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Impacts of Changing from Permissive/Protected Left-Turn to Protected-Only Phasing: Case Study in the City of Tucson, Arizona

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Abstract

Recent research has focused on the safety or mobility impacts of signal timing. Several studies have compared the choice between a protected-only left turn (PO) and a protected-permissive left turn (PPLT). However, few have compared both the safety and mobility impacts, and their tradeoffs. This study proposed data-driven methods to conduct a pilot study at an intersection in Tucson, Arizona. This study evaluated the impacts on vehicular mobility and multi-modal safety when changing from a PPLT to a PO. First, the daily and annual delay for the through and left-turn movements for the intersection was evaluated using a calibrated delay model and year-long 15-min traffic sensor data. Then, real-world near misses between cyclists, pedestrians, and vehicles were manually collected and analyzed using 48 h of videos. Last, both mobility and safety measures were converted into an annual cost to determine the trade-off between the before (PPLT) and the after (PO) situations. The results of this study demonstrate the feasibility of the proposed methods, providing practitioners with different options to evaluate left-turn phasing strategies effectively and efficiently.

In the United States, 37,461 fatalities occurred as a result of crashes in 2016 (*1*). The National Highway Transportation Safety Administration (NHTSA) reported that 24% of fatalities occurred at intersections in the same year (*2*). Delay at road intersections increased by 13.5% between 2000 and 2014 (*3*). Reducing delay can save people time and money, and reduce the amount of harmful exhaust emissions being introduced into the atmosphere (*4*).

Improving safety and mobility at signalized intersections is an important mission for most transportation agencies in the U.S.A. One obstacle that transportation engineers commonly face is finding a balance between safety and mobility (efficiency), especially for signalized intersections. Transportation engineers are often required to decide the most appropriate measures to improve intersection safety while still maintaining high levels of mobility.

Left-turn phasing is a particular area of concern in this category, because it has conflict points that correspond to some of the more severe types of crashes such as head-on collisions, angle crashes, and vehicle-to-pedestrian crashes. Left-turn phasing generally operates in one of five modes: permissive, protected, protected-permissive, split phasing, and prohibited (*5*). Even though general guideless, such as the Highway Capacity Manual and Signal Timing Manual are provided, choosing the most suitable left-turn phasing for a particular intersection is still very challenging because few guidelines and research projects discuss the trade-offs between safety and mobility (*5*, *6*).

The common left-turn phasing of the major signalized intersections in the City of Tucson is protected-permissive left turn (PPLT). Some studies have found that protected-only (PO) left turn could be safer than PPLT because a PO turn has fewer conflict points with pedestrians, bicycles, and vehicles crossing the intersection (*7*, *8*). On the other hand, PO turns could possibly increase delays at intersections (*9*). Finding a balance between mobility and safety is extremely important to determine the best left-turn phasing for large-scale

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implementation. To gain a better understanding of this left-turn phasing selection issue, this research effort was supported by the City of Tucson to conduct a data-driven pilot study at the intersection of Speedway Boulevard and Campbell Avenue, since this intersection is next to the University of Arizona and has both a large vehicular volume and multi-modal traffic, including pedestrians, cyclists, and buses. The results from this research can help the city and other jurisdictions to use the proposed data-driven approach to decide future implementations of PO in place of PPLT. It is expected that the proposed data-driven approach and lessons learned will be transferable and benefit other cities in the U.S.A.

The remainder of this paper is organized as follows. First, current safety and mobility practices as well as previous related studies are summarized. Next, the important characteristics of the study site are briefly introduced. Then an experiment is designed to evaluate the mobility impacts on the intersection. Similarly, the safety impacts are evaluated and discussed. A comparison is then made to combine safety and mobility into cost. Finally, the results of the experiment are summarized, and the limitations are discussed.

Literature Review

Most previous research has focused on the safety and mobility impacts of left-turn phasing separately, and much of the literature focuses on safety. Srinivasan et al. (*7*) found that changing an intersection from running a PPLT to a PO could lead to a significant reduction in left-turn crashes, but could increase the number of crashes for other crash types. This was further substantiated when Pauw et al. (*10*) found that using a PO does not reduce rear-end crashes. One of the ways that a PO could be safer than a PPLT is that a PO has fewer conflict points with pedestrians crossing the intersection. When an intersection is running a PPLT, a vehicle making a permissive left turn must yield to the pedestrians crossing the intersection parallel with the through movement. If the turning vehicle does not notice the pedestrian, it could cause a near miss or even a crash. A study by Chen et al. (*8*) found that when changing from a PPLT to a PO the number of pedestrian crashes was reduced. However, they also found that the safety benefits of this change were mostly negated because it caused an increase in crashes of other types. Some studies have used potential conflicts (near misses) as a safety measure, because crashes are rare and unpredictable events. Zaki et al. (*11*) found a relationship between the frequency of near misses and the number of crashes and developed a computer vision model to collect data on near misses involving pedestrians and vehicles. In a similar study Ismail et al. (*12*) also developed an automated video analysis system to collect data on vehicle-to-pedestrian near misses. A similar system was developed by Oh et al. (*13*), but instead of analyzing video it analyzed traffic images to extract data on vehicle-to-pedestrian near misses. To analyze the safety of cyclists Sayed et al. (*14*) conducted a computer vision analysis to collect data on vehicle-to-bicycle near misses. However, poor weather and lighting conditions could be an obstacle to automated methods of near-miss analysis.

