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Using Video Analytics to Improve Traffic Intersection Safety and Performance

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Abstract: Road safety has always been a crucial priority for municipalities, as vehicle accidents claim lives every day. Recent rapid improvements in video collection and processing technologies enable traffic researchers to identify and alleviate potentially dangerous situations. This paper illustrates cutting-edge methods by which conflict hotspots can be detected in various situations and conditions. Both pedestrian–vehicle and vehicle–vehicle conflict hotspots can be discovered, and we present an original technique for including more information in the graphs with shapes. Conflict hotspot detection, volume hotspot detection, and intersection-service evaluation allow us to understand the safety and performance issues and test countermeasures comprehensively. The selection of appropriate countermeasures is demonstrated by extensive analysis and discussion of two intersections in Gainesville, Florida, USA. Just as important is the evaluation of the efficacy of countermeasures. This paper advocates for selection from a menu of countermeasures at the municipal level, with safety as the top priority. Performance is also considered, and we present a novel concept of a performance–safety trade-off at intersections.

Keywords: intersection safety; pedestrian–vehicle conflicts; vehicle–vehicle conflicts; intersection performance

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1. Introduction

Intersection safety studies are essential because traffic intersections are prone to crashes leading to injury or fatality [1]. According to the USDOT, more than 50% of road crashes leading to fatality or injury happen at or near traffic intersections. With rapid technological advancement and price drops [2], video cameras are now commonly deployed as sensors in traffic intersections. Existing intersection safety assessment methodologies often require the analysis of historical data to infer current and future intersection user behavior. Although helpful, these data are often biased toward what has been reported, which is retrospective and often incomplete. Video analysis of traffic intersections has no reporting or survivorship biases because the analysis times from the fisheye camera [3] are precise and unbiased. This paper presents a methodology to systematically use the trajectory data from video analysis, severe events data, and signal phasing data to detect and analyze conflict hotspots and evaluate the efficacy of countermeasures to improve intersection safety. The trajectory data and severe events data are available from our previous work [4], which implemented video processing and severe event detection algorithms, while the signal phasing data are available from the advanced traffic controllers (ATC) at traffic intersections.

A novel evaluation engine is developed as a part of this paper. The engine ingests trajectory data, severe events data, and signal phasing data at a given intersection for different days of the week and times of the day. The evaluation engine has three primary data processing modules: the first computes pedestrian and vehicle volume hotspots; the second computes pedestrian–vehicle (P2V) and vehicle–vehicle (V2V) conflict hotspots; the third evaluates intersection service as a proxy to intersection performance for the study period. Multiple signal phasing configurations may be systematically analyzed using the evaluation engine to arrive at volume and conflict heatmaps and a performance–safety trade-off chart for the intersection. Traffic engineers may use this trade-off chart to select the optimal configuration for optimizing intersection safety and performance.

More detail about each module is presented below:

1. The volume hotspot detection module computes the peaks and troughs in pedestrian and vehicle volume. It is useful to understand where the volume peaks and spikes are and if there are valleys and troughs in the volume. This information helps a traffic engineer implement signal timing changes to address safety issues only during the peak period instead of throughout the day.
2. The conflict hotspot detection module computes the temporal hotspots of P2V and V2V conflicts by the conflict types and movements of the involved trajectories. P2V conflicts occur when a pedestrian and a vehicle come dangerously close, and their two trajectories intersect. V2V conflicts are defined as the occurrence of evasive vehicular actions and are recognizable by braking or weaving maneuvers [5]. If a hotspot pattern emerges in the conflict analysis, a traffic engineer could apply a countermeasure to address those conflicts. The evaluation engine uses a novel visualization scheme to simultaneously represent temporal conflict hotspots with the spatial locations within the intersection where the conflicts occur. We use the reciprocal of the number of conflicts as a measure of intersection safety.
3. The intersection-service evaluation module does a fine-grained aggregation of vehicle volume at subcycle levels and outputs an intersection service histogram that bins the number of vehicles entering an intersection in 5-s bins from the start of green. Vehicle volume is collected for 60 s. Vehicles from all cycles within the study period are aggregated to arrive at a single histogram. We use intersection-service evaluation as a proxy for a measure of intersection performance [6]. Specifically, we use the entering vehicle counts for all movements between the 5- and 15-s marks to represent the performance of the intersection. The rationale for aggregating the vehicle counts for 10 s, choosing the start and end points as 5-s and 15-s marks, respectively, is that we exclude the startup loss and measure the volume before saturation headway. This fine-grained aggregation of vehicle volume captures the effect of any temporal issues impacting intersection performance that may otherwise be unnoticeable in hourly aggregations. Examples of temporal issues impacting the performance may be the presence of many pedestrians at the intersection or a change in signal phasing configuration. We use the performance measure to compare two signal phasing configurations at the same intersection.

The evaluation engine with the modules above may be used for studying performance–safety trade-offs from multiple signal phasing configuration scenarios. We can analyze the current scenario using the evaluation engine and arrive at an appropriate countermeasure that can potentially improve safety or performance issues at the intersection. We demonstrate the operation of the evaluation engine on two different intersections using more than a week of data on each intersection. One of these intersections is near a high school with teenage pedestrians and drivers. The other intersection has a pedestrian presence of more than 40% of the total intersection users.

The key contributions of this paper are described as follows:

1. We have developed a systematic end-to-end software to analyze intersection data to find intersection safety and performance metrics.
2. We have formalized the simultaneous treatment of intersection safety and intersection performance producing performance versus safety trade-off charts
3. Additionally, our graphical heatmap output is very helpful to figure out not only the temporal hotspots for pedestrian–vehicle and vehicle–vehicle conflicts, but also the spatial locations. This concise representation that simultaneously captures both the temporal and spatial properties of the conflicts is not described in the existing literature.

The rest of the paper is organized as follows. Section 2 presents the related work while Section 3 presents the background for our paper. Next, Section 4 presents our system's in-built methodology and how we can use it systematically to discover safety issues and address them. Section 5 illustrates how to apply the steps to find the safety issues for both pedestrian–vehicle (P2V) and vehicle–vehicle (V2V) interactions at two different intersections. Finally, we discuss the key findings in Section 6.

2. Related Work

Traffic intersections are more at risk for near-miss events and accidents. This section first describes surrogate safety measures, what these are and how they are beneficial. The sensors available today to compute the surrogate safety measures are discussed next, and finally, the existing work on traffic safety analysis using video processing is presented.

2.1. Surrogate Safety Measures

Surrogate safety measures are indicators that strongly correlate to traffic conflicts [7,8]. Surrogate safety measures effectively detect near-miss events, which occur much more frequently than crashes and are generally not reported through traditional channels. Crash analysis studies require years of data because of the infrequent nature of actual traffic collisions [9,10]. Combined with the fact that crash data is often incomplete due to the under-reporting of crashes and injuries and that the geometry of the intersection may change over such long periods, the effectiveness of crash analysis studies diminishes significantly. Surrogate safety studies, on the other hand, can uncover important safety issues using about a week of video footage, making it a time- and cost-effective solution for monitoring traffic intersections.

The surrogate safety measures most commonly used for near-miss detection are time-to-collision (TTC) and post-encroachment-time (PET). TTC is the time remaining to prevent a collision (by applying brakes, steering away, or using some other preventive action), measured precisely as the difference between the time the road user takes action to the point where the collision can occur [11]. PET is the difference between the time when the first road user leaves a point and the second road user reaches that point [12]. Lower values of TTC and PET indicate higher risks of collision [13]. After computation of TTC and PET, one way to identify severe events is by applying thresholds on TTC and PET [14,15]. Several other proposed measures are based on either spatial proximity or acceleration–deceleration patterns of vehicles [16–18]. Our software considers TTC and PET (thresholded values) with other measures such as speed, acceleration, and distance between the two road users when a severe event happens. The thresholds we use for TTC and PET are 2 s for TTC and 3 s for PET. These values are configurable, so users can set them to different values if they desire. The early definitions of traffic conflicts indicate that only the most extreme of traffic interactions have been considered safety critical [19]. Hydén [20] proposed a hierarchy of traffic events varying in severity, and Arun et al. [18] note that there is still no consensus on what constitutes a safety-critical event or a near-miss. Vogel [21] compares headway and TTC as safety indicators, showing that these two measures are independent of each other. Peesapati et al. [22] evaluated and found that PET is effective as a surrogate measure for left turn and opposing through conflicts. Feng et al. [23] found a strong correlation between factors leading to near-misses and those leading to crashes, which highlights the benefits of analyzing the surrogate safety measures for severe near-miss events.

Johnsson et al. [24] find surrogate safety measures appropriate for vulnerable road users, including pedestrians and bicyclists. Fu et al. [25] developed a framework for assessing the safety of pedestrian–vehicle interactions. Chen at al. [26] developed lane-based models for evaluating pedestrian–vehicle interactions at non-signalized crosswalks.

Yang et al. [27] created the new surrogate measure risk status after fusing surrogate safety measures with crash analysis data. Surrogate safety measures also are used extensively in traffic simulation models [7,28] and also in connected autonomous vehicles [29,30].

2.2. Intersection Sensors

Loop detectors [31] are traditionally installed at intersections for monitoring traffic and signaling states. While these detectors are very effective in detecting traffic incidents [32], it is not possible to obtain the exact location of the conflict from these under-the-ground detectors. With recent technological advancements, various other types of sensors, such as video cameras, LiDAR cameras, and infrared (IR) cameras, are being used for intersection monitoring [33–35].

Video-based traffic monitoring is increasingly popular because it is relatively low-cost and fast to process and analyze [36]. Unlike data from loop detectors, video footage gives us rich information about the object trajectories, object classification (e.g., car, bus, truck, motorcycle, pedestrian), precise location and severity of traffic conflicts, and traffic violations. Unlike LiDAR and IR cameras, video cameras are easier to deploy and maintain [37] . Video data is also easier to review and understand compared to outputs of LiDAR and IR cameras. On the downside, video cameras depend on proper lighting conditions at intersections. The two main types of video cameras are ordinary cameras and fisheye cameras. The advantage of using fisheye cameras is that a single camera can monitor the whole intersection for smaller intersections, and two cameras are sufficient for the slightly bigger ones. On the other hand, with ordinary cameras, a traffic intersection would require as many cameras as there are approaches (typically four) to monitor the intersection completely [38].

The viability of video cameras for traffic monitoring has encouraged the development of robust video processing algorithms and surrogate safety measures. Hence, intersection safety assessment using video analysis is an active research topic. We will briefly review the existing work in this area. We reuse the video processing framework developed as a part of our previous paper [4]. Section 3 provides the details of our video processing algorithm.

The differences between this paper and our previous work [4] are as follows. The software [4] was used for processing the videos and generating a database of trajectory data and severe events over multiple days of the week and times of the day. In this paper, we develop an evaluation engine that uses the trajectory data, severe events data, and signal phasing data to perform a spatio-temporal analysis over multiple intersections to identify temporal conflict hotspots and volume hotspots. This paper presents a visual representation of P2V and V2V conflicts that annotates heatmaps with symbols that give the practitioner clues about the spatial locations of the conflicts and the movements of the involved trajectories for further analysis. Additionally, the evaluation engine deter-mines overall performance and safety metrics for a given signal phasing configuration scenario and plots a performance–safety trade-off chart for an intersection for multiple scenarios. Such a chart would be helpful to a traffic engineer for the selection of a counter-measure because it would give an idea of the performance safety characteristics of that or similar configurations.

2.3. Intersection Safety Analysis Using Video Cameras

This section presents a collection of existing work on traffic intersection monitoring using video cameras [39]. In the end, we compare the work in the current paper to two other recent papers on safety assessment using video analysis.

Saunier et al. [40] developed a framework to estimate collision probabilities and their spatial distributions based on video data collected in Kentucky. Ismail [41] in this thesis treats the use of computer vision techniques to process traffic video data for intersection safety analysis. Stipancic et al. [42] develop and evaluate crash frequency and severity models, incorporating GPS-derived surrogate safety measures as predictive variables. St-Aubin [43] developed a thesis studying computer vision techniques for traffic roundabouts.

Our paper is closely related to the work by Samara et al. [14], where the authors use video analysis for analyzing intersection traffic. The main difference is that the work [14] has not treated P2V conflicts. Further, our paper can identify movements of trajectories that help to pinpoint any persistent issues with specific movements. Moreover, the work [14] uses only PET as a safety indicator and does not discuss phase-based conflict hotspots for conflicts. There is also no treatment for countermeasures to improve intersection safety or a discussion of how intersection safety impacts intersection performance.

