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ABSTRACT
Serving protected left turn phases for one or two vehicles can often be an inefficient use of cycle green time when the opposing through movements are over capacity. This paper assesses the performance of an intersection based on the application of controller logic that delays the call for a protected left turn phase based on vehicle wait times. Four weeks of evaluation were carried out where the delay on left turn phase calls was varied in 25 second increments, from 0 to 75 seconds. The results indicate that delaying left turn phase initiation substantially increases the amount of green time for saturated through movements, while minimally increasing the travel delay for left-turning drivers. The paper concludes by recommending agencies consider using a delay in the range of 25 to 50 seconds for calling protected phases at intersections where the opposing through movement is oversaturated and could benefit from additional green time. This research presents one of the first quantitative studies in evaluating the potential intersection capacity and performance improvements with respect to left turn detector delay.

MOTIVATION

When all phases of a signalized intersection are undersaturated throughout the day, agencies typically focus on keeping cycle lengths short and providing good coordination (1). As intersections become more saturated, it is important to look at how efficiently phases are used. For example, serving only one or two left-turning vehicles with a protected phase may be inefficient when the opposing through phase is oversaturated. A protected left turn can easily use more than 10% of the cycle length for a single turning vehicle (minimum green + clearance time). Assuming left turn phases cannot be lagged (because of yellow trap) or omitted by time of day, it is desirable to reduce the occurrences of protected left turn phases using detector delay if the movement can be safely and efficiently be served by a permitted phase instead.

BACKGROUND & LITERATURE

One way to reduce the number of protected turn phases is to allow turning vehicles to use the permissive period and only call the protected turn phase when there is unserved demand. These protected "lagging" left turns have been widely used by transportation agencies (2) (3). However, these lagging phases may not always be necessary for a vehicle that arrives at the end of the permissive period and when they are called during coordination, the controllers typically dwell in that phase until it is time to cross the barrier.

In addition to the traditional lagging left turn approach, a number of innovative methods have been explored to reduce the number of protected left turn phase initiations for both actuated and semi-actuated systems. Xuan et al. (2011) explored the use of mid-block pre-signals as a means of dynamically calling a protected left turn phase for a variable number of lanes, based on turning demand; this shortened the duration of the phase, and in some cases eliminated it altogether (4). Additionally, the Federal Highway Administration (FHWA) recommends a number of indirect left-turn treatments, such as the median U-turn and the continuous flow intersection, to eliminate protected left turn phasing altogether in areas with recurring congestion (5).

At the controller level, some models contain internal features for advanced handling of protective/permissive left turns. This can include adaptive algorithms that account for not only the volume of left turning vehicles, but also the number of gaps in the opposing through movement. If the opposing through movement is light enough to have sufficient gaps, then a protected left phase is not called (6).

DELAYED CALL FOR PROTECTED LEFT TURN PHASE

The FHWA *Traffic Control Systems Handbook* suggests that a potential use of detection delay is to enable protected phase calling during time periods with heavier turning movements, or when the turning movement experiences long delay waiting for a permissive opportunity (7). Additionally, the detector delay parameter is often used for right-turn only lanes or combination right/through lanes to facilitate right turns on red (8). The *Traffic Signal Operations Handbook* supports these uses of vehicle detector delay, and for protected/permissive left turn movements, further suggests that a delay parameter value of between 7 and 15 seconds be set on the stop bar detector (9).

Although the use of delayed calls for protected left turn phasing is proposed in the literature, there have been few quantitative studies documenting the potential benefit of such an approach. This paper evaluates signal performance for several detector delay values on the operation of a protected/permitted movement, using high resolution controller event data.

CASE STUDY INTERSECTION

The intersection of US 36/SR 67 and CR 600W near McCordsville, Indiana was selected as a test site for the implementation of the left turn detector delay (see Figure 1). US 36/SR 67 carries approximately 12,000 vehicles per day, while CR 600W has a daily traffic volume of approximately 5,600 vehicles (10); these volumes, the geometry of the intersection, and the fact that all four approaches have five section protected/permissive left turn heads, make it an ideal intersection for this study. Both US 36/SR 67 and CR 600W service major arterial movements, and due to their suburban location within the Indianapolis metropolitan area, exhibit a predictable flow of vehicles at specific times of the day. In particular, during the PM peak period timing plan, 3PM (15:00) to 6PM (18:00), there are high volumes of vehicles travelling east on US 36/SR 67 (Phase 2, see Figure 2), which often results in substantial queuing on the through movement.

Figure 2 provides additional detail of the geometric layout of the study site. Each approach consists of a single through lane and left turn lane, with the eastbound approach having an additional right-turn-only lane. Inductive loops are used for both stop bar and advance detection, with advance detection only on the US 36/SR 67 approaches. Figure 3a shows the specific flow rates and volume-to-capacity (v/c) ratios for each of the intersection approaches; the Phase 1/Phase 2 pair will be the primary focus of this study, and Figure 3b shows that the Phase 1 left turn movement is significantly undersaturated compared to the Phase 2 through movement.

Illustrative Example of Protected Phase 1 Serving One Vehicle

An example of the protected left turn being called for a single vehicle at the study intersection can be seen in Figure 4a. In this example, there are a number of opposing vehicles queued at the red light on eastbound US 36/SR 67. The single left-turning vehicle shown places a call for Phase 1. Consequently, the eastbound queue of vehicles served by Phase 2 is forced to wait for an additional 12 seconds (left turn minimum green + clearance interval) while the turning vehicle is served. It is very likely that had the protected left phase not been called, this vehicle would have been able to complete its movement during the opposing through phase, or during the clearance interval upon phase termination. Omitting this underutilized left turn phase would allow more green time to be allocated to the saturated through movement served by Phase 2.

Figure 4b shows the phase configuration for a cycle where the protected left turn Phase 1 is called. In contrast, Figure 4c demonstrates a situation where Phase 1 is omitted, and additional green time that would have been used by Phase 1 is available for Phase 2.

OPERATION WITH DETECTOR DELAY

To illustrate how detector delay is handled at the signal controller, Figure 5 provides a snapshot of high resolution data for the Phase 1 protected left turn, where the detector delay is set for 25 seconds. The figure consists of three simultaneous streams of event data: the top line shows the status of the front stop bar detector, the middle line shows the call status of Phase 1 at the controller, and the bottom line shows the activity status of Phase 1 at the controller.