One of the common concerns when changing from a PPLT to a PO is the impact on mobility. Several previous studies have compared these two left-turn phasing schemes, with varying conclusions. Stamatiadis et al. (*9*) found that using a permissive left turn or a PPLT will create significantly less left-turn delay than a PO. In a similar study Al-Kaisy et al. (*15*) also drew the conclusion that using a PPLT could improve an intersection's overall efficiency and capacity. Additionally, they found that the opposing through volume does not have a significant impact on whether a PO is warranted. However, Zhang et al. (*16*) suggested that the opposite was true, and the opposing through volume is a major factor when deciding whether a PO is warranted.

As previous research has shown, safety and mobility are two major concerns when changing left-turn phasing. Therefore, several studies focus on comparing both the mobility and safety impacts of different left-turn phasing strategies. In one such study by Qi et al. (*17*), mathematical models were developed based on potential conflicts between vehicles to estimate the safety impacts of using PPLT phasing for an intersection, and were combined with mobility impacts so that practitioners could select whether to run a PO or a PPLT. Another similar study by Pratt et al. (*18*) used vehicle-to-pedestrian conflicts (near misses) to develop guidelines for whether to use a PO or a PPLT based on total volume, left-turn volume, and the number of pedestrians. In addition, Zhang et al. (*19*) developed a model to combine vehicle-to-vehicle and vehicle-to-pedestrian conflicts. In a study by Stamatiadis et al. (*9*), an exponential regression model was developed to describe the relationship between crashes and delay using several types of left turns. They found that longer delays had fewer crashes, and shorter delays had more crashes. However, all of these studies consider either vehicles or pedestrians without considering multi-modal safety impacts.

Most of the previous studies focused on investigating the impacts of left-turn phasing on either safety or mobility. A few of the previous studies compared safety and mobility, but considered only vehicle conflicts and pedestrian conflicts. Safety impacts were based on measurements made only during peak hours. In this study, methods are developed to compare the safety and

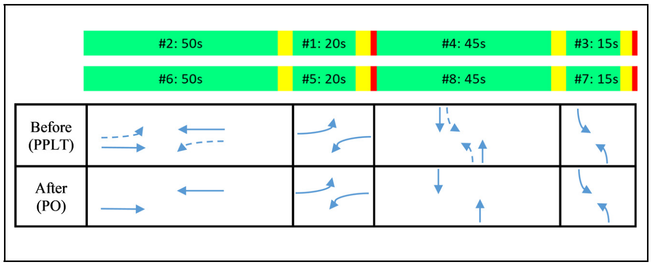

Figure 1. Signal phasing sequence and the timing plan during peak hours.

mobility impacts of changing the left-turn phasing from using a PPLT to a PO. Mobility impacts are quantified using an innovative method of estimating delay from occupancy data. Safety impacts are quantified using near misses between vehicles, pedestrians, and cyclists. The near misses are collected during a 24-h day, before and after, totaling 48 h of video analyzed. The near-miss videos are analyzed through human observation to ensure that each near miss is reasonable, as it can be hard for computer vision to have a reasonable judgment for each near miss. All the impacts are annually scaled using volume data at the study intersection and converted to cost so that a comparison can be made. The developed methods are simple enough to be useful for practitioners while maintaining a high enough level of accuracy to make a valid data-driven comparison between signal timings.

Study Site Description

The intersection of Speedway Boulevard and Campbell Avenue in Tucson, Arizona, was selected as the study intersection to evaluate the impacts of changing the phasing from PPLT to PO. This study intersection is one of the busiest intersections in Tucson, with high traffic volumes and large numbers of pedestrians, largely because of its close proximity to the University of Arizona. The study intersection is a four-leg intersection with 11 ft wide lanes and a 35 mph speed limit. In addition, the eastbound (EB) and westbound (WB) directions each have a right-turn bay, a single lane left-turn bay, and three through lanes. Southbound (SB) and northbound (NB) also each have a right-turn bay and three through lanes, but they have two-lane left-turn bays.

The signal timing of the study intersection is running the designed timing (130 s) during peak hours (7:00–9:00 a.m.; 4:00–6:00 p.m.) to generate progression along the Speedway corridor. Outside of peak hours, the signal controller is running with fully-actuated signal control. Before February 9, 2018, a lagging PPLT phase (a permissive left turn followed by a protected-only left turn) was used for the intersection at all times. The City of Tucson only changed the left-turn phase from PPLT to PO on February 9, 2018. Figure 1 shows the timing plan during peak hours which remained unchanged before and after operating the PO.

Impact on Mobility

Data Collection

Four datasets were used to evaluate the impact of mobility. The first dataset is the queue length for each lane. The queue length data was manually collected by assigning two students for each left-turn movement and each through movement during the morning peak (7:30–8:15 a.m.) and afternoon peak (4:00–5:45 p.m.). Every 10 s students recorded the queue length for their respective study section so the ground-truth time-in-queue delay (TIQD) can be calculated. Note that only the innermost lanes were selected for the through and left-turn movements. That is, a total of eight lanes (four through and four left-turn lanes) were observed.