Kronprasert et al. [44] study safety performance using a video-based traffic conflict analysis system. They do not use fisheye cameras but rather regular ones that monitor the direction they point to. The advantage of fisheye cameras is that one camera can monitor the whole intersection. Multiple regular cameras must be installed to obtain a complete view of the intersection, one for each approach. Moreover, the videos from all the cameras must be merged to obtain complete information about the intersection trajectories. Furthermore, the safety surrogate measure used in [44] was TTC only. Our work presented in this paper considers P2V conflicts. For P2V and V2V conflict hotspots, we conduct a more refined level of conflict categorization regarding the movements of the involved trajectories.

3. Background

Given a video captured by a fisheye camera at an intersection, the steps in our video analytics system are: process the video to extract trajectories that are time-stamped (x, y) coordinates; fuse the trajectories with signaling information; process the trajectories to mine features that help with safety analysis; find all P2V and V2V conflict events; filter the events to retain only the "severe events"; and categorize the event based on the movements of the involved trajectories. These steps have been presented previously in [4] and included here for completeness.

3.1. Video Analysis

With a fisheye video as input, the video analysis software draws a bounding box around each object in a video frame, identifies the object's class based on several previously annotated images, and finds the (x, y) coordinates of the object as the center point of the bounding box. A video frame is a static snapshot. The fisheye cameras installed at the intersections capture 10 video frames per second. The object detection and tracking module utilize YOLOv4 [45] to detect different road participants, including cars, buses, trucks, pedestrians, and motorcyclists. A modified DeepSORT algorithm [46] associates detections across frames and assigns a unique ID for each object. The (x, y) coordinates are in the circular fisheye space. A fisheye lens has a very wide angle, creating a panoramic or hemispherical non-rectilinear image. So we apply a post-processing step to map the coordinates to rectilinear space using fisheye-to-perspective transformation followed by thin-plate spline (TPS) warping [47–49]. The new time-stamped coordinates in the rectilinear space are stored in a database (DB) table.

3.2. High-Resolution Controller Log Analysis

The high-resolution controller logs [50] provided by the City of Gainesville are analyzed to extract signal phasing information for an intersection. Fusing the signal phasing with object trajectory coordinates over the time axes gives us a holistic view of a trajectory based on when the object arrived and left the intersection. We use this information later to count the vehicles that pass the stopbar in any one direction in intervals of five seconds after the traffic light turns green.

3.3. Feature Computation

The following is a list of the key features we compute:

1. Standard near-miss attributes: We compute the standard risk assessment metrics for every event, such as TTC and PET.
2. Signal phase information: The fused video and signal phasing dataset is used to determine features, such as the current vehicle signal, current pedestrian signal, and if the event occurs during the beginning (first 10% of the cycle), middle, or end (last 10% of the cycle) of the current signaling phase.

3. Trajectory features: The trajectory-related features are the trajectory's movement, associated phases, and lanes or crosswalks.
4. Speed features: These include the current speeds and accelerations for vehicle–vehicle interactions.
5. Distance: Spatial distance between two users at the time of the conflict.

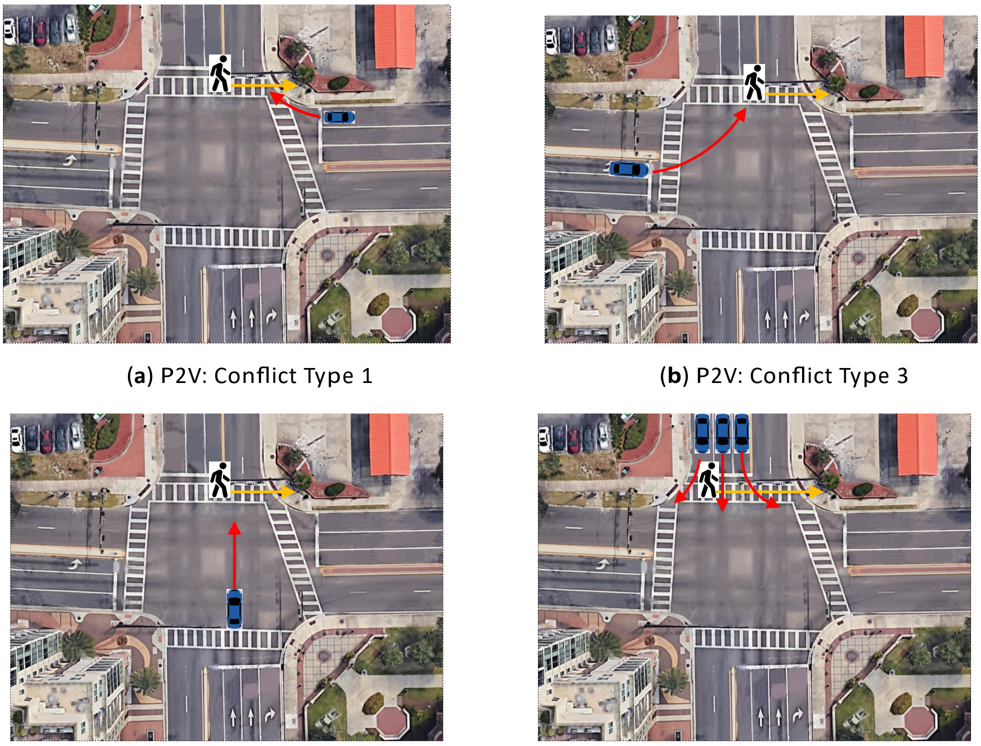
3.4. Categorization of Severe Events

The categorization of the P2V and V2V conflicts is described in this section and used in the rest of the paper.

1. P2V Conflicts: The following are the main conflicts between vehicles and pedestrians at signalized intersections:

- Conflict Types 1 and 2: Right-turning vehicle with the pedestrian in an adjacent parallel crosswalk (Figure 1a) and near-side crosswalk (Figure 1d), respectively.
- Conflict Types 3 and 4: Left-turning vehicle with the pedestrian in the far-side crosswalk (Figure 1b) and near-side crosswalk (Figure 1d), respectively.
- Conflict Types 5 and 6: Through vehicle with pedestrian in the far-side crosswalk (Figure 1c) and the near-side crosswalk (Figure 1d), respectively.

Among these conflicts, Conflict Types 1 and 3 are possible conflicts between pedestrians and vehicles at signalized intersections if all vehicles and pedestrians strictly follow the traffic rules (assuming a three- or four-leg intersection, which is the most common).



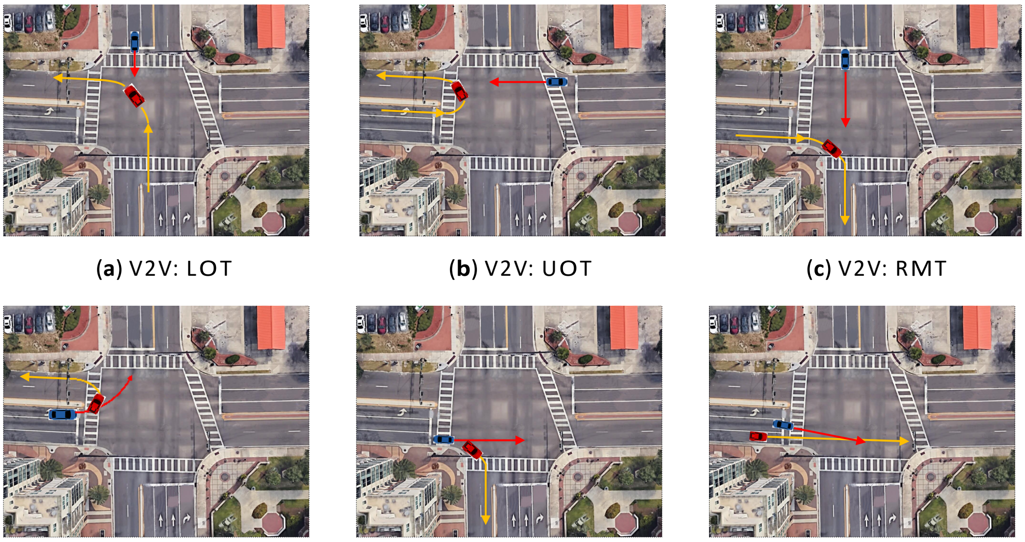
(**a**) P2V: Conflict Type 1
(**b**) P2V: Conflict Type 3
(**c**) P2V: Conflict Type 5
(**d**) P2V: Conflict Types 2, 4, and 6

Figure 1. P2V conflict types.

2. V2V Conflicts: As the primary purpose of signalization is to reduce or eliminate conflicting movements at the intersection, the following are the possible conflicts between vehicles at signalized intersections if all vehicles strictly follow the traffic rules (assuming a three- or four-leg intersection, which is the most common):

- Left turn and opposing through (LOT): A left-turning vehicle in a permitted phase conflicts with an opposing through movement (Figure 2a).

- U-turn and opposing through (UOT): A U-turning vehicle in a permitted phase conflicts with an opposing through movement (Figure 2b).
- Merging right and through (RMT): A right-turning vehicle merging on the same lane as a through vehicle (Figure 2c).
- U-turn and a following left-turn (UFL): A leading U-turn with a following left-turning vehicle (Figure 2d).
- Right turn and a following through (RFT): A leading right-turning vehicle with a following through vehicle (Figure 2e).
- Lane change and adjacent through (LCC): A lane-changing vehicle conflicting with adjacent through (Figure 2f).
- Rear-end conflicts (REC): A leading vehicle moves slower than the following vehicle in the same lane.
- A U-turn and an adjacent right turn.



(**a**) V2V: LOT (**b**) V2V: UOT (**c**) V2V: RMT

(**d**) V2V: UFL (**e**) P2V: RFT (**f**) V2V: LCC

Figure 2. V2V conflict types.

If one or more vehicles do not strictly follow the traffic rules (e.g., run the red light), other conflicts are possible, namely, adjacent through movements and left turn and adjacent through. Some conflict types may be inherently more dangerous than the other types. For example, the left-turn and opposing through conflicts may lead to a more serious crash than a merging, a diverging, or a rear-end conflict. Further, the left-turn and opposing through conflicts are more dangerous when the slow left-turning vehicle is the first to cross the conflict point. The less dangerous, relatively common occurrence is when the left-turning vehicles yield to the through vehicles before completing the turn.

4. Methodology

This paper presents an evaluation engine that uses trajectory data and severe events from many videos over different days of the week and hours of the day to compute temporal volume and find conflict hotspots. The spatio-temporal analysis helps discover safety issues in the intersection and when and where they occur. This knowledge is crucial for arriving at effective countermeasures with minimal impact on the rest of the traffic.

4.1. Evaluation Engine Modules

Figure 3 shows our evaluation engine and the various engine modules with their inputs and outputs. The evaluation engine modules are described in detail below.

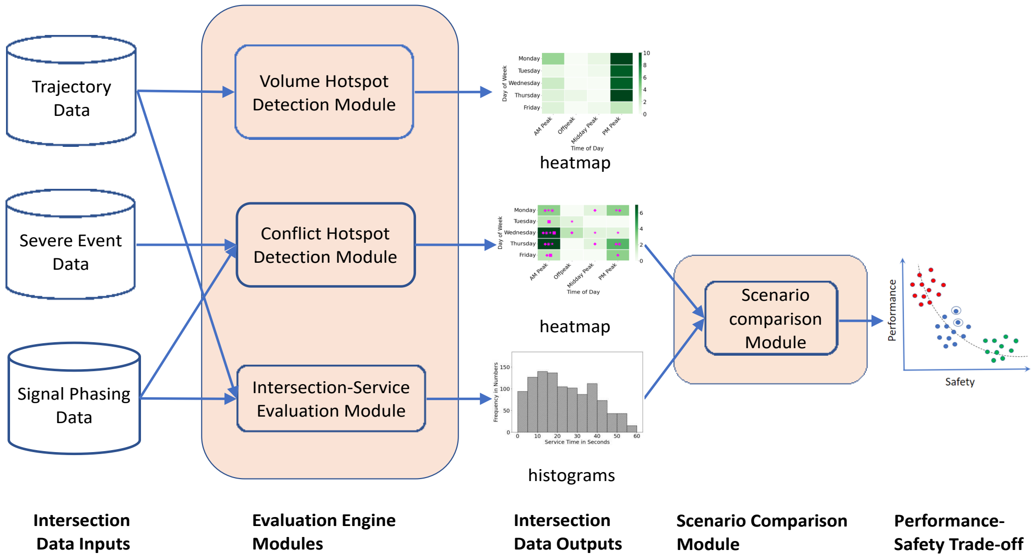


Figure 3. Evaluation engine modules with their inputs and outputs.