Callouts *i* and *ii* show intervals in which the detector was activated, but no call was placed for the turn phase, because the detector was on for less than 25 seconds in both cases. At 15:15:25, the detector is activated a third time, but this time it remains on for more than 25 seconds. Consequently, at 15:15:50, 25 seconds after detector activation occurs, the detector delay expires, and a call is placed for the protected left turn phase. At 15:16:10, the protected left turn Phase 1 is activated, and the waiting vehicle completes its turn (as seen by the detector call terminating at 15:16:25). Finally, callout *iii* shows a second vehicle also completing a turn while Phase 1 is active. Once the detector is no longer occupied and the gap timer expires, Phase 1 terminates at 15:16:35.

Detector Delay & Cross Switching Configuration

The procedure for changing the left turn detector delay parameter at the controller is straightforward. Within the signal controller menu, the delay feature is typically found under the detector setup options, depending on the make and model of the controller. In addition to the left turn detector delay time, cross phase switching was enabled for each of the left turn detectors. This feature switches the vehicle detector from calling and extending the left turn phase to extending the same-direction through phase after the left turn phase terminates; this keeps the same-direction through phase from gapping out while vehicles are still present in the left turn lane, even if no vehicles are present for the through movement (11).

Table 1 shows the schedule that was used for setting the detector delay parameter for the left turn lanes at the study intersection. A series of delay values ranging from no detector delay to 75% of the 100-second cycle length were examined. Thus, a total of four detector delay values were tested, ranging from 0 seconds to 75 seconds. Each value was tested for a total of five weekdays, with the daily test period running during the PM peak period (15:00 – 18:00).

Video Groundtruthing

To evaluate the impact of the various detector delays, the researchers examined the residual queue length of the turn lane for each cycle; that is, at the end of the permitted through phase for each approach, how many vehicles were queued in the opposing left turn lane? Four cameras with 10-second time lapse shutters were mounted on signal poles at the intersection, with a clear view of each turn lane. The images captured by these cameras were then manually processed to count the vehicles remaining at the end of each opposing through phase.

RESULTS

The westbound left turn (Phase 1) and eastbound through (Phase 2) movements are of particular interest for this study, given their large disparity in traffic volumes during the PM peak period. The results for this phase pairing are discussed in detail below.

Effect on Intersection Capacity

Figure 6 shows the cumulative green time (seconds) allocated to the Phase 1 protected left turn for each of the four detector delay values. The lighter trend lines are the individual cumulative green time measurements for each day of data collection, while the darker trend lines represent the average value of cumulative green time for each delay setting. As expected, for increasing values of the detector delay parameter, there is a decrease in the cumulative green time for the protected phase. Over three hours, the median cumulative green time is approximately 560s, 350s, 210s, and 90s for detector delays of 0s, 25s, 50s, and 75s, respectively.

Fixed force off coordination allowed unused green time to be used by subsequent phases. In this example, Phase 2 has higher cumulative green time when left turn detector delays are higher, as shown in Figure 7a. The vertical time scales are different, so the visual difference is not as dramatic, but the median cumulative green time for Phase 2 is approximately 3920s, 4390s, 4750s, and 5080s for detector delays of 0s, 25s, 50s, and 75s, respectively. Figure 7b shows the changes in cumulative green time and capacity for Phase 2, assuming a 2 s/veh saturated flow headway, relative to the 0s delay value.

These results suggest that for Phase 2, capacity (as measured in terms of total available green time) is substantially improved with increasing values of left turn detector delay. For example, with a change in green time from 3920s to 4390s, the capacity of Phase 2 increases by 235 vehicles.

Effect on Left-Turning Detector Occupancy

It is important to ensure that the increases in green time for Phase 2 do not come at the expense of long left turn queues on the opposing Phase 1. Figure 8 shows a cumulative frequency distribution of the detector presence time for the Phase 1 protected left turn. This is a measure of the vehicle wait time at the front stop bar detector, rather than total wait time in the turn lane (12). The vertical axis of the cumulative frequency diagram represents the percentage of drivers who experience a detector wait time less than or equal to the corresponding value on the horizontal axis; in this figure, a separate distribution is shown for each of the left turn detector delay values.

From this, it can be seen that there is not a dramatic change in detector presence time from the 0s detector delay to the 75s detector delay. For example, the median (50th percentile) presence time changes by approximately 1 second. Even at the 90th percentile, the front detector presence time only increases by 9s when the detector delay increases from 0 to 75s. Furthermore, it can be seen that all four distributions reach the 100th percentile within 100 seconds of the front detector first activating. Since the cycle length is 100 seconds, this indicates that virtually all left turn demand was served in a single cycle.

Effect on Left-Turning Queuing

Time lapse cameras recorded an image of the left turn queue five seconds after the termination of the coordinated Phase 2/Phase 6 through movements, and the number of queued vehicles was manually counted to generate the residual left turn queue lengths for each cycle. Figure 9a is a cumulative frequency distribution of the Phase 1 residual queue lengths; because the values for queue length are discrete, the distribution is represented as a stepwise function. For example, the figure indicates that for a 0 second left turn detector delay, approximately 20% of cycles during the 15:00 – 18:00 PM peak period had no queue in the Phase 1 protected left turn lane at the end of the permissive phase.

This part of the figure indicates a small increase in the left turn lane residual queue length for increasing values of left turn detector delay. Additional, the largest increase in queue length increases between the 25s and 50s detector delay values. The median queue length increases from between zero and one vehicles to between one and two vehicles, while the 90th percentile queue length increases from between two and three vehicles to between three and four vehicles. It can also be seen in the upper tails of the distributions that in rare instances, the queue length can exceed eight vehicles for certain values of detector delay. However, repeated site observation revealed that these longer queue lengths are largely the result of random vehicle arrival patterns, rather than an indication of repeated split failure.