The second dataset was event-based data collected by commercially available video-based sensors automatically. Figure 2 shows that two types of detectors are configured in the video-based sensor: a presence event detector (PED) and an advance event detector (AED) in Figure 2*a*. The PED is located next to the stop line for detection of vehicles and the AED is located upstream from the stop line for green time extensions. The AED and PED can record the timestamps when the vehicles are triggering and leaving the detectors. The difference in time between each detector's on and off events indicates the time occupancy in seconds. In addition, the signal phases changing events are also recorded in the database by the signal controller. The green time for each phase can be exported from the signal events dataset. Time occupancy and green time were collected on November 14, 2017 and March 21, 2018 and were aggregated into 15-min intervals to be used to estimate the delay for mobility evaluation.

The third dataset was the occupancy percentage data collected by virtual loop detectors automatically. As shown in Figure 2*b*, two types of virtual loop detectors were configured on each lane: the advance detector (AD) and the presence detector (PD). The PDs were located next to the stop line and the ADs were located upstream from the stop line. Both AD and PD collected the percentage of the time that vehicles occupied the detectors during a 15-min interval. The time percentage can be a potential indicator of the congestion and these were used to estimate the 24-h delay. The fourth dataset is the 24/7 turning movement count data collected from the count detector (CD) as shown in Figure 2*b*.

The mobility impact was evaluated through the estimated delay. First, the queue length of through and left-

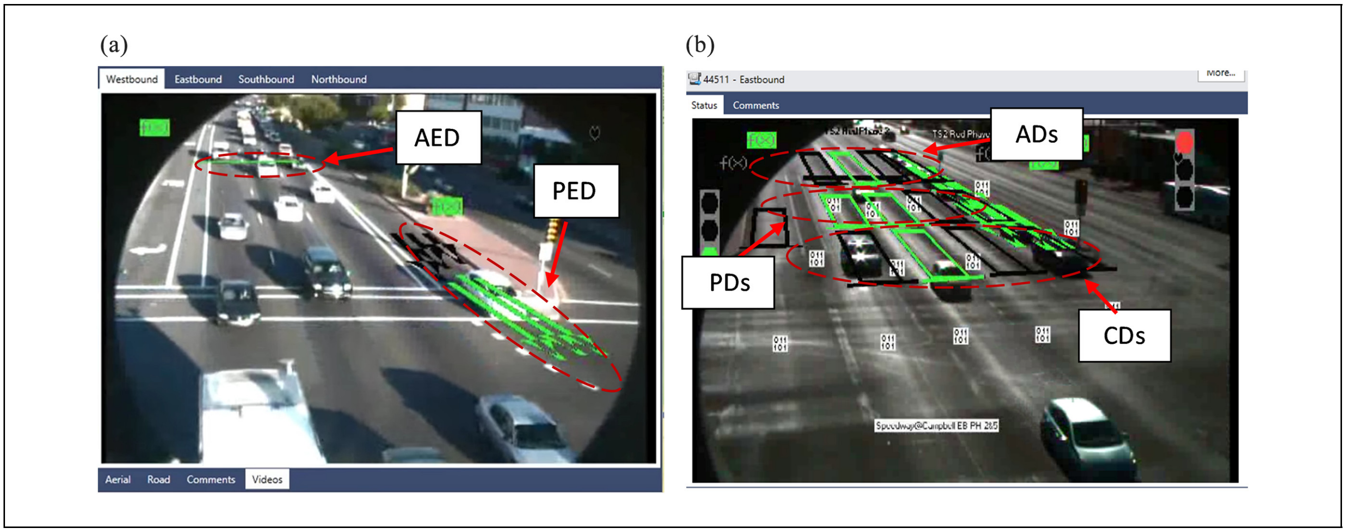

Figure 2. The layout of the video-based sensors: (*a*) event detectors and (*b*) virtual loop detectors.

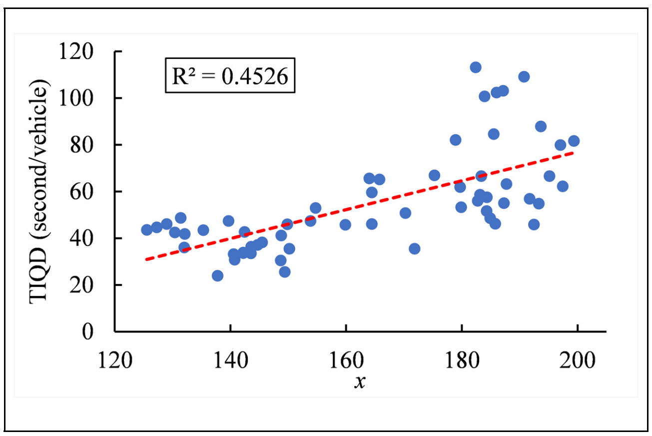

Figure 3. Proposed TIQD model for movements with presence event detector.

turn movements at four directions at the study intersection was collected manually on November 13, 2017. Then, the queue length data can be used to calculate the TIQD which was considered as the ground-truth delay. The left-turn delay estimation model was built between the ground-truth delay with the event-based data during peak hours on November 13, 2017. The delay estimation models were applied to calculate the delay during peak hours on November 14, 2017 and March 21, 2018.