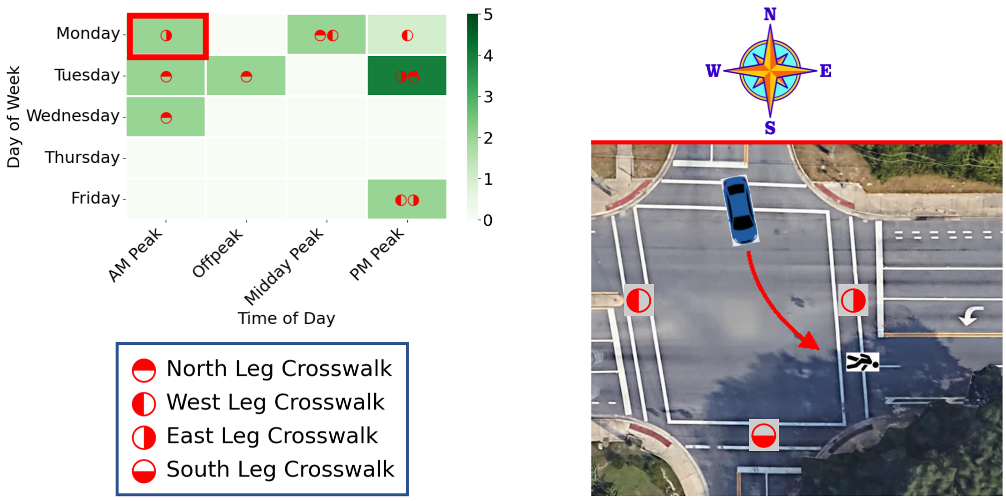
4.1.1. Volume Hotspot Detection Module

The volume hotspot detection module is the first module of the evaluation engine that estimates (1) pedestrian volume on the different crosswalks and (2) volume peaks and troughs by the time of day and day of the week. For example, this module will help answer a query such as "How many pedestrians crossed using the north crosswalk leg of intersection X between 12 PM and 1 PM"? or "When does pedestrian volume aggregated on an hourly basis exceed a threshold T in intersection X for a given time period Y"? Thus, the pedestrian hotspot detection module exposes the times of day when the pedestrian volume peaks and provides a guideline to a traffic engineer about the time of day when countermeasures for alleviating potential P2V conflicts may be implemented. Usually, such countermeasures penalize intersection performance, so implementing such countermeasures in targeted time intervals instead of throughout the day may benefit pedestrians and vehicles.

Similarly, the vehicle hotspot detection module may be used to compute vehicle volume. In contrast to video cameras, the loop detectors installed in the intersection cannot distinguish between through and right-turning vehicles. The vehicle hotspot detection module exposes times of the day and days of the week when the vehicle volume peaks for a given movement. The volume hotspot detection module could output turning movement counts (TMC) for all movements over user-selected time intervals. For example, the module can output the total number of vehicles with movement NBT, NBL, NBR, SBT, SBL, SBR, EBT, EBL, EBR, WBT, WBL, and WBR every 15 min during the AM peak.

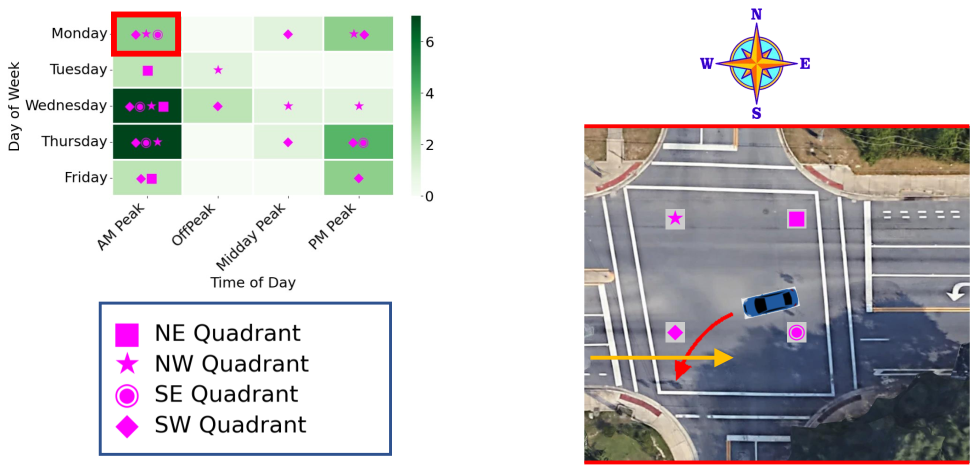
4.1.2. Conflict Hotspot Detection Module

The second module in the evaluation engine computes the temporal hotspots of P2V and V2V conflicts and the conflict types. Examples of conflict types are, for P2V, left-turning vehicle with a pedestrian on the far-side crosswalk (Figure 4b); for V2V conflicts, left-turning vehicle conflicting with an opposing through vehicle (LOT, Figure 5b). Section 3.4 gives a complete listing of conflict types in the "severe event" database.



(a) (b)

Figure 4. Annotated heatmap: (**a**) encodes the spatial location of P2V conflicts for the conflict type vehicle turning left with pedestrian on the far-side crosswalk. Given the P2V conflict type and the crosswalk direction, the movements of the trajectories may be derived; (**b**) on-the-field depiction of the conflict in the red box in (**a**), where a pedestrian on the east leg crosswalk has a conflict with a left turning vehicle. The movement of the vehicle may be hence derived as SBL.



(a) (b)

Figure 5. Annotated heatmap: (**a**) encodes the spatial location of V2V conflicts for the conflict type left opposing through (LOT). Given the V2V conflict type and the crosswalk direction, the movements of the trajectories may be derived; (**b**) on-the-field depiction of the diamond conflict in the red box in (**a**). The diamond indicates the conflict has occurred in the SW quadrant. Thus, the conflicting vehicles must have movements EBT and WBL for a LOT conflict to occur on the SW quadrant.

This paper develops a visualization scheme to describe the spatial location in the intersection where the conflicts happen. This is illustrated in Figures 4 and 5. Given the conflict type and the quadrant information, it is possible to derive the movements of the trajectories involved in the conflicts. For example, for the P2V conflict chart in Figure 4a, there are a few conflicts in the east crosswalk on Monday's AM Peak. Since the type of the P2V conflict is a vehicle turning left with a pedestrian on the far-side crosswalk, we can derive the vehicle movement as SBL, as illustrated in Figure 4b. Similarly, the V2V conflict chart in Figure 5a shows a LOT conflict in the SW quadrant on Monday's Midday Peak. This implies that the movements of the conflicting trajectories are WBL and EBT, as shown in Figure 5b. If a specific combination of phases emerges repetitively from this analysis, the traffic engineer could selectively address those. Otherwise, a countermeasure that impacts all phases must be applied if all phases have similar conflicts. Discovering such patterns is crucial for arriving at effective countermeasures.

This paper defines an intersection safety measure as the reciprocal of the sum of conflicts over the study period. The sum may be weighted to put more weight on the severe conflicts. For example, a sample weighting scheme could assign a weight of 10 to P2V conflicts of any type, a weight of 5 for V2V LOT conflicts, and a weight of 1 for all other conflict types.

4.1.3. Intersection-Service Evaluation Module

The evaluation engine analyzes intersection service using a subcycle level vehicle volume analysis that bins the number of vehicles entering the intersection in five-second intervals beginning from the start of green and plots service histograms. Since trajectory data may be aggregated by lane, phase, or a combination of lanes or phases, this module could compute the histograms for specific lanes, phases, or combinations of lanes and phases. Using trajectory data instead of loop detector data allows us to analyze all lanes irrespective of whether a loop detector is installed under that lane.

All signal cycles are considered for a given study period, and vehicle volumes for the 5-s bins from all signal cycles are added for all vehicle movements. This aggregation results in a single histogram for the entire study period. The histogram contains the vehicle counts for up to 60 s after the signal turns green.

This paper defines an intersection performance metric computed from the subcycle-based histograms. Specifically, the metric is computed as the sum of the vehicle volume (or histogram bar lengths) between 5 s and 15 s after the beginning of green, thereby aggregating the vehicle volume in the second and third bars in the histogram, representing a 10-s interval between the 5-s and the 15-s mark. The rationale for aggregating the vehicle counts for 10 s, choosing the start and end points as 5-s and 15-s marks, respectively, is that we exclude the startup loss and measure the volume before saturation headway is reached. Figure 6 illustrates the metric computation. We use the metric to compare different signal phasing configurations within the same intersection and not across intersections.

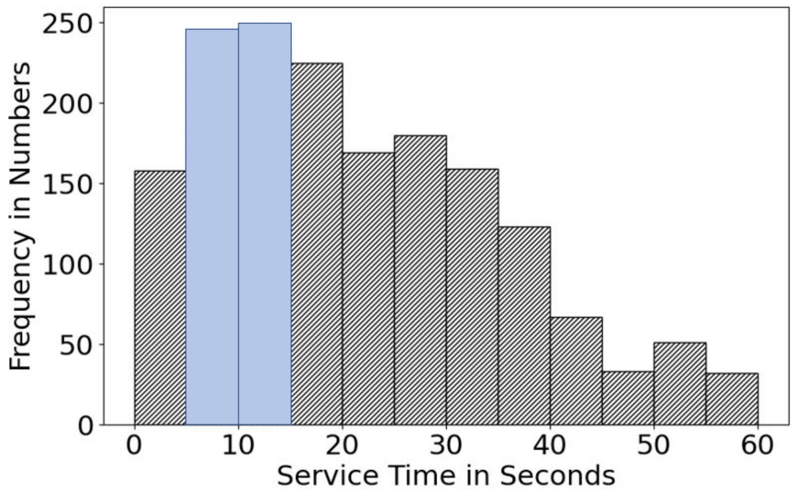
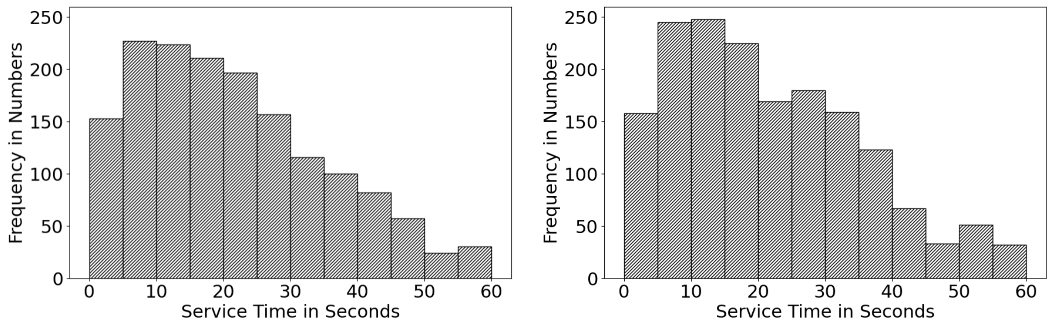


Figure 6. Illustration of performance metric computation as equal to the sum of the second and third bars (that are blue colored). Here, there are 480 vehicles approximately.

Defining intersection performance metrics using the fine-grained vehicle aggregation scheme captures the effect of any temporal issues impacting intersection performance that may otherwise be unnoticeable in hourly aggregations. Examples of temporal issues impacting the performance may be the presence of many pedestrians at the intersection, a change in signal phasing configuration, or simply the presence of more vehicles than the intersection's capacity.

The intersection performance metric helps us spot any temporal issues during specific times of the day and equips us to compare the intersection performance across different signal phasing configuration scenarios in the same intersection. Figure 7a,b show an example of histogram comparison in a before-and-after study, where the signal phasing was changed. The performance metric for Signal Plan 1 is 451, while that for Signal Plan 2 is 493. Thus, the Signal Plan 2 signal phasing configuration increases intersection performance by about 9%. We also confirmed by applying the K-S Test that the vehicle distribution using Signal Plan 2 is statistically higher than the vehicle distribution using Signal Plan 1.



(**a**) (**b**)

Figure 7. Intersection service histograms in a before-and-after study upon changing signal phasing: (**a**) Signal Plan 1: Traffic into school (morning); (**b**) Signal Plan 2: Traffic into school (morning).