The observations on left turn queue length are further decomposed in Figure 9b. Here, the residual queue lengths are split between those cycles where a protected left turn is called before the opposing through, and those cycles where the protected left turn is omitted. Again, it can be seen that for higher detector delay values, the distribution of the histogram shifts slightly to the right, suggesting a general increase in left turn residual queue length. The slight increase can be attributed to the fact that fewer turning vehicles are served during a protected phase, and instead make it through the intersection during the permitted phase or clearance interval. It can also be seen that for detector delay values above 50s, there is a modest increase in the frequency of queues of eight vehicles or more. However, it appears that the cycles where a protected left turn is called see a more substantial rightward shift in distribution (i.e., an increase in residual queue length) than the cycles which immediately begin with the through movement. This likely occurs at the peak volume time where heavy movements occur on all approaches, and less time is redistributed to Phase 1 by the controller.

This change in distribution provides substantive evidence that eliminating low-volume protected left turn phases not only increases the capacity of the opposing through movement, but also the capacity of the left turn movement in cases where sufficient gaps exist to serve the left turn demand. Accordingly, it appears that a detector delay value of at least 25 seconds can be set at the controller with minimal increase in delay for left turning vehicles.

Effect on Phase Initiation & Phase Splits

Figure 10 shows the number of phase initiations for the Phase 1 protected left turn for each of the detector delay values, as measured using high resolution data from the signal controller; the individual bars in each detector delay group represent the individual weekdays for which data was collected. A generally steady downward trend can be seen when comparing phase calls between delay groups. This supports the evidence presented previously in Figure 6; namely, that the decrease in cumulative green time for Phase 1 comes from a decrease in the total number of phase initiations, rather than a shortening of the duration for each phase due to lower demand and gap-outs.

Finally, Figure 11 shows the relative distribution of Phase 1 and Phase 2 splits for each individual day of data collection, grouped by detector delay value. For each day, the magnitude of the phase split is shown in terms of cumulative green time from the 15:00 to 18:00 time period; on the right side of the figure is the average daily PM peak period cumulative green time, summed across Phase 1 and Phase 2.

This figure more clearly shows the tradeoff between Phase 1 and Phase 2 green time for increasing left turn detector delay values; as the detector delay value increases, there is a steady downward trend in the Phase 1 split, and a corresponding increase in green time allocated to Phase 2. Furthermore, this figure supports previous explanation that shows a generally increasing amount of green time from the 0s to 75s detector delay values, from 78.8 minutes to 86.3 minutes, respectively.

CONCLUSION

This following conclusions can be reached based on the implementation of varying left turn detector delay values:

- Using a detector delay for protected left turns should be considered where a lightly traveled left turn has high volume and queuing on the opposing through movement, such as illustrated in Figure 4a. Specifically, consideration should be given to using this technique on movements where the left turn lane has a low v/c ratio (less than 0.5), and the opposing through movement has a v/c ratio near 1.0 (approaching saturation). As the v/c ratio for the left turn lane approaches 1.0, the benefits of detector delay become negligible, since the protected turn phase will be called for most cycles, regardless of the delay setting.
- In this study, the detector delay for calling the protected left turn phase was varied from 0 seconds to 75 seconds, with turning vehicles able to utilize the permissive turning period in lieu of a dedicated turn phase. Increasing the left turn detector delay on the westbound approach resulted in an increase in capacity of 235 vehicles, 415 vehicles, and 580 vehicles on the eastbound through movement over the three-hour PM peak period for delay, for delay values of 25s, 50s, and 75s, respectively (Figure 7b).
- For higher values of left turn detector delay, the number of queuing vehicles in the left turn lanes increased slightly, since fewer vehicles are serviced with a protected turn phase; however, the added delay to vehicles was modest, and most drivers were able to complete their turns on the permissive turn phase (Figure 9b).
- Based on the results of this study, in particular the effect of detector delay on left turn queues (Figure 9) a detector delay value of between 25 and 50 seconds was found to represent the best tradeoff between higher capacity on the saturated movements, and increased left turn wait times. While there is not strong evidence of substantial breakdown of throughput even for higher delay values, the range of 25s to 50s was recommended as a conservative starting point for individual agencies.
- Various measures of groundtruthing, including photographic measurement of queue lengths and referencing of high resolution controller data, were utilized to verify intersection performance. These tools can serve as a valuable and easily deployable means of monitoring individual intersections across multiple weeks.

There are a number of opportunities for further study on this subject, such as using the results to warrant protected phases for very small time frames or exploring even larger delay times, perhaps in excess of a single cycle length. Additionally, expanding this methodology to additional intersections is important to provide an opportunity to quantitatively characterize benefits under different volume conditions. Finally, econometric modeling of the individual vehicle wait times (perhaps using a hazard model or Tobit approach) could provide a more comprehensive illustration of the relationship between detector delay time and intersection performance.

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TABLE 1 Schedule of Field Data Collection for Programmed Detector Delay Times on the Signal Controller

Time Period	Detector Delay
6/03/2013 – 6/07/2013	0 seconds
6/10/2013 – 6/14/2013	25 seconds
6/17/2013 – 6/21/2013	50 seconds
6/24/2013 – 6/28/2013	75 seconds