Results Analysis

The TIQD was used to evaluate mobility in this study. The TIQD was calculated using the volume and queue length, as shown in Equation 1 (*20*), and the empirical adjustment factor is one in this study.

$$D = I_s{}^* \frac{\sum V_{iq}}{V} \tag{1}$$

where D is the ground truth TIQD; $\sum V_{iq}$ is all the vehicles in a queue counted for a 15-min interval; V_q is the number of vehicles stopping in the queue; i is the i^{th} I_s during each 15-min interval; V is the total volume during a 15-min interval; I_s is the time interval counting the queue, equaling 10 s.

Collecting TIQD manually is a time-consuming process. Converting the video-based sensor data into TIQD would be a cost-efficient approach. Time occupancy has a positive relationship with the TIQD while the total green time has a negative relationship. The interaction variable x between time occupancy and total green time was introduced as the independent variable, calculated by Equation 2. The variable was then used to build a linear regression model with the ground truth TIQD. Equation 3 was utilized to estimate the TIQD for the movements that had the PED configured. Figure 3 visualizes the results of the proposed TIQD model. The R-squared statistic is 0.45. Even though the goodness of fit is not high, the model could be utilized to estimate roughly the TIQD to be used to evaluate the mobility impacts. Since the model will be used for estimating the trend of traffic delay, the R-squared is considered a reasonable value. Figure 3 shows a very clear trend between the independent and dependent variables.

$$x = \frac{Occ}{\ln(g)} \tag{2}$$

$$\hat{D} = 0.6199x - 46.937 \tag{3}$$

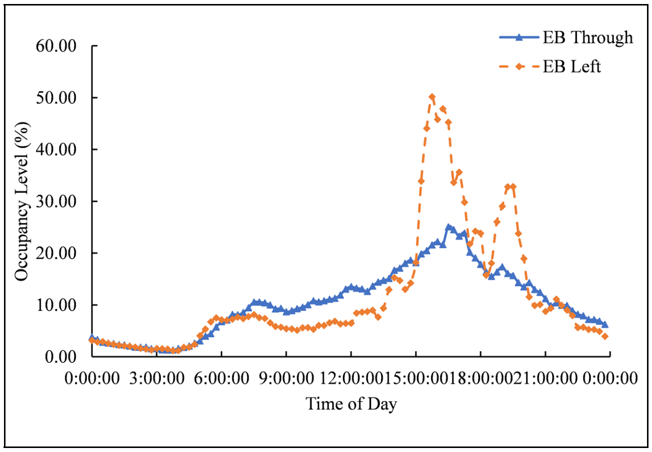

Figure 4. Occupancy level for EB through and left-turn movements.

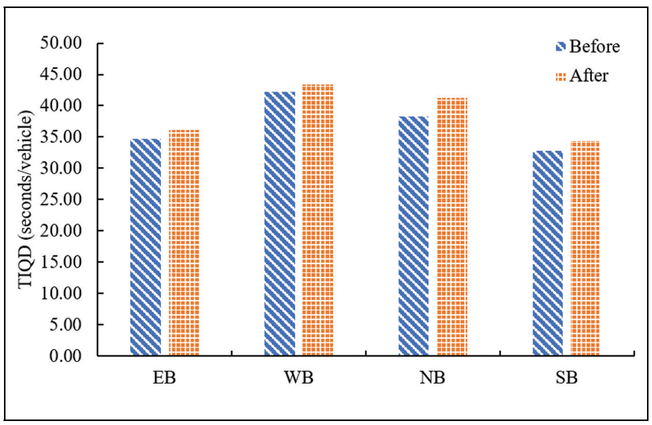

Figure 5. Daily average TIQD per vehicle for each movement per direction.

where *Occ* means the time occupancy; *g* is the total green time for each 15-min interval; and $\hat{D}$ is the estimated TIQD.

One limitation is that Equation 3 was developed using only peak-hour delay. Therefore, this equation can only be applied to estimate delay during the peak hours. For this reason, the TIQD was estimated during peak hours, and was extrapolated to the whole day using the occupancy percentage data in the third dataset collected by virtual loop detectors. To understand the daily congestion level, "occupancy level" was introduced as a new variable to be used in the extrapolation and was simply a combined moving average of the occupancy percentage data with a one-hour window. Figure 4 shows an example of occupancy level for EB through and left-turn movements.

The TIQD was scaled using the occupancy level, and the before and after results compared. Figure 5 shows that the left turns in each direction had an increase in TIQD when changing from running a PPLT to a PO. The average left-turn delay for all directions when using a PPLT was 37 s per vehicle, and when it was changed to a PO it increased to 38.8 s per vehicle.

The impacts on through vehicles were estimated using the same methods. Instead of using time occupancy from event-based data from the PED, occupancy data generated by the virtual loops at the study site was directly used. This method was chosen because the AED for each direction spans all the way across the three lanes, whereas the occupancy data from the video sensor gives occupancy in a lane-by-lane format. In this way the through movement delays were more accurately estimated. The daily left-turn and through movement delay per vehicle was scaled to the whole year (weekdays only) using daily occupancy level trends and the annual turning movement count data from the video-based sensors (the fourth dataset). Table 1 shows the calculated results for daily and annual delays for the study intersection.

The results show an increase in delay of 4.9% and 24.7% for the left-turn and through movements, respectively, for the entire study intersection. The largest increase observed was in the WB through movement. One possible reason for this large increase could be because the WB left-turn bay at the study site is shorter in comparison with the other approaches. This could make it more susceptible to spill-over, which would affect the through movement.