4.1.4. Scenario Comparison Module

Using data generated by the modules described so far for multiple scenarios, the evaluation engine plots a point for each signal phasing configuration scenario on a performance–safety graph. For example, applying a countermeasure would change performance and safety, generating a new point. The horizontal axis of the performance–safety graph represents intersection safety, while the vertical axis represents intersection performance. The performance–safety graph created from the multiple scenarios under study may be used to select a promising set of signal phasing configurations for further consideration.

Figure 8 shows an example of a performance–safety graph. A rough sketch of what this might entail is as follows: if an intersection has a high performance and no severe events, it is ideal. It is acceptable if an intersection has low performance with no severe events. It is also potentially acceptable with high performance and a few severe events (still avoiding crashes). However, it is unacceptable if an intersection has a low performance and multiple severe events. Thus, using the Pareto curve in the performance–safety graph, a traffic engineer can select a configuration that improves intersection safety without a substantial drop in intersection performance.

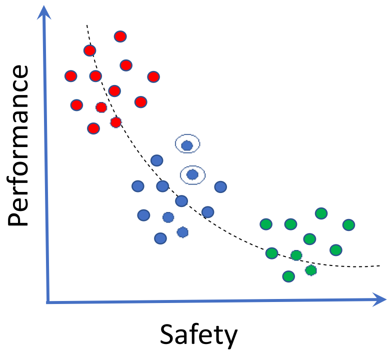


Figure 8. An example of a performance-safety trade-off graph. Each dot represents a scenario. The optimal scenarios are circled.

Some possible countermeasures are listed below.

1. Change in signal phasing or sequencing pattern [51].
2. Implementation of leading pedestrian interval (LPI) which typically gives pedestrians a 3–7 s head start when entering an intersection with a corresponding green signal in the same direction of travel [52].
3. Implementation of exclusive pedestrian phasing (EPP), which stops all vehicular movement and allows pedestrians access to cross in any direction at the intersection [52].

We demonstrate the use of the evaluation engine for improving intersection safety in Section 5.

5. Experiments

This section presents several studies conducted on traffic intersections under different pedestrian and vehicle demand conditions. The selected traffic intersections have different sizes, geometry, and user compositions. These case studies demonstrate our evaluation engine's effectiveness in analyzing an intersection's safety and performance and the impact of any countermeasures in improving the safety of an intersection.

The intersections being presented are shown in Table 1. Videos from these intersections were collected for a week in November 2021, between 6 AM and 11 PM, for each day and each intersection. We also collected several videos at other times for the evaluation of countermeasures. Thus, over 200 h of video footage were collected from these intersections and processed for the spatio-temporal study. The high-resolution controller logs were also collected for information about signal phasing during the same period. The speed limit column gives the major/minor street speed limits, while the pedestrian presence column in Table 1 gives the percentage presence of pedestrians among all users, both pedestrians and vehicles.

Table 1. The details of the two intersections being studied. These intersections are located in Gainesville, Florida, USA. The column "Speed Limit" gives the major/minor street speed limits.

ID	Intersection	Speed Limit (mph)	Pedestrian Presence (%)	Left Turn Type	Flashing Yellow Arrow	Right Turn on Red
1	NW 23rd Ave. and NW 55th St.	45/30	1.6	Protected/ Permissive	No	Yes
2	University Ave. and 17th St.	25/25	41.8	Protected/ Permissive	Yes	Yes

This paper presents the observations and analyses for each intersection based on a time-of-day segmentation obtained using the changes in the signal timing patterns. The City of Gainesville is using these timings at most of its locations. The time segments are defined as follows:

For weekdays:	
AM Peak	07:00–09:30
Off-Peak	09:30–11:00
Midday Peak	11:00–14:30
PM Peak	14:30–18:00

Henceforth, this paper refers to the intersections by ID (1 and 2). We begin with a detailed image of each intersection, study the pedestrian volume during weekdays, identify potential problem areas and solutions, and evaluate countermeasures that were feasible to implement. There are also detailed charts for each intersection representing vehicle volume, which are omitted here for conciseness. Instead, as a reference point, the peak vehicle volume in any one direction is cited for Intersections 1 and 2.

5.1. Intersection 1

Figure 9 shows Intersection 1. The maximum vehicle volume at this intersection is about 500 vehicles per hour [WBT, PM Peak]. We first present the volume and conflict characteristics at this intersection.

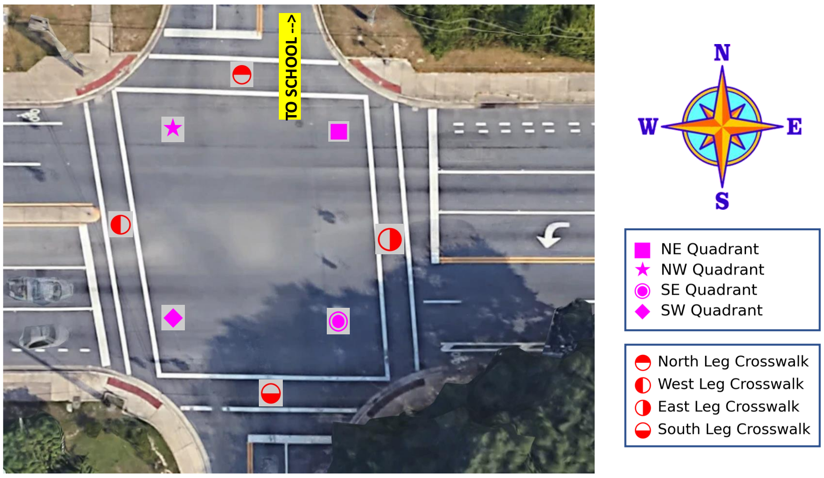


Figure 9. Intersection 1: Crosswalks and intersection quadrants are marked. The school is located to the north. The intersection has a moderate pedestrian presence comprising high school students. The two main issues at this intersection are school traffic conflict and congestion management.

5.1.1. Pedestrian Volume

Figure 10 shows the pedestrian volume over the week. Although the pedestrians-per-hour rate is moderate, the pedestrians are often clustered together before and after school for about 30 min. School starts at 8:30 AM, which falls in the AM peak, and ends at 2:42 PM, which falls in the PM peak. The high pedestrian volume in the west leg during the PM peak can be explained by the students leaving school. Specifically, the sidewalk from school to the intersection leads to the west leg, so many students cross the west leg first.

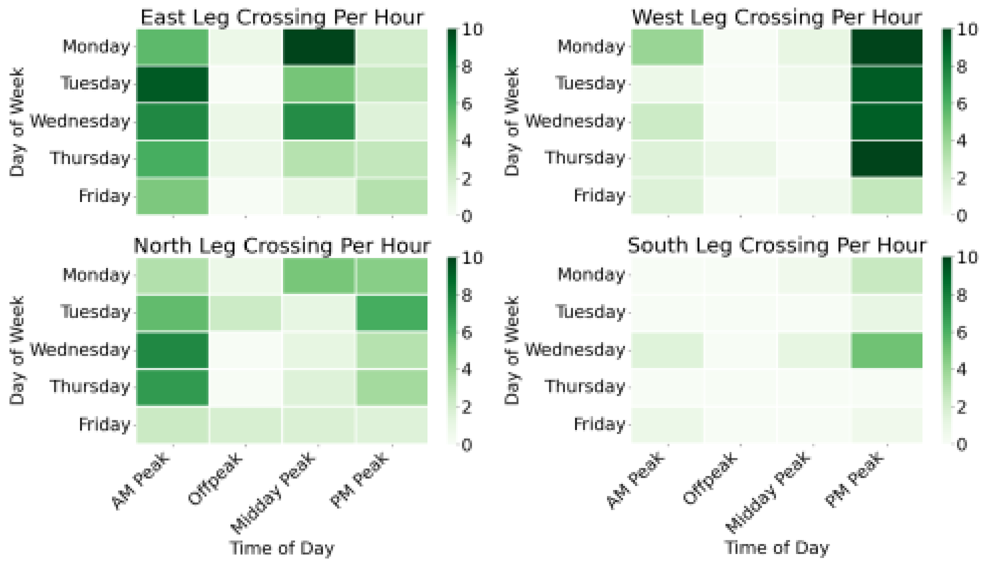
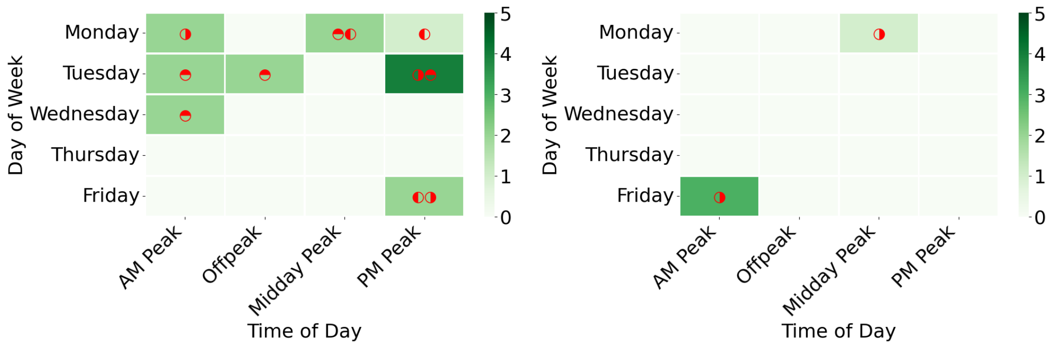


Figure 10. Intersection 1: Pedestrian volume during the weekdays. Pedestrian traffic is high during AM and PM peaks, aligning with school start and dismissal times.

5.1.2. P2V Conflicts and Suggested Countermeasures

Figure 11 illustrates the P2V conflicts. These conflicts are rather severe because drivers and pedestrians are relatively inexperienced. Thus, the situation may warrant changes in the traffic phases for a short period of time. Specifically, the intersection could have an exclusive pedestrian phase or increased traffic enforcement (such as speed limit) on drivers. These changes, which restrict vehicles, are motivated by the types of conflicts present at the intersection, which indicate vehicles are likely at fault. To counteract the dangers to students, the change would need to be implemented for only a relatively short period, less than an hour in total.

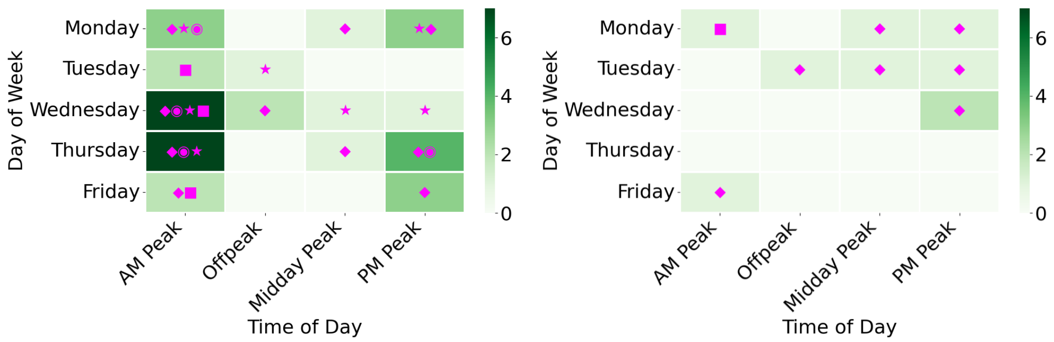


(**a**) (**b**)

Figure 11. Intersection 1: P2V conflicts during the weekdays. The two main types of conflicts are: (**a**) vehicle turning left while pedestrian is on far-side crosswalk (vehicle is likely at fault), and (**b**) vehicle turning right while pedestrian is on the near-side crosswalk (vehicle is likely at fault). The criticality of these conflicts multiplies for this intersection because it serves many teen pedestrians and drivers, who tend to be less experienced.