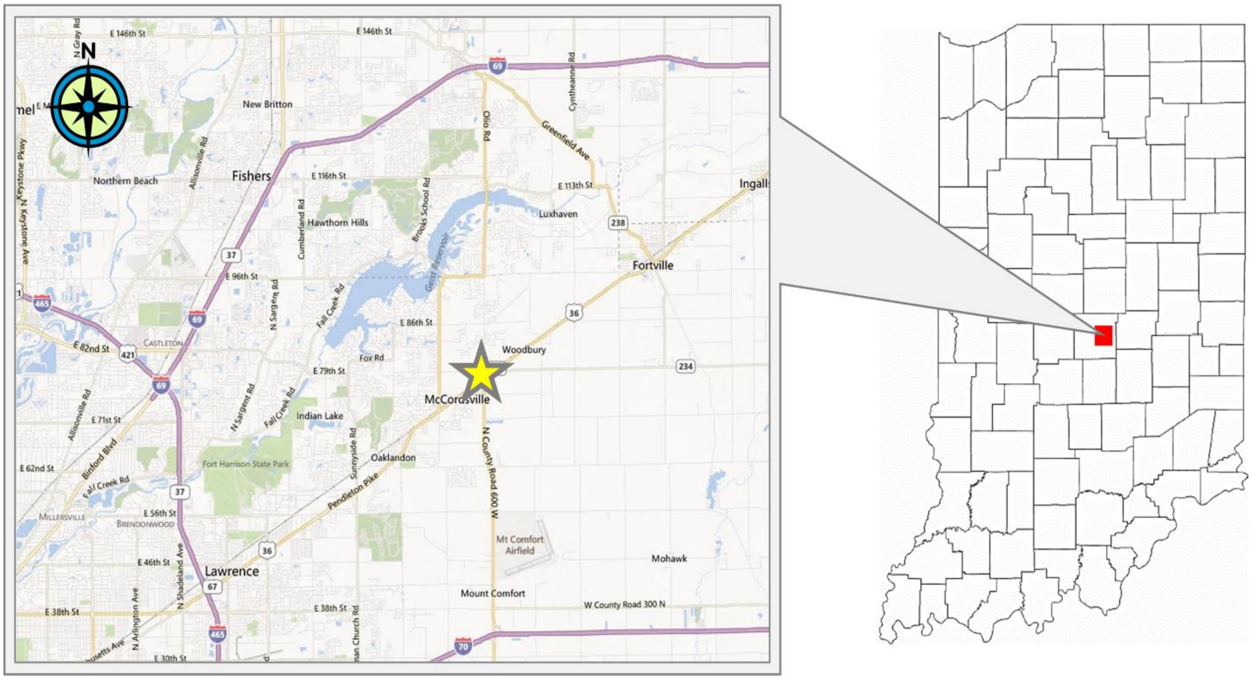


FIGURE 1 Location of the study site at US 36/SR 67 and CR 600W near McCordsville.