Table 1. Comparison of Daily and Annual Delay for Left Turns and Through Movements

	Movement	Daily delay (hour)	Annual delay (hour)
Before	Left turn	208.51	72,891.43
	Through	779.04	283,569.73
After	Left turn	218.66	76,441.11
	Through	971.66	353,682.44
Difference	Left turn	10.15	3,549.68
	Through	192.62	70,112.71

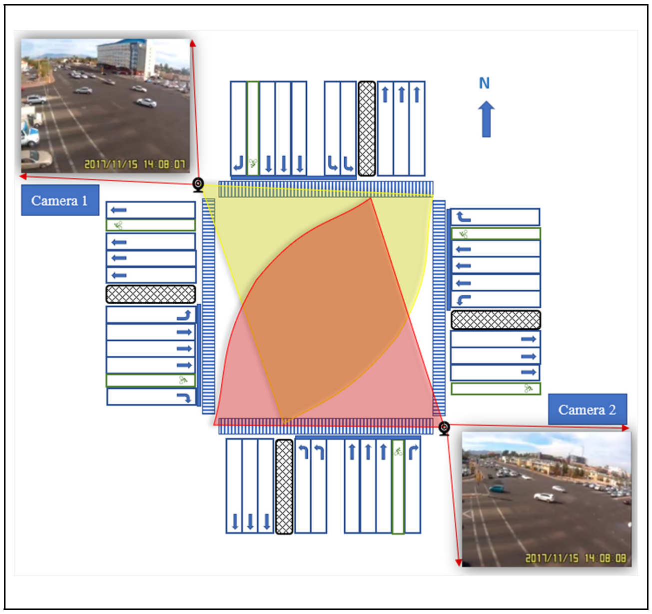

Figure 6. Layout of video cameras installed at the study intersection.

Impact on Safety

Data collection

To evaluate near misses at the study site, video data of the intersection was collected. To cover the entire intersection, two cameras capable of one week of video collection were mounted on the existing traffic signal poles in the configuration shown in Figure 6. After all the videos were carefully reviewed, 24-h videos on November 15, 2017 (Wednesday) and March 21, 2018 (Wednesday) were selected for before and after studies, respectively. Consistency in relation to collecting data on the same day of the week, with the same signal timing, weather conditions, and total traffic were considered to reduce bias. The "before" mobility and safety data were collected at different dates. This is because students collected mobility data on November 14, 2017 causing an increased pedestrian volume compared with usual volumes. To avoid the impact of students, the safety data was collected one day later (November 15, 2017).

It was first necessary to clarify what qualified as a left-turn related near miss and develop classifications for each type of possible conflict. A left-turn near miss was defined as any impedance to either party interacting with the left-turn vehicles resulting in decelerating or even stop involved within the intersection. An example of this would be if a left-turn vehicle had to stop to avoid hitting a pedestrian when the vehicle had already started, or a cyclist having to swerve to avoid a left-turn vehicle. Near misses were classified into three categories: vehicle to vehicle (VtoV), vehicle to bicycle (VtoB), and vehicle to pedestrian (VtoP). Reviewing videos is a time-consuming process. The videos were first reviewed by multiple researchers to identify all potential near misses and the time stamp of every possible near miss was recorded. Based on the time stamps, the videos were further reviewed by a single researcher who had been trained to distinguish real near misses. In this case, the near misses could be accurately and consistently classified based on the predefined criteria.

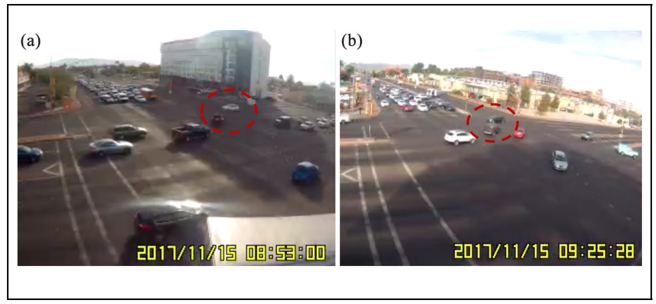

Figure 7. Samples of VtoV: (*a*) during permissive period and (*b*) red light running.

Results Analysis

Figure 7 shows some samples of VtoV near misses of two cameras. In Figure 7*a*, the vehicle made a left turn in advance during permissive time and did not yield to the opposing through vehicle. That type of near miss is very commonly observed for PPLT. Another type of VtoV near miss is that the through vehicle runs a red light resulting inconflict with a left-turn vehicle, as shown in Figure 7*b*. Figure 8*a* and *b* shows VtoP near misses. Figure 8*a* shows that the vehicle started to make a left turn during permissive time leading to conflict with one pedestrian crossing the pavement. In Figure 8*b*, the pedestrian crossed the intersection during the flashing DON'T WALK indication, resulting in conflict with vehicles making a left turn. Figure 9 shows some examples of VtoB near misses. The VtoB near misses happen because of a bicycle running the red light, as shown in Figure 9*a*, or because of a cyclist crossing the crosswalk illegally without getting off the bicycle (*21*), as shown in Figure 9*b*.