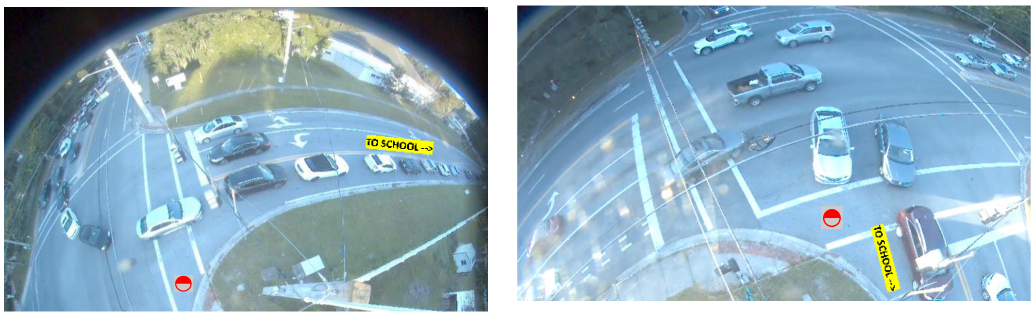
5.1.3. V2V Conflicts

Figure 12 exhibits the V2V conflicts that occur at the intersection. The conflicts are multidirectional but are higher (at least for LOT) during the AM peak. This may indicate that vehicles come from all directions before the start of school. Both the LOT/RFT conflicts at this intersection are caused, or at least aggravated by, school traffic, especially students coming to school in the morning. Figure 13 depicts two very common occurrences that would be characterized as LOT conflicts that occur during the morning. The vehicle congestion shown is clearly unsafe and specifically has two significant consequences. For one, the north leg crosswalk (to the right in the first image and the bottom in the second image) is blocked for pedestrians, so if students need to cross, they will need to walk between cars quite dangerously. This helps explain the issues discussed above, and the situation is aggravated because the time when the north side of the intersection will overflow with vehicles is just when most students will be walking through the crosswalk: at the start of school. The second issue is the blockage of the WBT traffic. Figure 13a shows cars completely blocking the NW side of the intersection, which regularly happens on school mornings.



(**a**) V2V LOT conflict. (**b**) V2V RFT conflict.

Figure 12. Intersection 1: V2V conflicts during the weekdays. More conflicts happen during the AM peak and a ese conflicts happen in all directions during the AM peak.

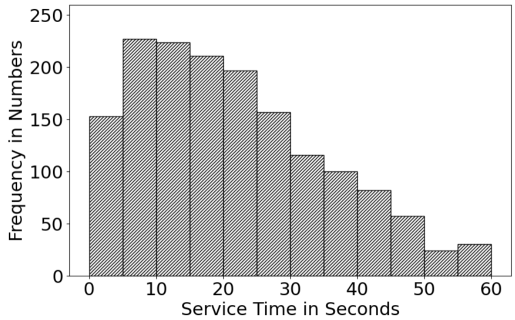


(**a**) Congestion scenario 1 (**b**) Congestion scenario 2

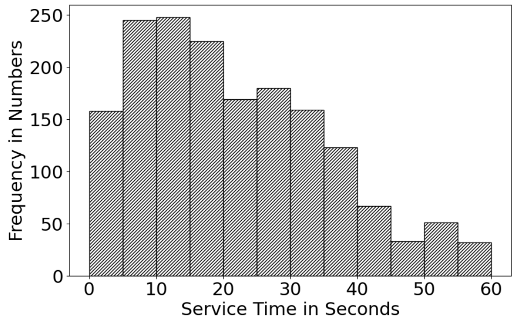
Figure 13. Intersection 1: Two scenarios of severe congestion in the morning. The north leg crosswalk is marked, and the direction to the high school is also marked for convenience: (**a**) congestion to school in the morning; (**b**) another snapshot showing vehicle congestion.

5.1.4. Countermeasure Evaluation for Performance Metric

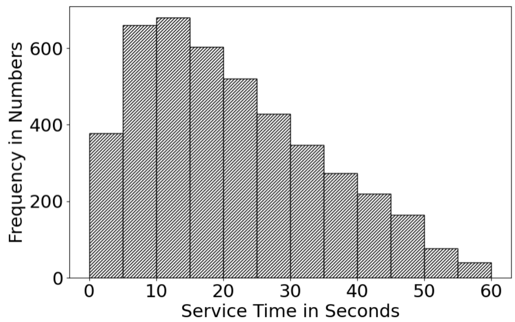
This paper presents the results of two signal phasing configurations evaluated to address the traffic congestion at this intersection. The configurations are presented as Signal Plan 1 and Signal Plan 2 because the signal phasing was switched from the previous phasing to reflect the congestion countermeasure. Signal Plan 1 is standard phase 8, where NBL and SBL are served together first, then NBT and SBT are served. Signal Plan 2 is SOP 5 [51] with permissive WBL. In Signal Plan 2, NBT and NBL are served together, followed by SBL and SBT. In the afternoon, SBL and SBT are served first, followed by NBT and NBL. Figure 14 presents four sets of histograms with comparative data on Intersection 1. Figure 14a,b represent traffic entering into school in the morning, which includes movements EBL, WBR, and NBT. Figure 14c,d show traffic in the remaining movements in the morning. Figure 14e,f exhibit traffic coming out of school and comprises traffic movements SBL, SBT, and SBR. Figure 14g,h illustrate the remaining traffic in the afternoon. Thus, the histograms on the left of Figure 14 are for traffic in Signal Plan 1, and those on the right are for traffic in Signal Plan 2. The morning time is between 8:15 and 8:35, while the afternoon time is between 14:50 and 15:10. We evaluate the performance over ten days for Signal Plan 1 and ten days for Signal Plan 2.



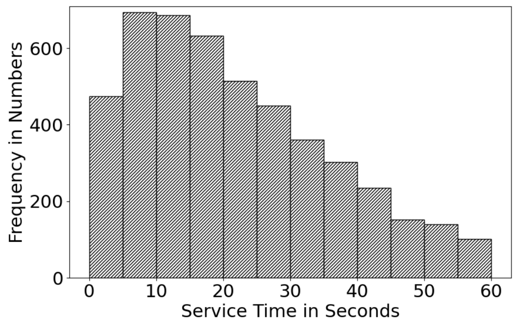
(**a**) Signal Plan 1: Traffic into school (morning).



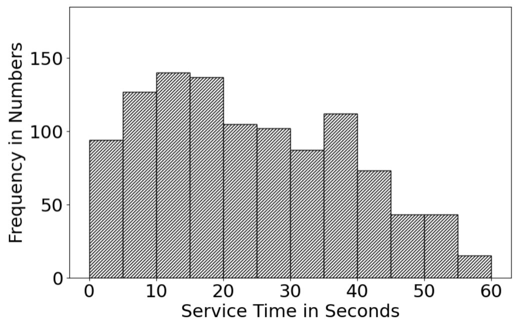
(**b**) Signal Plan 2: Traffic into school (morning).



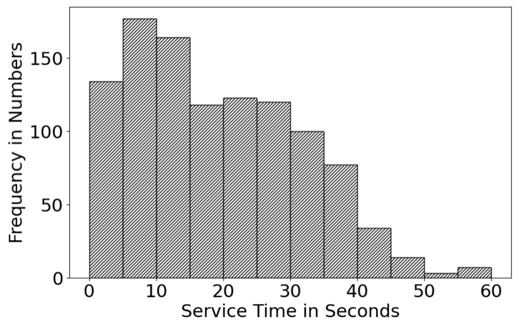
(**c**) Signal Plan 1: Remaining traffic (morning).



(**d**) Signal Plan 2: Remaining traffic (morning).

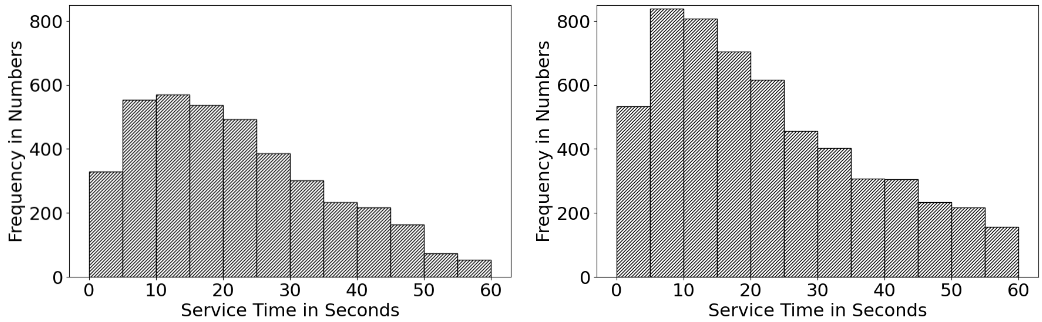


(**e**) Signal Plan 1: Traffic out of school (afternoon).



(**f**) Signal Plan 2: Traffic out of school (afternoon).

Figure 14. Cont.



(**g**) Signal Plan 1: Remaining traffic (afternoon). (**h**) Signal Plan 2: Remaining traffic (afternoon).

Figure 14. Intersection 1: Intersection-service evaluation during the weekdays. The service level is computed separately for morning and afternoon times for Signal Plan 1 and Signal Plan 2 configurations. Signal Plan 1 is standard phase 8; Signal Plan 2 is SOP 5 [51] with permissive WBL. In SOP 5, NBT and NBL are served together, and then SBL and SBT are served together. In the afternoon, SBL and SBT are served first, followed by NBT and NBL. We show by summing the second and third buckets after the green signal that Signal Plan 2 has better performance during AM and PM.

This paper computes intersection service as the number of vehicles that pass through an intersection for every 5-s interval after the signal turns green. Intersection service is separated for morning and afternoon times for increased granularity. The 5-s rule provides the buckets of the histograms, and we compute a total over 10 days. In order to compare Signal Plans 1 and 2, the four sets of histograms must be compared. This can be completed by direct computation with bucket sizes. Specifically, performance is computed as the sum of the vehicle volume (or histogram bar lengths) between 5 s and 15 s after the beginning of green. In essence, this adds the two buckets after the first one. The first bucket is skipped because start-up costs dominate. We also only measure for 10 s because this is a better measure of how fast the intersection can dissipate traffic. Adding too many buckets would make the results more of a function of the number of cars waiting at the intersection in the first place.

5.1.5. Countermeasure Evaluation for Safety Metric

From a safety perspective, we count the number of V2V conflicts for Signal Plans 1 and 2 and compare them. A count of the conflicts is given in Table 2, and more detailed plots are depicted in Figure 15. We find that the V2V conflicts using Signal Plan 2 are higher most times except in the morning when Signal Plan 1 caused slightly more conflicts. Overall, it is reasonable to conclude that Signal Plan 2 has more safety conflicts. Please note that in summing up the conflicts, we have assigned equal weights to all types of conflicts. The user can also set weights for each type of conflict and determine a weighted sum.

No P2V conflicts were observed in the study period in either Signal Plan 1 or 2.

Table 2. Sum of the V2V conflicts of Signal Plans 1 and 2 with equal weight to all types of conflicts.

Traffic Involved	Signal Plan 1	Signal Plan 2
Vehicles going into school (morning)	5	4
Remaining intersection vehicles (morning)	1	6
Vehicles out of school (afternoon)	1	2
Remaining vehicles (afternoon)	3	5

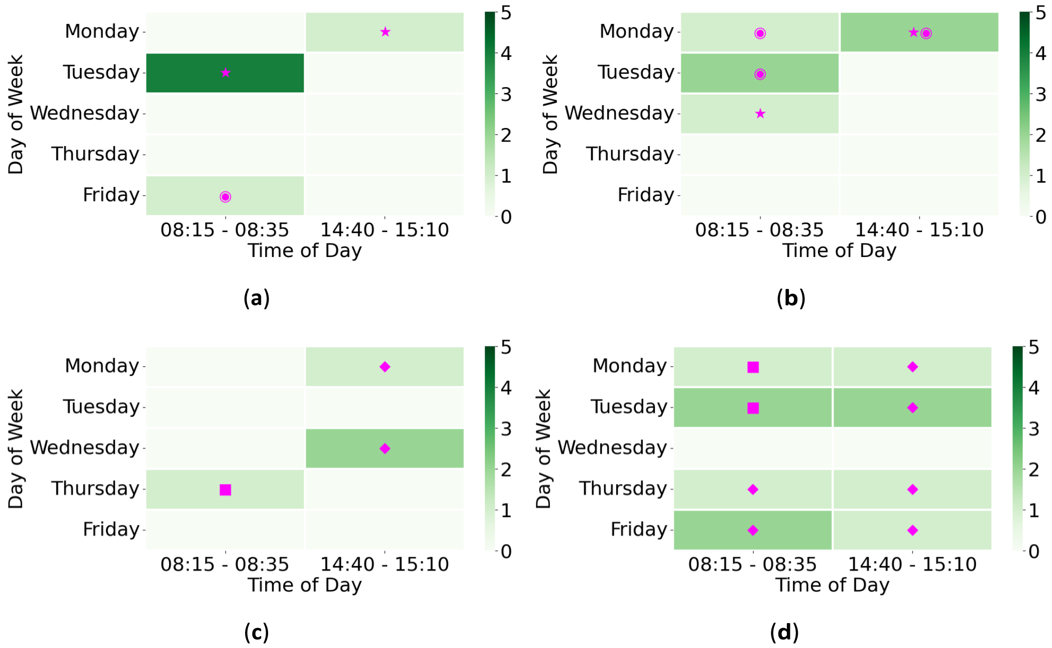
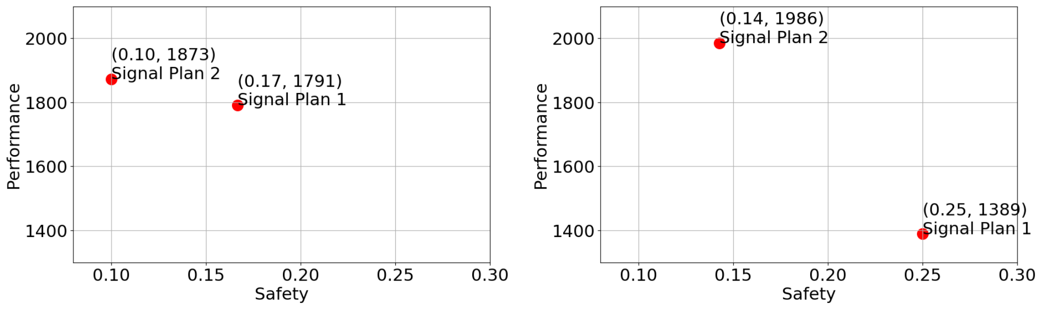