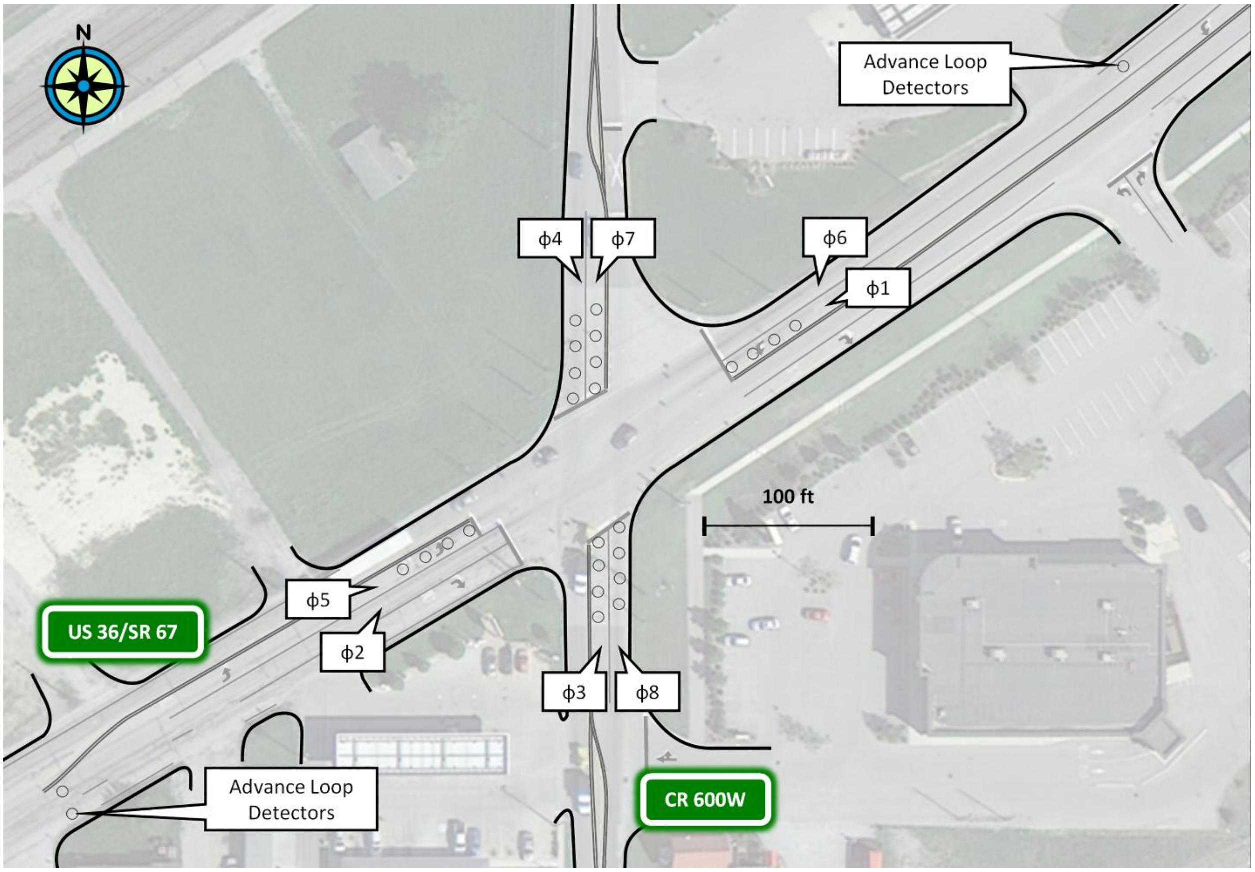
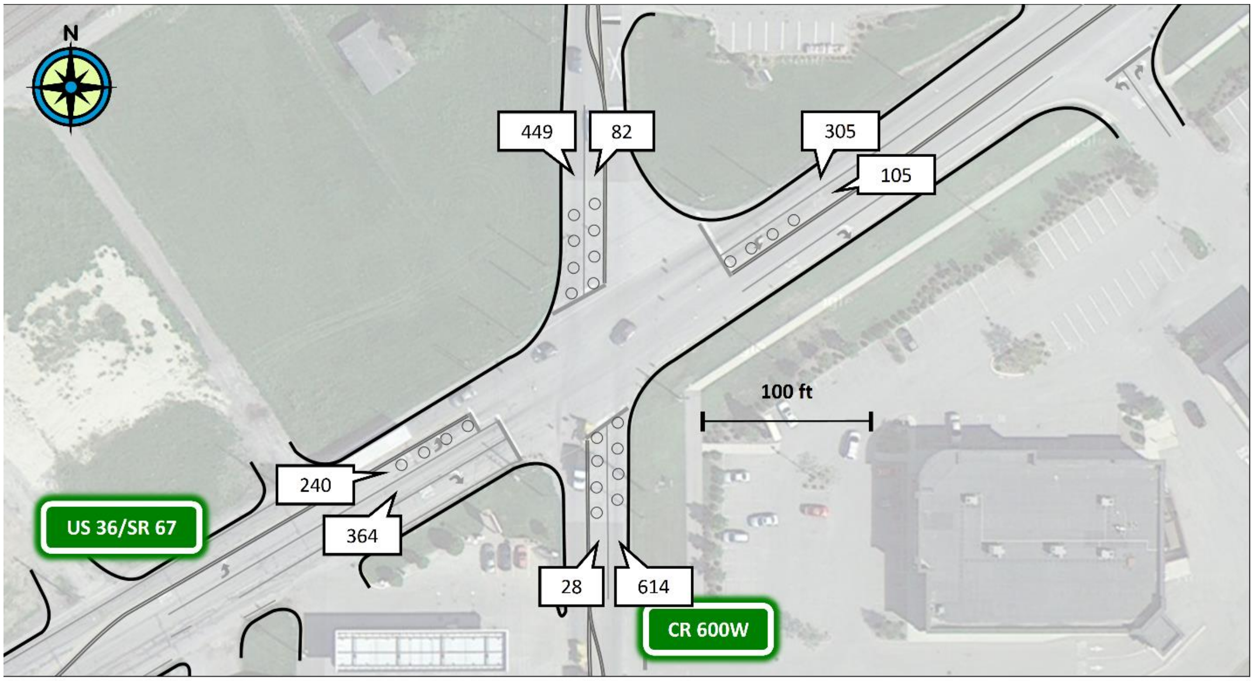
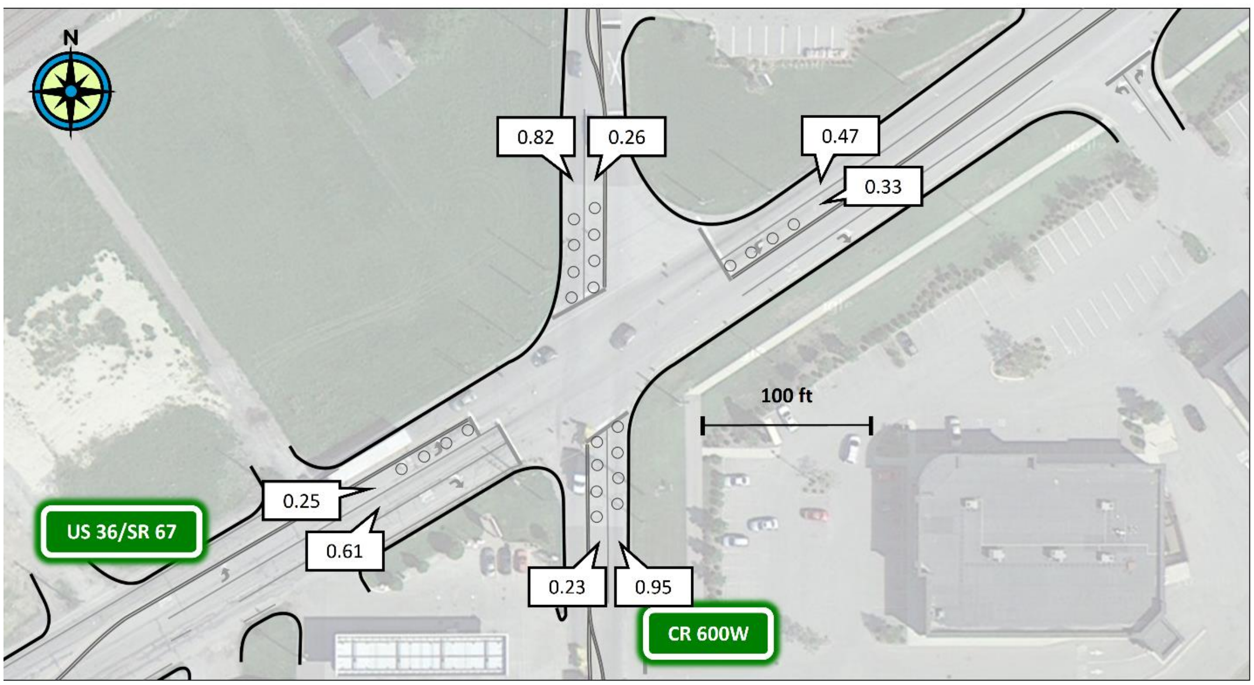


FIGURE 2 Lane configuration, phase numbering, and location of pavement loop detectors at the study intersection.