A total of 33 near misses were observed on the "before" day and a total of 24 near misses were observed on the "after" day. Figure 10 shows the near-miss results for each category. The VtoP with the intersection operating the PPLT and PO near misses were the highest proportion compared with the other two types of near misses. The number of the VtoP near misses is only reduced by two after running the PO. The VtoB near miss is the smallest proportion and is not affected by the change in left-turn phase. On the contrary, the VtoV

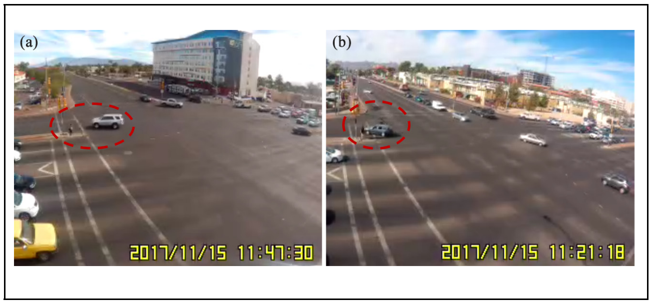

Figure 8. Samples of VtoP: (*a*) during permissive period and (*b*) disregarded the pedestrian signal.

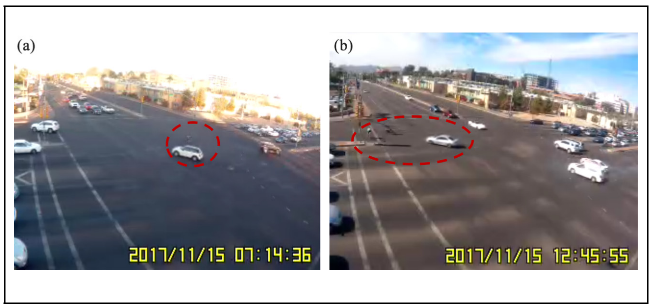

Figure 9. Samples of VtoB: (*a*) bicycle running red light and (*b*) bicycle crossing the intersection illegally.

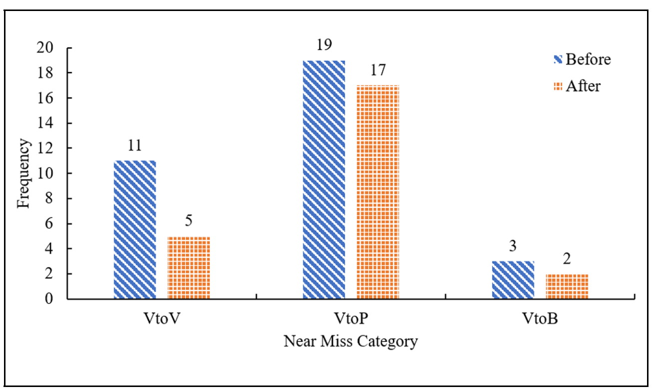

Figure 10. Left-turn related near misses, comparison by category.

near misses decreased from 11 to five. Therefore, changing from the PPLT to PO has different impacts on different categories of near misses, but the change could not reduce all potential conflicts, as mentioned in previous studies (*7*, *8*, *10*).

The causes of near misses required further investigation to identify some of the specific safety impacts of changing the PPLT to a PO. Only VtoV and VtoP are considered because they have a higher contribution to total near misses. Based on the video observations, there

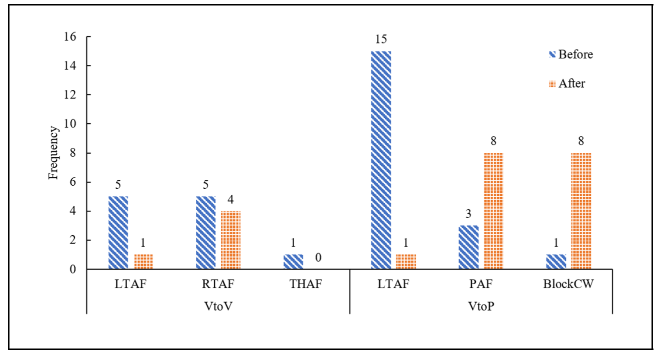

Figure 11. Causes of near miss for VtoV and VtoP.

are three reasons that would cause the VtoV near miss to occur:

- Left-turn vehicle at fault (LTAF): The near misses are caused by vehicles making a left turn during permissive time without yielding to the opposing through vehicles or running a red light.
- Right-turn vehicle at fault (RTAF): The near misses are caused by the opposing right-turn vehicles not yielding to the vehicles making a left-turn.
- Through vehicle at fault (THAF): The near misses are caused by the opposing through vehicles running a red light.

In addition, there are three reasons for a VtoP near miss:

- Left-turn vehicle at fault (LTAF): Vehicles are making left turns during the permissive time and do not yield to the pedestrians walking through the crosswalk or the left-turn vehicles run a red light.
- Pedestrian at fault (PAF): The pedestrians cross the pavement under the pedestrian signal of stop walking indication.
- Vehicle block crosswalk (BlockCW): The left-turn vehicles block the crosswalk when pedestrians are walking through.