Figure 15. Intersection 1: V2V conflicts for vehicles into and out of school and remaining traffic using Signal Plan 1 and Signal Plan 2. The V2V conflicts for the remaining vehicles were comparable in the morning but higher for Signal Plan 2 for the remaining vehicles: (**a**) Signal Plan 1: V2V conflicts involving vehicles into and out of school; (**b**) Signal Plan 2: V2V conflicts involving vehicles into and out of school; (**c**) Signal Plan 1: V2V conflicts between remaining vehicles; (**d**) Signal Plan 2: V2V conflicts between remaining vehicles.

5.1.6. Performance–Safety Trade-Off

A fundamental trade-off exists between performance and safety. It is imperative to consider safety at this intersection because of the school students. The performance of the intersection can be increased significantly but at potential costs to safety. For example, pedestrian walking times can be shortened. Signal Plan 2 was shown to have better performance in Figure 14, but it is key that this comes at a cost to safety. Adding exclu-sive pedestrian phases for a short period during a critical period considers both safety (pedestrian-friendly) and performance (short, targeted period).

Figure 16 shows a performance–safety trade-off plot using Signal Plan 1 and Signal Plan 2 for the morning and afternoon times corresponding to school start and school dismissal times. Because there are just two plans, there are two points in the graph. The change from Signal Plan 1 to Signal Plan 2 is detrimental in the morning because it impacts safety for an insignificant performance gain. On the other hand, the change may be beneficial for the afternoon because performance improves remarkably with a relatively minor impact on safety.



(**a**) In the morning. (**b**) In the afternoon.

Figure 16. Performance-safety trade-off for the Signal Plan 1 and Signal Plan 2 scenarios. The effect of the Signal Plan 2 configuration had a bigger impact on the afternoon traffic than on the morning traffic.

5.2. Intersection 2

Figure 17 shows Intersection 2 near the University of Florida (UF). This intersection has a maximum volume of more than 700 vehicles per hour [EBT, PM Peak]. We start by analyzing the volume and conflict characteristics at this intersection below.

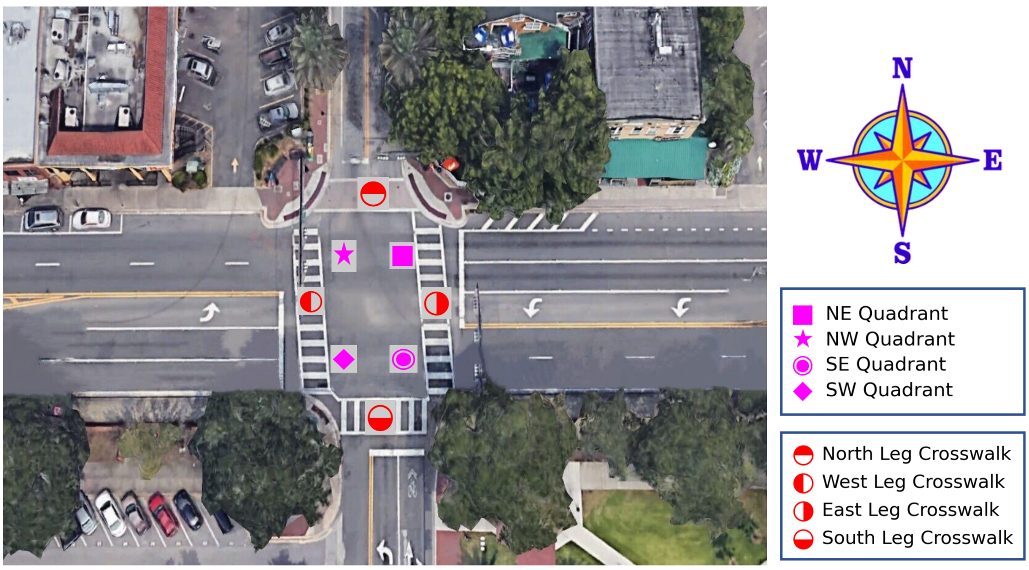


Figure 17. Intersection 2: Crosswalks and intersection quadrants are marked. UF is at the south of the intersection. University Avenue, the arterial adjacent to UF, runs east to west. The intersection has a heavy pedestrian and vehicle presence. The size of the intersection is quite small, and it serves many pedestrians throughout the day and night and a large number of vehicles. The main issue at this intersection is P2V conflicts.

5.2.1. Pedestrian Volume

Figure 18 shows the pedestrian volume during the weekdays. There is increased pedestrian traffic during the Midday and PM peaks, coinciding with lunch hour and class dismissal times. Thursday has sparse traffic in the morning for the Veteran's Day holiday, though the volume picks up later in the day. At its peak, there are about 120 pedestrians per hour on a crosswalk. The pedestrian volume is higher on the west leg crosswalk because more restaurants are accessible by the west leg.

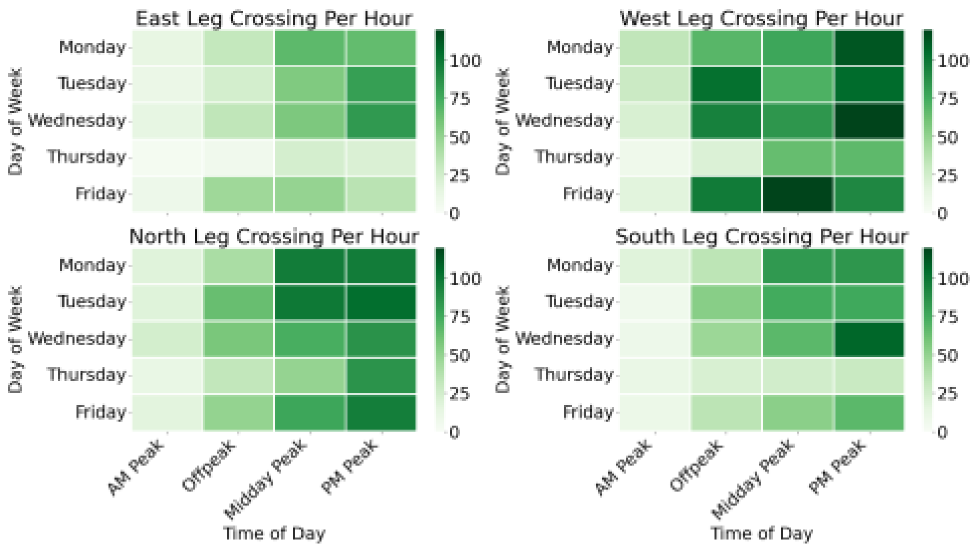


Figure 18. Intersection 2: Pedestrian volume during the weekdays. There is an increase during Midday and PM peaks, coinciding with lunch hour and class dismissal times. At its peak, there are about 120 pedestrians per hour. The pedestrian volume is higher on the west leg crosswalk because more restaurants are accessible by the west leg.

5.2.2. P2V Conflicts

Figure 19 shows P2V conflicts during the weekdays. There are many conflicts on all crosswalk legs, particularly involving left-turning vehicles with pedestrians on the far-side crosswalk, as shown in Figure 19a. This intersection has protected/permissive left turns, and the vehicles often initiate a left turn in the permissive phase, even in the presence of pedestrians on the far-side crosswalk. Pedestrians sometimes violate their walk signal and start crossing while a protected left turn is being served.

There were several other conflicts where a right-turning vehicle did not yield to a pedestrian on the adjacent parallel or the near-side crosswalk (Figure 19c). The conflicts involving a through-vehicle and a pedestrian (Figure 19d) are likely the pedestrian's fault because vehicles tend to follow their signals at this intersection.

5.2.3. V2V Conflicts

Figure 20 shows the V2V conflicts during the weekdays. There are far fewer V2V conflicts compared to P2V conflicts. We can see that the NE quadrant is affected during the AM Peak for RFT conflicts because there is a heavy inflow of people going to work. Both the NE and the SW quadrants are high in LOT conflicts during the PM peak because many cars take EBL and WBL permissive turns, and the uptick in WBT and EBT traffic during the PM peak compounds the problem.

5.2.4. Suggested Countermeasures

The excessively high P2V conflicts at this intersection may be addressed by applying LPI or EPP in the afternoon to address the conflicts in Figure 19a,b. A no-right-turn-on-red directive may reduce the conflicts involving right-turning vehicles in Figure 19c.

For the V2V LOT conflicts, split phasing of the major phases at this intersection, especially during the PM peak, might fix this issue, though this will impact performance.

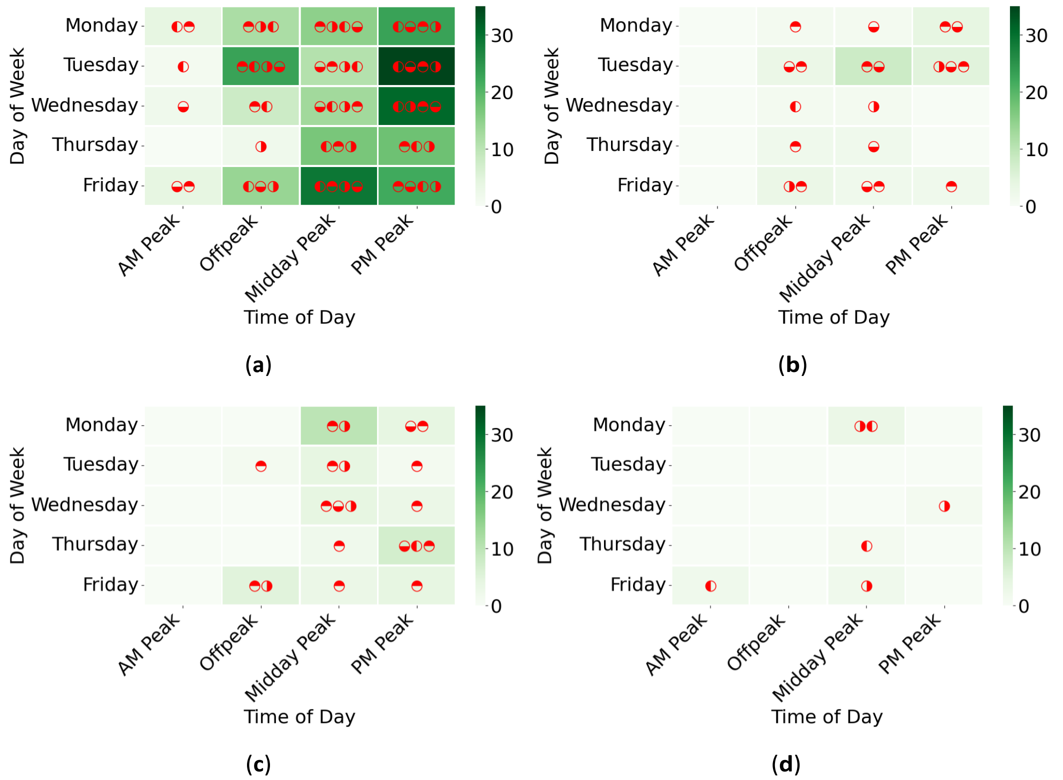
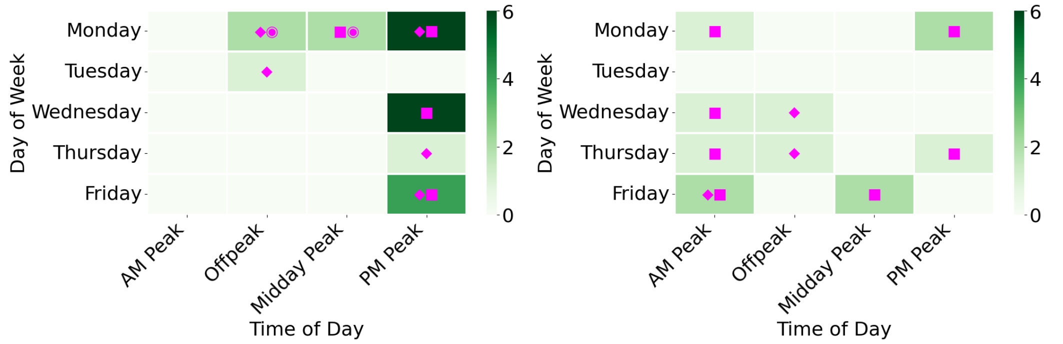


Figure 19. Intersection 2: P2V conflicts during the weekdays. Overall, there are a great deal of P2V conflicts at this intersection: (**a**) vehicle turning left and pedestrian on far-side crosswalk (vehicles are likely at fault); (**b**) vehicle turning left and pedestrian on near-side crosswalk (pedestrians are likely at fault); (**c**) vehicle turning right and pedestrians on near-side crosswalk (vehicles are likely at fault); (**d**) through vehicle and pedestrians on far-side crosswalk (pedestrians likely at fault).