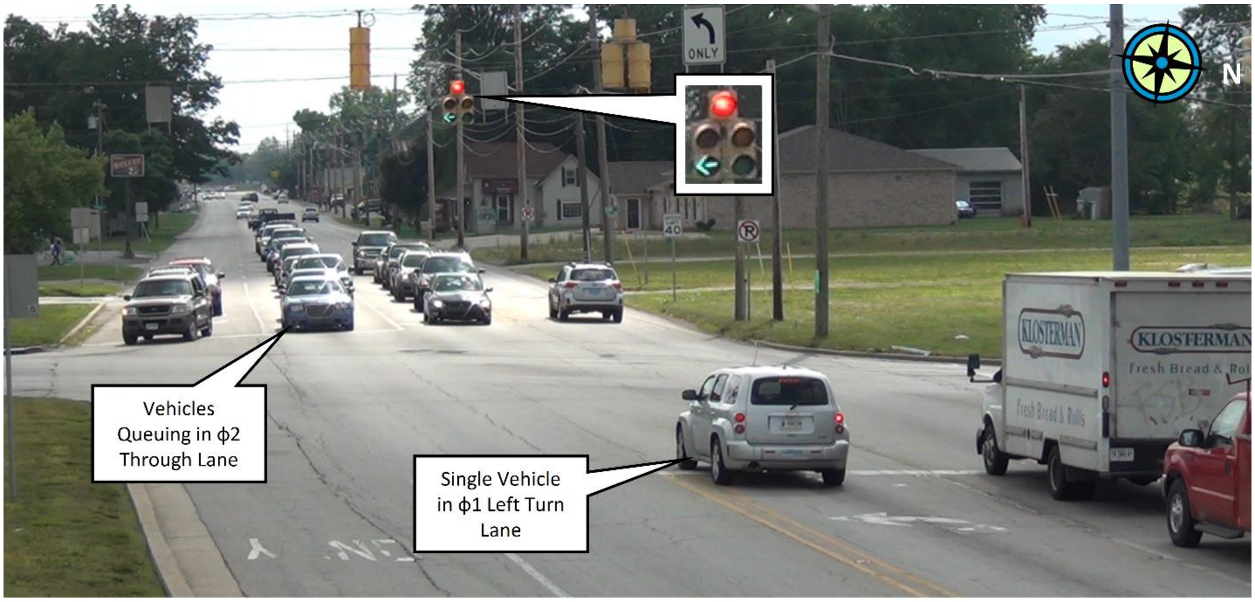


(a)

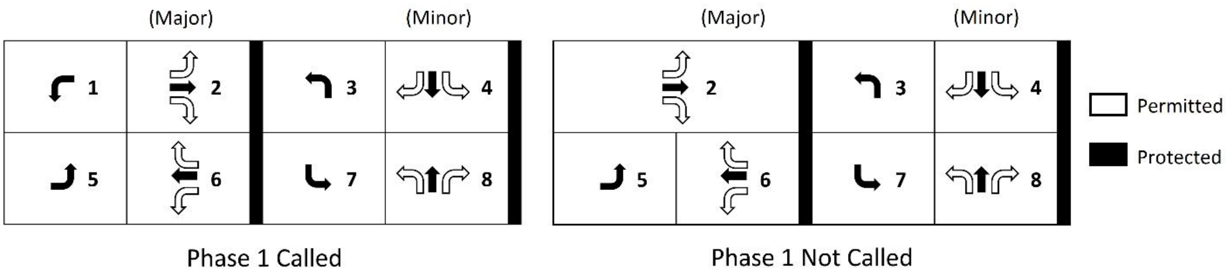


(b)

FIGURE 3 Flow rate (veh/hr) and volume-to-capacity (v/c) ratio for each lane group at the study intersection.



(a)



(b) (c)

FIGURE 4 (a) Protected left phase calls can consume valuable cycle time, here showing a single vehicle proceeding left on Phase 1 green while Phase 2 vehicles queue; (b) a typical eight-phase ring diagram showing the inclusion of a protected left turn for Phase 1.

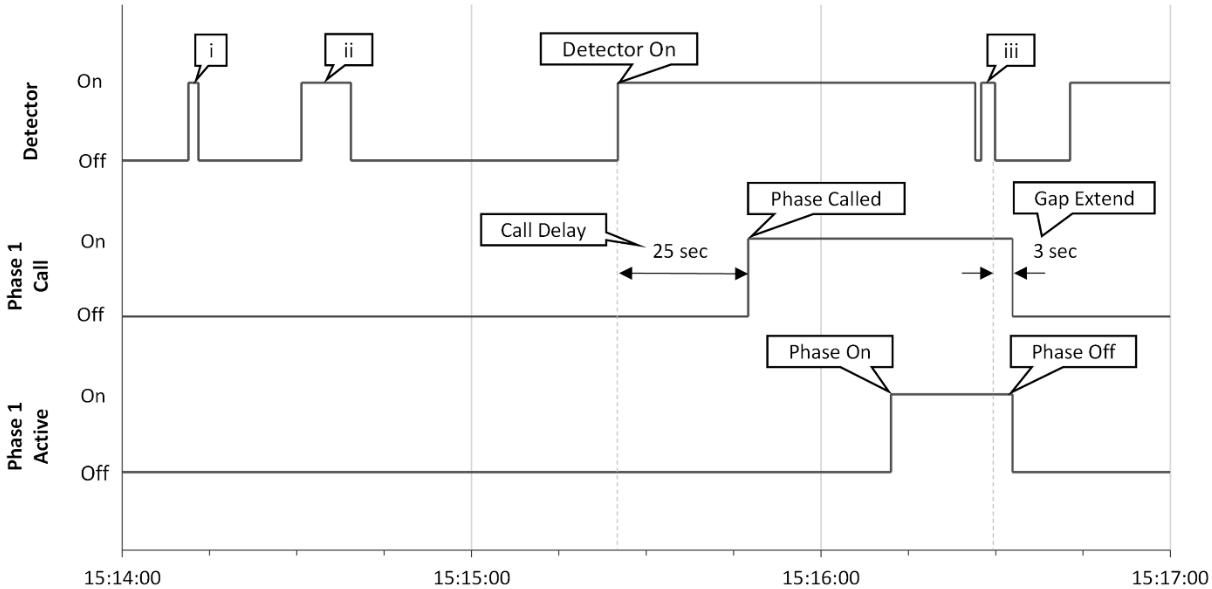


FIGURE 5 An example of signal controller response and phase initiation based on 25 second programmed detector delay (Phase 1 shown).