Figure 11 shows the causes of VtoV and VtoP near misses. Most VtoV near misses are caused by LTAF and RTAF when operating PPLT. However, after changing to the PO, RTAF becomes the main cause resulting in VtoV near misses, and the near misses caused by LTAF were reduced from five to one. Only one near miss caused by LTAF was because of the vehicle running a red light. This is reasonable because the PO eliminates the near misses caused by vehicles making left turns during the permissive time. Therefore, PO could benefit by reducing the VtoV near misses caused by LTAF, but not by RTAF. For the same reason, the

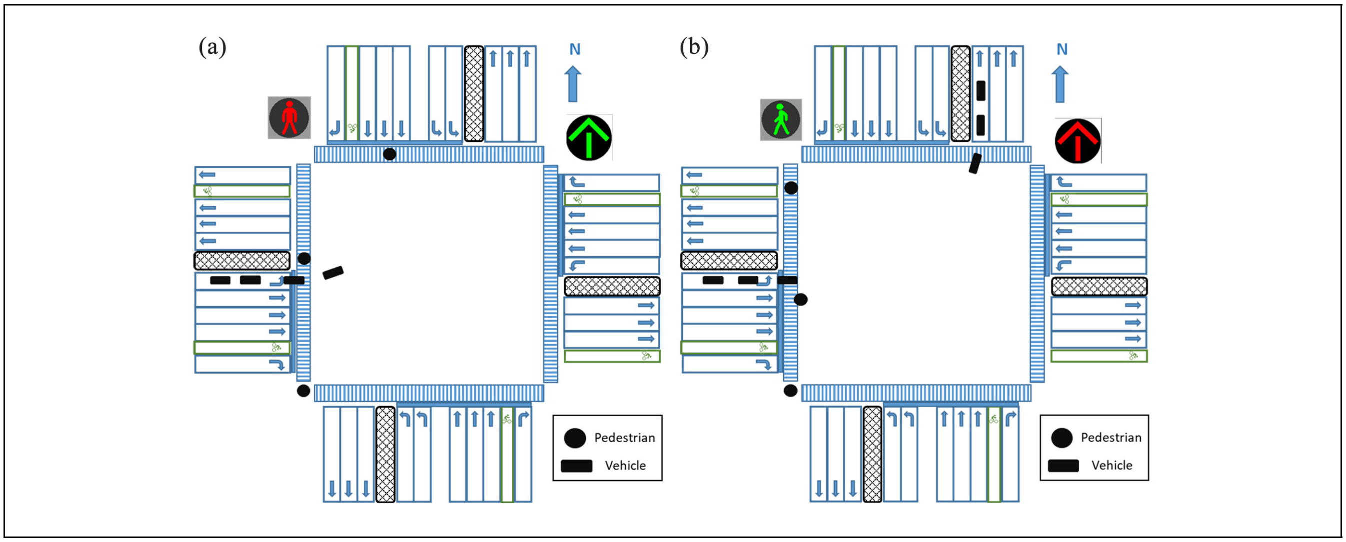

Figure 12. Side effects after operating the PO: (*a*) near misses caused by PAF and (*b*) near misses caused by BlockCW.

PO can also reduce the VtoP near misses caused by LTAF substantially from 15 to one. Only one VtoP near miss was also because of the vehicle running a red light. However, the VtoP near misses caused by PAF and BlockCW were unexpectedly increased, from three to eight and one to eight, respectively. This suggests that increased pedestrian near misses could be considered as a side effect on safety of the PO. Both of the two VtoP near misses have a close relationship with human behavior.

Discussion

After operating the PO, the VtoP near misses caused by PAF were increased. There are two major situations where pedestrians disregarded the signal. One is that the pedestrians started to walk in advance while the vehicles are making a left turn. This illegal pedestrian activity leads to a near miss occurring at the beginning of vehicles making the left-turn. Figure 12*a* shows one pedestrian walking to SB on the west crosswalk and having a conflict with the vehicle starting to make a left turn. The other is that the pedestrians start to walk at the end of the green time. Figure 12*a* shows one pedestrian walking EB on the north crosswalk, and there would be a potential conflict between the pedestrian and the vehicles making a left turn when vehicles arrive at the crosswalk. For the first type of pedestrians who disregarded the signal, if the left-turn vehicles remain behind the stop line, and the through vehicles have already all gone through the intersection, it may appear to pedestrians as if the phase has ended if they are not familiar with PO phasing. For the second type of pedestrians who disregarded the signal, one possible reason is that the pedestrians are confident that they can pass the intersection before the left-turn vehicles arrive, because the left-turn vehicles should start from the stop line under the PO instead of from the center of the intersection under the PPLT. This difference could result in more pedestrians starting to walk later in the green time.

For the VtoP near misses caused by BlockCW, it is mostly because of drivers having poor comprehension of the PO and PPLT. When operating the PPLT, the left-turn vehicles could move ahead to the center of intersection to wait for an available gap to make a left-turn. However, when running a PO, the left-turn vehicles are not allowed to move ahead to the center of intersection for waiting for the gap during the through phase's green time. In this case, the number of vehicles being able to make a left turn for each cycle is reduced when operating the PO compared with the PPLT. After the change to PO, many drivers are not aware of the change, and so are confident that they have time to proceed through the intersection. Once the vehicles are making the left turn, sometimes the light turns red while they are still moving, causing some vehicles to stop over the crosswalk, or even have to back up into the left-turn bay. As shown in Figure 12*b*, one vehicle had to stop on the crosswalk when the left-turn phase just turned red. The pedestrians are then forced to walk outside of the crosswalk and are exposed to the risk of the through vehicles moving SB. This side effect may be improved over time after drivers become more accustomed to the PO.

