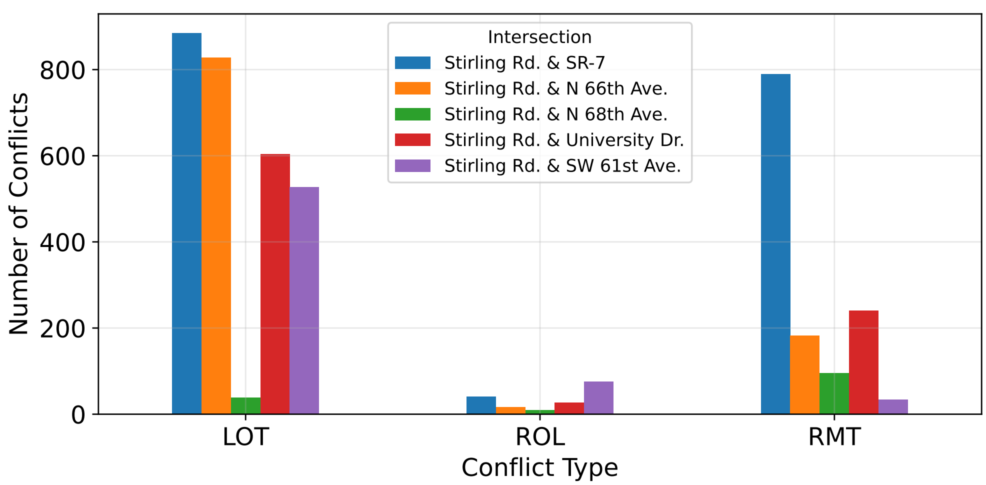


(b) V2V Conflicts by Directionality

FIGURE 27: Number of Conflicts by Directionality across all intersections.



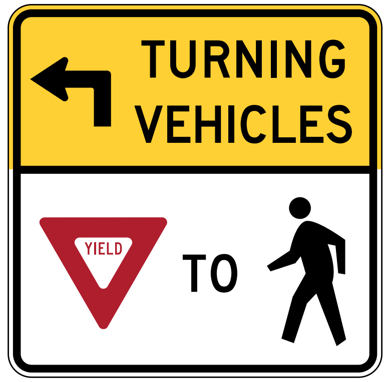
(a) P2V



(b) V2V

FIGURE 28: V2V conflicts by vehicle movement.

(a) Left Turn Yield on Green sign, with MUTCD code R10-12 (*22*).



(b) Left turning vehicles yield to pedestrian sign, with MUTCD code R10-15L (*22*).

(c) Yield Here to Pedestrians sign for right-turn vehicles, MUTCD code R1-5 (*22*).

(d) Watch for Pedestrians sign for through vehicles with MUTCD code W40-3 (*22*).

FIGURE 29: Traffic signs to improve intersection safety.

As shown in Figure 27a, the highest occurring vehicle movement in a P2V conflict is the NBL, followed by the WBL. Thus, there is a repeating pattern where left-turning vehicles are involved in high rates of conflicts. In previous literature, the R10-15 sign (Figure 29b) has been proven to increase yielding behavior from cars to pedestrians (*23*). Thus, to provide a visual signifier for motorists to be cautious during their turn, the R10-15L sign (a variant for left-turning cars instead of right-turning cars) may prevent left-turning vehicles from conflicting with pedestrians. Namely, this signage may be effective in the Stirling Road & State Road 7 intersection and the Stirling Road & 61st Avenue intersection.

Right-turning vehicles will, at times, enter the intersection with speed to conduct a turn without considering the possibility of a pedestrian currently on the crosswalk. This pattern is shown within the 68th Ave. intersection and the SR-7 intersection, as evidenced by Figure 27a and their significant numbers of P2V conflicts with right-turning vehicles. The "Yield Here to Pedestrians" sign in Figure 29c can encourage motorists to let the pedestrians finish crossing before entering the crosswalk to execute a right turn.

In a more general sense, all intersections may benefit from a simple "Watch for Pedestrians" sign in Figure 29d.

Additionally, many P2V conflicts occur with pedestrians who do not have the right of way, as they at times ignore traffic signals. However, a countermeasure that discourages risky behavior is audible pedestrian walk signals, where a speaker plays sound to indicate when it is safe to cross. Audible signals are correlated with a decrease in pedestrian-involved accidents in intersections with high traffic volumes (*24*). This correlation may be due to an audible "wait" sound that deters pedestrians from jaywalking.

FIGURE 30: An image of an audible walk signal. (*25*)

More drastic changes to the intersections may also reduce conflicts. Examples include centerline hardening, which was demonstrated by Hu & Cicchino to reduce P2V conflicts by 70.5% (*26*). An example of centerline hardening within an intersection is demonstrated in Figure 31. This method influences cars to take more careful turns, which increases awareness of pedestrians. While any of the intersections within our study may benefit from centerline hardening, it may be feasible only on non-narrow roads.