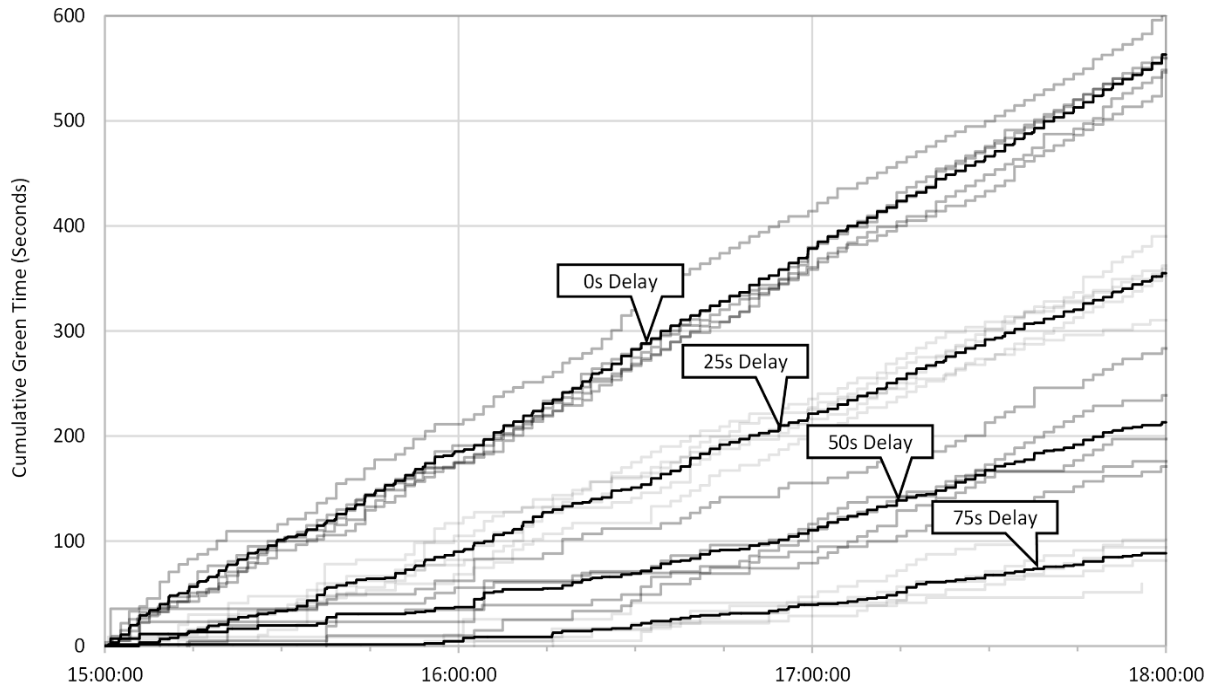


FIGURE 6 Summary of cumulative green time served on Phase 1 (westbound protected left) for 0s, 25s, 50s, and 75s detector delay parameter values, with average cumulative service time highlighted for each delay setting.

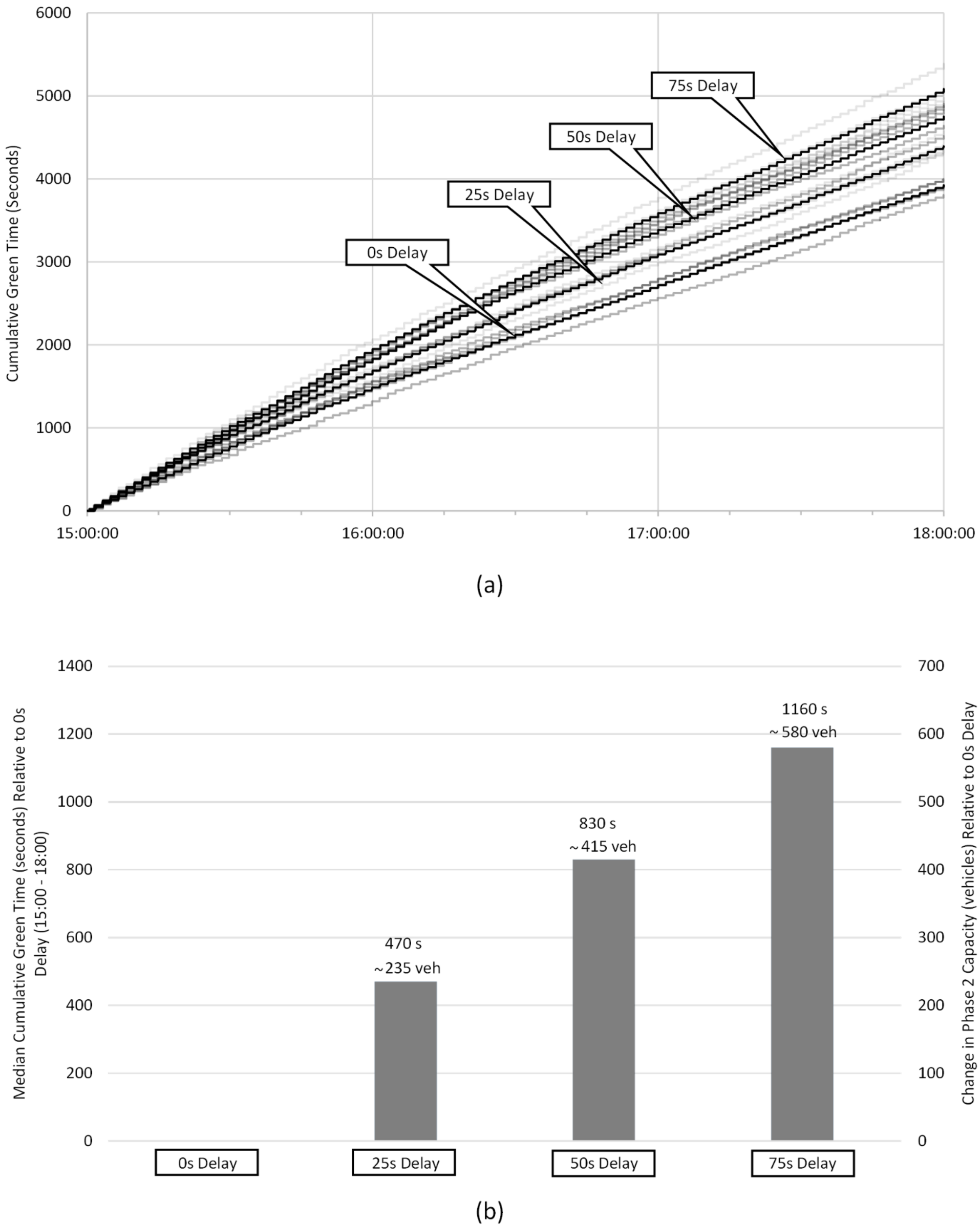


FIGURE 7 (a) Summary of cumulative green time served on Phase 2 (eastbound through) for 0s, 25s, 50s, and 75s detector delay parameter values, with average cumulative service time highlighted for each delay setting; (b) additional green time and capacity served.