(**a**) V2V LOT conflict. (**b**) V2V RFT conflict.

Figure 20. Intersection 2: V2V conflicts during the weekdays. There are far fewer V2V conflicts compared to P2V conflicts. The PM Peak is particularly affected, most likely due to an outflow of workers from UF.

5.2.5. Countermeasure Evaluation: EPP

EPP is implemented in this intersection on Thursday, Friday, and Saturday evenings, 8 PM through 1 AM, because the P2V conflicts may be very dangerous at night. Specifically, many bars and nightclubs in the area draw the predominantly young college student population. The evening traffic for one hour, 8 PM–9 PM, was collected and analyzed for Wednesdays (no countermeasure) and Thursdays (with EPP countermeasure), presented in Figure 21a,b, respectively. The benefit of the EPP is clearly seen: most P2V conflicts are resolved in Figure 21b. The only conflict (on Thursday, 21 April 2022) happened because the pedestrian violated the walk signal. The pedestrian volume is illustrated in Figure 22a,b for Wednesdays and Thursdays, respectively.

Performance–Safety Trade-off: While the EPP effectively resolves P2V conflicts, the performance is impacted. To evaluate the approximate impact on the performance of the intersection, we measure the volume of vehicles on both days and find fewer vehicles per 10-min intervals with EPP implemented as in Figure 22c,d. However, the decrease in volume was not particularly large, and the overall number of vehicles may have been lower on Thursday to begin with. This indicates that the performance cost caused by the countermeasure is minimal. Therefore, the added safety of the exclusive pedestrian phase is well worth the slight inconvenience to the vehicles.

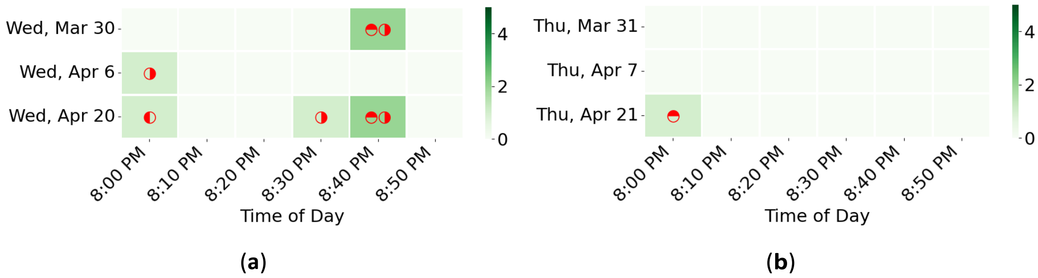


Figure 21. Intersection 2: Countermeasure—EPP. From 8 PM onward, EPP is implemented on Thursday, Friday, and Saturday: (**a**) shows the P2V conflict heatmap on Wednesdays; (**b**) shows the P2V conflict heatmap on Thursdays with EPP implemented. The reduction in the number of conflicts is pronounced. The one conflict that happened on 21 April was due to a pedestrian violating signals.

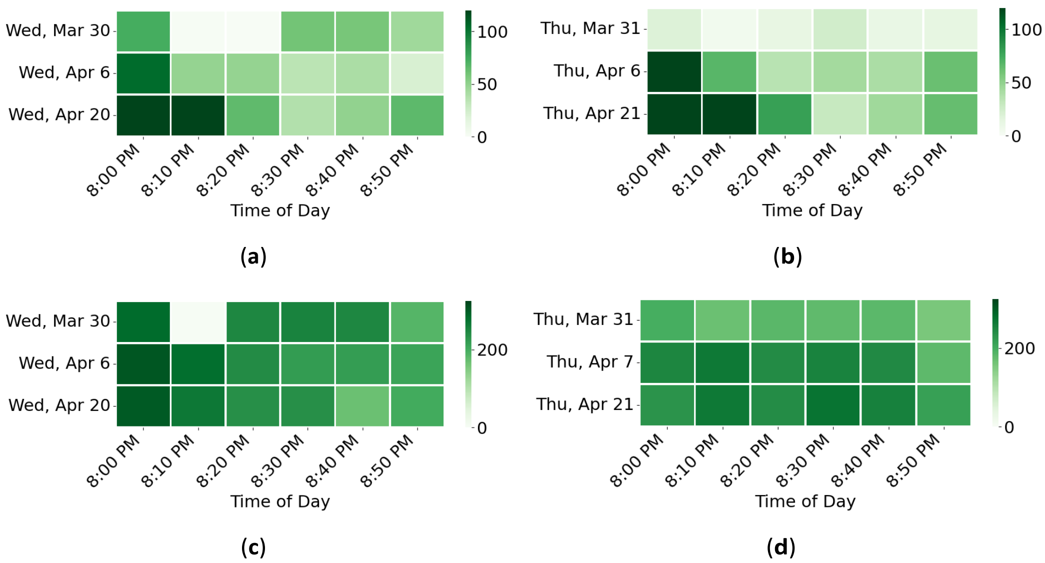


Figure 22. Intersection 2: Pedestrian and vehicle volume during the countermeasure study period. On Wednesday, 30 March, between 8:10 and 8:20, the video was corrupted; hence, it was dropped from analysis: (**a**) pedestrian volume on Wednesdays; (**b**) pedestrian volume on Thursdays; (**c**) vehicle volume on Wednesdays; (**d**) vehicle volume on Thursdays.

6. Discussion

Road safety is highly relevant in today's societies as vehicle accidents claim lives every day. Intersections are especially prone to crashes which lead to the worst outcomes. Recent rapid improvements in video collection and processing technologies enable us to identify and alleviate dangerous situations. This paper uses trajectory, severe event, and signal phasing data for conflict and volume hotspot detection and intersection performance analysis. The selection of appropriate countermeasures is demonstrated by extensive analysis and discussion of the two intersections in this paper. Additionally, we evaluate the efficacy of countermeasures in an understandable and replicable manner.

Our evaluation engine takes inputs from the intersection: trajectory data, severe event data, and signal phasing data. The inputs are generated using our previous work on processing intersection videos [4] and from the intersection ATC. The evaluation engine has three primary modules: the first computes pedestrian and vehicle volume hotspots; the second computes pedestrian–vehicle (P2V) and vehicle–vehicle (V2V) conflict hotspots; the third evaluates intersection service as a proxy to intersection performance for the study period. The evaluation engine then outputs histograms and conflict and volume hotspot charts, where each conflict chart is annotated with information that identifies the traffic phases involved in the conflicts. These outputs would allow for practicable use by researchers and traffic engineers. This paper also shows how to compute performance–safety trade-off charts for intersections. The knowledge about performance–safety trade-offs is crucial for arriving at effective countermeasures with minimal impact on intersection performance. The readability of the trade-off graph makes it easy to compare and select appropriate countermeasures. We demonstrate the operation of the evaluation engine on two different intersections using more than a week of data on each intersection. More than 200 h of video are collected and processed in the demonstration of our engine, and with the level of automation achieved, more videos can be analyzed at little cost.

Intersection 1 has many teenage pedestrians and drivers near a high school. Our analysis showed that it had a vehicle volume of up to 500 vehicles per hour during the PM Peak. The analysis also reflects the out-sized impact of two critical periods in congestion and hotspot generation, namely the time directly before school and after. The degree of congestion influences the implementation of a congestion countermeasure, which we analyze thoroughly. For one, the countermeasure is found to increase V2V conflicts somewhat. The impact on performance is distinct in the morning and afternoon: in the morning, slight performance improvement is evident, whereas in the afternoon, the performance increases by over 40%. The conclusion is that the congestion countermeasure is ineffective in the morning but effective in the afternoon.

Intersection 2 is located near UF and has a high pedestrian presence. We find that the intersection has a maximum vehicle volume of more than 700 vehicles per hour during the PM peak. The number of pedestrians on the west leg is consistently the largest because of local restaurants, which is reflected in the greater number of P2V conflicts with pedestrians on the west leg. The number of V2V conflicts is relatively small and is primarily associated with people coming to and going from work. A large number of P2V conflicts and the inherent danger due to evening conflicts influence the implementation of an EPP countermeasure. The countermeasure decreases the number of P2V conflicts a great deal. Furthermore, the impact on performance is not particularly significant relative to the safety enhancement at the intersection, justifying the continued use of the countermeasure.

This paper aims to help the practitioner find any safety issues within an intersection that may not have resulted in a crash but could very well result in one in the future. In fact, this paper is the result of a close interactive feedback loop between researchers and traffic practitioners. For example, our analysis uncovered the common pedestrian–vehicle conflict situations observed in Intersection 2, where the pedestrian was given a walk signal, and the left-turning vehicles were given a permissive left a few seconds later. The conflicts did not lead to crashes or injuries but often to near-miss conflicts. This information finally allowed the practitioners to test the countermeasure of exclusive pedestrian signaling in Intersection 2. As a result of implementing the exclusive pedestrian phases only for limited times of the day, the number of severe conflicts was reduced. This made the intersection safer for the pedestrians.

A direction of potential future study is the automation of additional steps in the process we have outlined, including, but not limited to, the suggestion, analysis, and implementation of countermeasures on the fly. In addition, the precept of a performance–

safety trade-off in intersection analysis developed in this paper can be applied further and potentially more broadly in road safety.

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Abbreviations

The following abbreviations are used in this manuscript:

UF	University of Florida
EBT, WBT, SBT, NBT	East/West/South/North bound through
EBL, WBL, NBL, SBL	East/West/North/South bound left
EBR, WBR, NBR, SBR	East/West/North/South bound right
NE, NW, SE, SW	Northeast, Northwest, Southeast, Southwest
P2V, V2V	Pedestrian–vehicle, Vehicle–vehicle
LOT	Left opposing through
RMT	Right merging through
LPI	Leading Phase Interval
EPP	Exclusive pedestrian phasing
RFT	Right following through
REC	Rear end conflict
FDOT	Florida Department of Transportation
USDOT	U.S. Department of Transportation
SOP	Signal Operating Procedure
TPS	Thin-plate spline
DB	Database
TTC	Time-to-collision
PET	Post-encroachment time
ATC	Advanced Traffic Controller

References

1. Fatality Analysis Reporting System (FARS). Available online: https://www.nhtsa.gov/research-data/fatality-analysis-reporting-system-fars (accessed on 15 August 2022) .
2. Historical Item Averages Cost. Available online: https://www.fdot.gov/programmanagement/estimates/documents/historicalitemaveragecostsreports (accessed on 10 June 2022).
3. Takeda, H.; Yamasaki, M.; Moriya, T.; Minakawa, T.; Beniyama, F.; Koike, T. A Video-Based Virtual Reality System. In VRST '99: Proceedings of the ACM Symposium on Virtual Reality Software and Technology; Association for Computing Machinery: New York, NY, USA, 1999; pp. 19–25. [CrossRef]
4. Banerjee, T.; Chen, K.; Almaraz, A.; Sengupta, R.; Karnati, Y.; Bryce Grame, E.P.; Poddar, S.; Schenck, R.; Dilmore, J.; Srinivasan, S.; et al. A Modern Intersection Data Analytics System for Pedestrian and Vehicular Safety. In Proceedings of the IEEE 25th International Conference on Intelligent Transportation Systems (ITSC), Macau, China, 8–12 October 2022.
5. Traffic Conflict Techniques for Safety and Operations—Observers Manual. Available online: https://www.fhwa.dot.gov/publications/research/safety/88027/88027.pdf (accessed on 19 April 2022).