Table 2. Before-and-After Annual Cost Comparison between Safety and Mobility

	Before (PPLT)		After (PO)		
	Safety	Mobility	Safety	Mobility	Annual safety and mobility cost difference*
Lu's method	$760,533.32	$1,616,731.90	$661,641.46	$1,695,463.86	–$20,159.90
Hydén's method	$792,077.02		$697,956.64		–$15,388.42
Yu's method	$45,316.63		$32,957.55		$66,372.88

Note: * Annual safety and mobilty cost difference = the total cost of After (PO) – the total cost of Before (PPLT).

Trade-off between Safety and Mobility

To make a tangible, data-driven comparison between safety and mobility it was decided to conduct a cost comparison. For this, it was necessary to convert each measure into a dollar figure. For mobility, the annual left-turn delay measured in vehicle hours was multiplied by $22.18 per hour, the mean hourly wage in Tucson, Arizona (*22*). In this manner a total cost for the before and after periods can be calculated. To estimate the cost of near misses, near misses are converted to crashes, and then the KABCO scale is used to determine the cost (*23*). This approach was chosen because several studies have shown that there is a high correlation between crashes and near misses (*24–26*). Because there are several equations to convert near misses to crashes, three different methods were compared. The first method used to convert from near misses to crashes was obtained from the study by Lu et al. (*27*), and is shown in Equation 4.

$$A = \frac{E}{189.01E + 6670.5} \tag{4}$$

where A is the average number of accidents per 10,000 vehicles; and E is the average number of near misses per 10,000 vehicles.

The second method used is from a study by Hydén (*28*) by means of a direct conversion factor multiplied by the near misses to obtain crashes. The converting factor for VtoV near misses was 3.2×10^{-5} crashes per near miss and the factor for VtoP and VtoB near misses it was 15.3×10^{-5} crashes per near miss. To convert the crashes obtained from these two methods to a dollar value, the most recent crash statistics provided by the Arizona Department of Transportation (ADOT) were used (*23*). Using the percentage of crashes of each type on the KABCO scale, and using ADOT's average costs for each type, the crashes were converted to a dollar value. The final conversion method was used to convert directly from near misses to a dollar value using the results of a survey in the report by Yu et al. (*29*) which determined that the average cost of a near miss was $4. All of these costs for each method were then scaled using volume trends to represent annual cost, and summarized in Table 2. The near-miss data only included left-turn related near misses, and so was only compared with left-turn delay costs.

Different methods for estimating the value of near misses lead to different results. For example, when using Lu's method, the PO seems advantageous, but when using Yu's method, the PPLT seems advantageous. This highlights the need to be cautious when choosing a method to convert near misses into a dollar value. Overall, each intersection must be analyzed on a case-by-case basis, but these comparison methods will provide useful information when making important signal timing decisions. Compared with the previous studies (*7–10*), this study investigated the mobility and safety impacts using the dollar value. Also, it is proven more efficient and proactive for practitioners to quantify the safety impacts using near-miss data instead of crash data because the proposed evaluation method can be used right after a new phasing scheme is implemented without waiting for crashes to occur. Instead of considering one or two types of potential conflicts (near misses) as in previous studies, for example (*17*, *19*), this study further explored the possible reasons for different types of near misses in multimodal scenarios.

Conclusion

The study proposed data-driven methods that can be used to evaluate the trade-off between safety and mobility when changing PPLT to PO at an intersection. Mobility impacts were quantified by estimating delay using existing infrastructure. Safety impacts were evaluated using a multi-modal near-miss analysis. Both measures were converted to annual cost and compared. It was found that different equations for estimating the cost of near misses can result in different conclusions of the value of the signal timing change. Therefore, it is recommended that when using these methods great care is taken in choosing which method to use, to ensure a valuable result.

The primary findings of this paper are summarized as follows:

- Near misses can be used as the safety index because analysis of near misses is consistent with the analyses of crashes (*7*, *8*, *10*), the left-turn related conflicts are reduced but other types of conflict are increased, for example, PAF and BlockCW.
- Mobility and safety data can be collected and converted to a dollar value to justify a signal timing change using a data-driven approach.
- Equations to convert near misses to a dollar value should be chosen carefully to ensure an accurate result.

To improve this study, a before-and-after safety analysis could be conducted for the through lanes. This would allow for the comparison of the intersection in its entirety, which would show any possible side effects on the through movements. To further study in this area, more before-and-after studies could be conducted at different intersections, and more types of left turns could be compared. In the paper, the peak hour delay was scaled to the 24-h delay based on the assumption where the delay has a linear relationship with the occupancy level. In fact, the relationship between the delay and the occupancy level may be nonlinear and requires continuing efforts to improve the accuracy of the model of scaling short interval delay to 24-h delay. The delay estimation model could be further improved with additional data or new modeling techniques. Additionally, equations to convert near misses into a cost could be summarized and evaluated for improved accuracy. Moreover, the causes of PAF and BlockCW should be further investigated through additional before-and-after studies and the corresponding measures can be calculated to reduce these side effects of PO.

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Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: Y-JW, XL, AW, AC; data collection: AW, XL, AC; analysis and interpretation of results: XL, AW, AC; draft manuscript preparation: AC, XL, Y-JW. All authors reviewed the results and approved the final version of the manuscript.

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