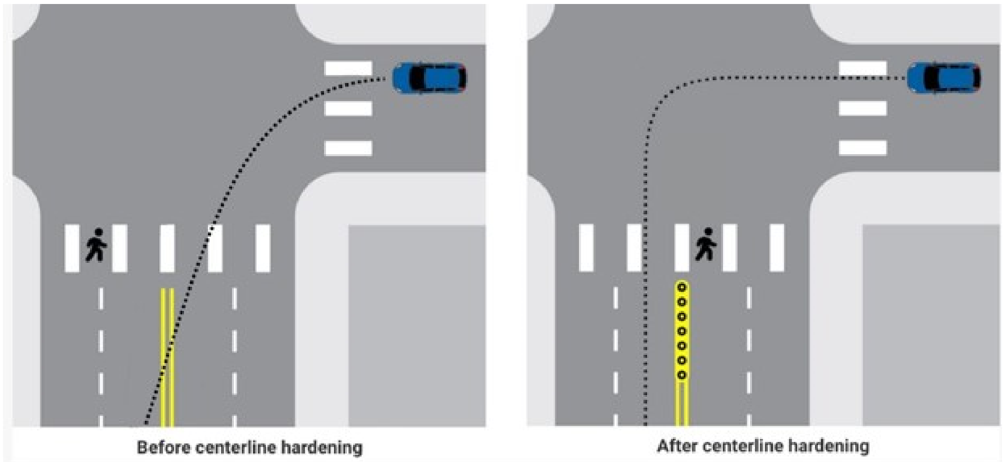


FIGURE 31: Diagram of centerline hardening, adapted from (*27*).

Another alteration to the intersection is adding a "leading pedestrian interval," or LPI, to intersections with many P2V conflicts. With LPI, pedestrians are allowed to proceed through the crosswalk with a headstart while the cars must remain waiting at the red light. As pedestrians gain the opportunity to progress through their path, motorists have greater visibility of those pedestrians, which can decrease P2V conflicts (*28*).

Additionally, to improve contrast, the pedestrian crossing area can be enhanced with white crosswalk lines and patterns against a dark black background. This can help drivers more easily spot pedestrians on crosswalks.

A before-and-after study is warranted to assess the efficacy of these countermeasures in decreasing the rate of conflicts. Further, the categorization of conflicts demonstrates potential for creating an AI-powered algorithm to suggest the ideal countermeasure for various signalized intersections.

CONCLUSIONS

The case study presented in this paper demonstrates the effectiveness of utilizing video analytics and artificial intelligence to derive safety solutions specific to vehicle movements observed at a given intersection in Broward County, Florida. By leveraging traffic cameras and advanced AI-based methods, we were able to generate and process the trajectories of pedestrian and vehicle movements, providing critical insights into traffic behaviors and identifying potential risks. Our comprehensive analysis using surrogate safety measures such as TTC and PET, coupled with an event filter, allowed us to focus on the most severe near-miss incidents, thereby making the analysis more manageable and actionable for practitioners.

The findings revealed significant conflict points, particularly during left-turn movements, where both driver and pedestrian behaviors contributed to increased risks. The data indicated that these movements often result in dangerous situations due to the complexity and timing of the interactions involved. Additionally, there were conflicts with pedestrians and right turning and through vehicles.

To address these issues, we propose a range of countermeasures. These include installing additional signage to improve driver awareness, modifying intersection geometry to streamline traffic flow, and adjusting signal timing to better accommodate the varying needs of both vehicles and pedestrians. These measures aim to reduce the likelihood of accidents by making intersections safer and more intuitive for all users.

For future work, the proposed countermeasures will be implemented, and a follow-up study will be conducted to evaluate any changes in conflict situations that result from these measures.

Our research underscores the importance of data-driven decision-making in urban planning and traffic management. The implications of the case study extend beyond the local context of Broward County, offering valuable insights and methodologies that can be applied to similar urban environments at other places. By sharing our findings and recommendations, we hope to contribute to the broader goal of creating safer, more efficient, and more sustainable urban traffic systems.

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AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: Conceptualization, M.L., T.B., A.R. and S.R.; data curation, J.F., H.L., and K.K.; formal analysis, J.F., H.L., and K.K.; funding acquisition, M.L., A.R. and S.R.; investigation, J.F. and T.B.; methodology, J.F. and T.B.; project administration, A.R. and S.R.; software, J.F., H.L., K.K., and and T.B.; supervision, A.R. and S.R.; visualization, J.F.; writing—original draft, J.F., H.L., K.K., and T.B.; writing—review and editing, M.L., T.B., A.R. and S.R. All authors reviewed the results and approved the final version of the manuscript.

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