6. Traffic Analysis Toolbox Volume VI: Definition, Interpretation, and Calculation of Traffic Analysis Tools Measures of Effectiveness. Available online: https://ops.fhwa.dot.gov/publications/fhwahop08054/sect6.htm (accessed on 2 September 2022).
7. Gettman, D.; Head, L. Surrogate Safety Measures from Traffic Simulation Models. Transp. Res. Rec. **2003**, 1840, 104–115. [CrossRef]
8. Wang, C.; Stamatiadis, N. Surrogate Safety Measure for Simulation-Based Conflict Study. Transp. Res. Rec. **2013**, 2386, 72–80. [CrossRef]
9. Lord, D.; Mannering, F. The statistical analysis of crash-frequency data: A review and assessment of methodological alternatives. Transp. Res. Part Policy Pract. **2010**, 44, 291–305. [CrossRef]
10. Abdel-Aty, M.; Pande, A. Crash data analysis: Collective vs. individual crash level approach. J. Saf. Res. **2007**, 38, 581–587. [CrossRef]
11. Hayward, J.C. Near miss determination through use of a scale of danger. Highw. Res. Rec. **1972**, 384, 24–34.
12. Allen, B.L.; Shin, B.T.; Cooper, P.J. Analysis of traffic conflicts and collisions. Transp. Res. Rec. **1978**, 667, 67–74.
13. Jiang, X.; Zhang, G.; Bai, W.; Fan, W. Safety evaluation of signalized intersections with left-turn waiting area in China. Accid. Anal. Prev. **2016**, 95, 461–469. [CrossRef]
14. Samara, L.; St-Aubin, P.; Loewenherz, F.; Budnick, N.; Miranda-Moreno, L. Video-Based Network-Wide Surrogate Safety Analysis to Support a Proactive Network Screening Using Connected Cameras: Case Study in the City of Bellevue (WA); Technical Report; Transportation Research Board: Washington, DC, USA, 2021.
15. Sayed, T.; Zaki, M.H.; Autey, J. Automated safety diagnosis of vehicle-bicycle interactions using computer vision analysis. Saf. Sci. **2013**, 59, 163–172. [CrossRef]
16. Mahmud, S.S.; Ferreira, L.; Hoque, M.S.; Tavassoli, A. Application of proximal surrogate indicators for safety evaluation: A review of recent developments and research needs. IATSS Res. **2017**, 41, 153–163. [CrossRef]
17. Shi, X.; Wong, Y.; Li, M.; Chai, C. Key risk indicators for accident assessment conditioned on pre-crash vehicle trajectory. Accid. Anal. Prev. **2018**, 117, 346–356. [CrossRef]
18. Arun, A.; Haque, M.M.; Bhaskar, A.; Washington, S.; Sayed, T. A systematic mapping review of surrogate safety assessment using traffic conflict techniques. Accid. Anal. Prev. **2021**, 153, 106016. [CrossRef] [PubMed]
19. Amundsen, F.H. Workshop on Traffic Conflicts. In Proceedings: First Workshop on Traffic Conflicts Oslo 77; Norwegian Council for Scientific and Industrial Research: Oslo, Norway, 1977.
20. Hydén, C.; Linderholm, L. The Swedish Traffic-Conflicts Technique. In International Calibration Study of Traffic Conflict Techniques; Springer: Berlin/Heidelberg, Germany, 1984; pp. 133–139. [CrossRef]
21. Vogel, K. A comparison of headway and time to collision as safety indicators. Accid. Anal. Prev. **2003**, 35, 427–433. [CrossRef]
22. Peesapati, L.N.; Hunter, M.P.; Rodgers, M.O. Evaluation of Postencroachment Time as Surrogate for Opposing Left-Turn Crashes. Transp. Res. Rec. **2013**, 2386, 42–51. [CrossRef]
23. Feng, G.; Klauer, S.G.; McGill, M.; Dingus, T. Evaluating the Relationship Between Near-Crashes and Crashes: Can Near-Crashes Serve as a Surrogate Safety Metric for Crashes? Transp. Res. Board **2010**, 811, 382.
24. Johnsson, C.; Laureshyn, A.; Ceunynck, T.D. In search of surrogate safety indicators for vulnerable road users: A review of surrogate safety indicators. Transp. Rev. **2018**, 38, 765–785. [CrossRef]
25. Fu, T.; Miranda-Moreno, L.; Saunier, N. A novel framework to evaluate pedestrian safety at non-signalized locations. Accid. Anal. Prev. **2018**, 111, 23–33. [CrossRef]
26. Chen, W.; Wang, T.; Wang, Y.; Li, Q.; Xu, Y.; Niu, Y. Lane-based Distance-Velocity model for evaluating pedestrian–vehicle interaction at non-signalized locations. Accid. Anal. Prev. **2022**, 176, 106810. [CrossRef]
27. Yang, D.; Xie, K.; Ozbay, K.; Yang, H. Fusing crash data and surrogate safety measures for safety assessment: Development of a structural equation model with conditional autoregressive spatial effect and random parameters. Accid. Anal. Prev. **2021**, 152, 105971. [CrossRef]
28. Astarita, V.; Festa, D.C.; Giofrè, V.P.; Guido, G. Surrogate Safety Measures from Traffic Simulation Models a Comparison of different Models for Intersection Safety Evaluation. Transp. Res. Procedia **2019**, 37, 219–226. [CrossRef]
29. Morando, M.; Tian, Q.; Truong, L.; Vu, H. Studying the Safety Impact of Autonomous Vehicles Using Simulation-Based Surrogate Safety Measures. J. Adv. Transp. **2018**, 2018. [CrossRef]
30. Wang, C.; Xie, Y.; Huang, H.; Liu, P. A review of surrogate safety measures and their applications in connected and automated vehicles safety modeling. Accid. Anal. Prev. **2021**, 157, 106157. [CrossRef] [PubMed]
31. Anderson, R. Electromagnetic loop vehicle detectors. IEEE Trans. Veh. Technol. **1970**, 19, 23–30. [CrossRef]
32. Karnati, Y.; Mahajan, D.; Rangarajan, A.; Ranka, S. Machine Learning Algorithms for Traffic Interruption Detection. In Proceedings of the 2020 Fifth International Conference on Fog and Mobile Edge Computing (FMEC), Paris, France, 20–23 April 2020; pp. 231–236. [CrossRef]
33. Kamijo, S.; Matsushita, Y.; Ikeuchi, K.; Sakauchi, M. Traffic monitoring and accident detection at intersections. IEEE Trans. Intell. Transp. Syst. **2000**, 1, 108–118. [CrossRef]
34. Zhao, H.; Cui, J.; Zha, H.; Katabira, K.; Shao, X.; Shibasaki, R. Monitoring an intersection using a network of laser scanners. In Proceedings of the 2008 11th International IEEE Conference on Intelligent Transportation Systems, Beijing, China, 12–15 October 2008; pp. 428–433. [CrossRef]

35. Ling, B.; Zeifman, M.I.; Gibson, D.R. Multiple pedestrian detection using IR LED stereo camera. In Proceedings of the Intelligent Robots and Computer Vision XXV: Algorithms, Techniques, and Active Vision; Casasent, D.P., Hall, E.L., Röning, J., Eds.; International Society for Optics and Photonics (SPIE): Bellingham, WA, USA, 2007; Volume 6764, p. 67640A. [CrossRef]
36. Messelodi, S.; Modena, C.; Zanin, M. A computer vision system for the detection and classification of vehicles at urban road intersections. Pattern Anal. Appl. **2005**, 8, 17–31. [CrossRef]
37. Schwach, J.; Morris, T.; Michalopoulos, P. Rapidly Deployable Low-Cost Traffic Data and Video Collection Device; CTS (Series: Minneapolis, Minn.); 750 Intelligent Transportation Systems Institute, Center for Transportation Studies, University of Minnesota: Minneapolis, MN, USA, 2009.
38. Datondji, S.R.E.; Dupuis, Y.; Subirats, P.; Vasseur, P. A Survey of Vision-Based Traffic Monitoring of Road Intersections. IEEE Trans. Intell. Transp. Syst. **2016**, 17, 2681–2698. [CrossRef]
39. Zhang, X.; Feng, Y.; Angeloudis, P.; Demiris, Y. Monocular Visual Traffic Surveillance: A Review. IEEE Trans. Intell. Transp. Syst. **2022**, 23, 14148–14165. [CrossRef]
40. Saunier, N.; Sayed, T.; Ismail, K. Large-Scale Automated Analysis of Vehicle Interactions and Collisions. Transp. Res. Rec. **2010**, 2147, 42–50. [CrossRef]
41. Ismail, K. Application of Computer Vision Techniques for Automated Road Safety Analysis and Traffic Data Collection. Ph.D. Thesis, University of British Columbia, Vancouver, BC, Canada, 2010.
42. Stipancic, J.; Miranda-Moreno, L.; Saunier, N.; Labbe, A. Network screening for large urban road networks: Using GPS data and surrogate measures to model crash frequency and severity. Accid. Anal. Prev. **2019**, 125, 290–301. [CrossRef]
43. St-Aubin, P.; Saunier, N.; Miranda-Moreno, L.; Ismail, K. Use of Computer Vision Data for Detailed Driver Behavior Analysis and Trajectory Interpretation at Roundabouts. Transp. Res. Rec. **2013**, 2389, 65–77. [CrossRef]
44. Kronprasert, N.; Sutheerakul, C.; Satiennam, T.; Luathep, P. Intersection Safety Assessment Using Video-Based Traffic Conflict Analysis: The Case Study of Thailand. Sustainability **2021**, 13, 12722. [CrossRef]
45. Bochkovskiy, A.; Wang, C.; Liao, H.M. YOLOv4: Optimal Speed and Accuracy of Object Detection. arXiv **2020**, arXiv:2004.10934.
46. Wojke, N.; Bewley, A.; Paulus, D. Simple online and realtime tracking with a deep association metric. In Proceedings of the 2017 IEEE International Conference on Image Processing (ICIP), Beijing, China, 17–20 September 2017; pp. 3645–3649. [CrossRef]
47. Wood, S.N. Thin plate regression splines. J. R. Stat. Soc. Ser. (Stat. Methodol.) **2003**, 65, 95–114. [CrossRef]
48. Mundhenk, T.N.; Rivett, M.J.; Liao, X.; Hall, E.L. Techniques for fisheye lens calibration using a minimal number of measurements. In Proceedings of the Intelligent Robots and Computer Vision XIX: Algorithms, Techniques, and Active Vision; Casasent, D.P., Ed.; International Society for Optics and Photonics: Bellingham, WA, USA, 2000; Volume 4197, pp. 181–190. [CrossRef]
49. Huang, X.; Banerjee, T.; Chen, K.; Varanasi, N.; Rangarajan, A.; Ranka, S. Machine Learning based Video Processing for Real-time Near-Miss Detection. In Proceedings of the 6th International Conference on Vehicle Technology and Intelligent Transport Systems (VEHITS), Prague, Czech Republic, 2–4 May 2020; pp. 169–179. [CrossRef]
50. Zhou, Q.; Mohammadi, R.; Zhao, W.; Zhang, K.; Zhang, L.; Wang, Y.; Roncoli, C.; Hu, S. Queue Profile Identification at Signalized Intersections with High-Resolution Data from Drones. In Proceedings of the 2021 7th International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS), Heraklion, Greece, 16–17 June 2021; pp. 1–6. [CrossRef]
51. Signal Operating Procedure. Available online: https://www.fdot.gov/docs/default-source/roadway/DS/13/IDx/17870.pdf (accessed on 5 November 2021).
52. Safety. Available online: https://safety.fhwa.dot.gov (accessed on 20 February 2022).