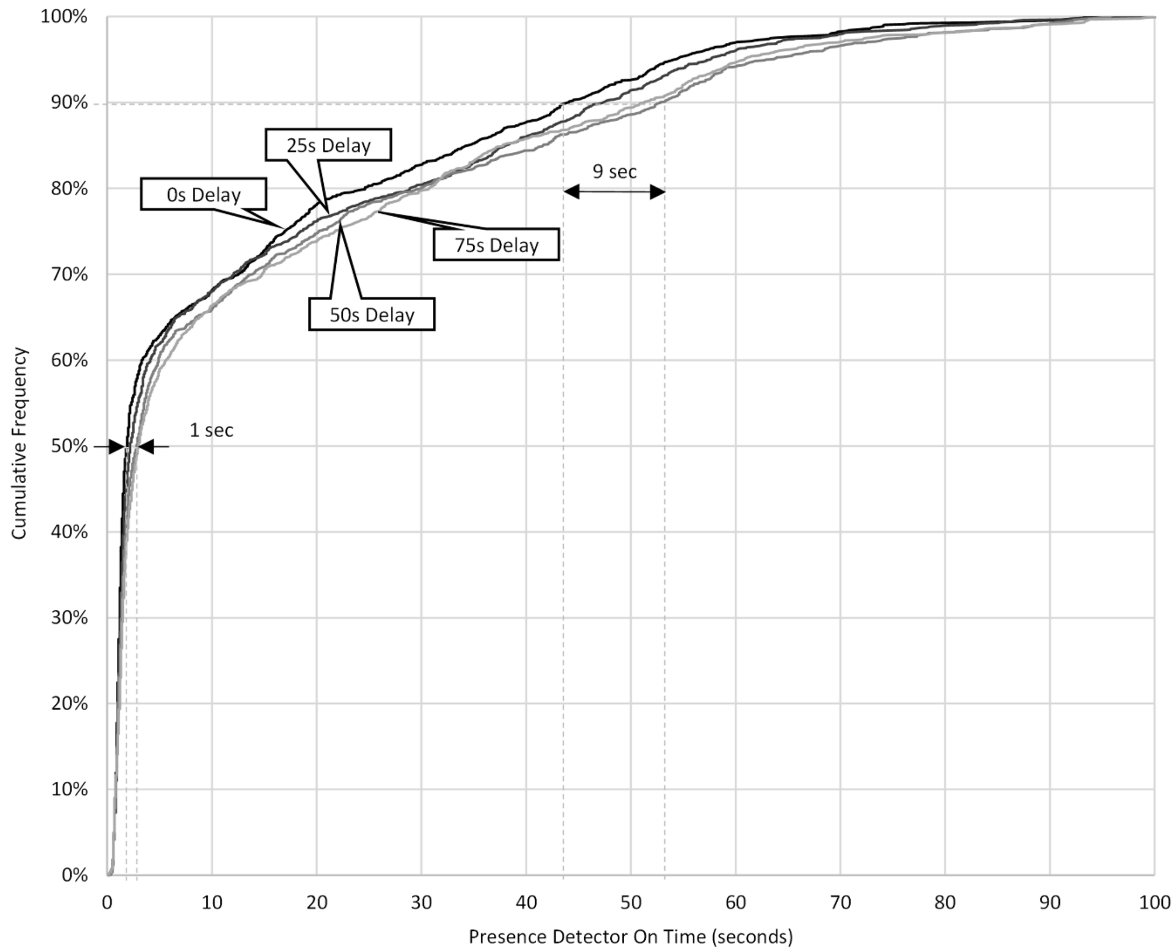
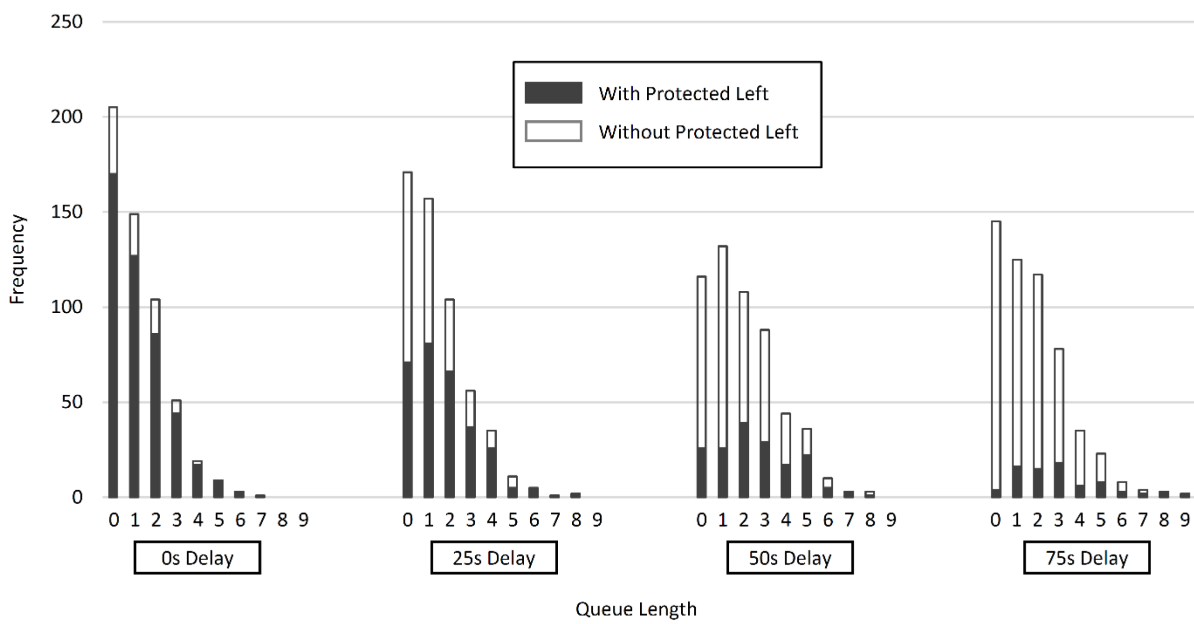


FIGURE 8 Front detector presence times on Phase 1 (westbound protected left) for 0s, 25s, 50s, and 75s detector delay parameters.

(a)



(b)

FIGURE 9 Cumulative distribution of vehicle queue lengths on Phase 1 (westbound protected left) for 0s, 25s, 50s, and 75s detector delay parameters, based on time lapse camera footage.

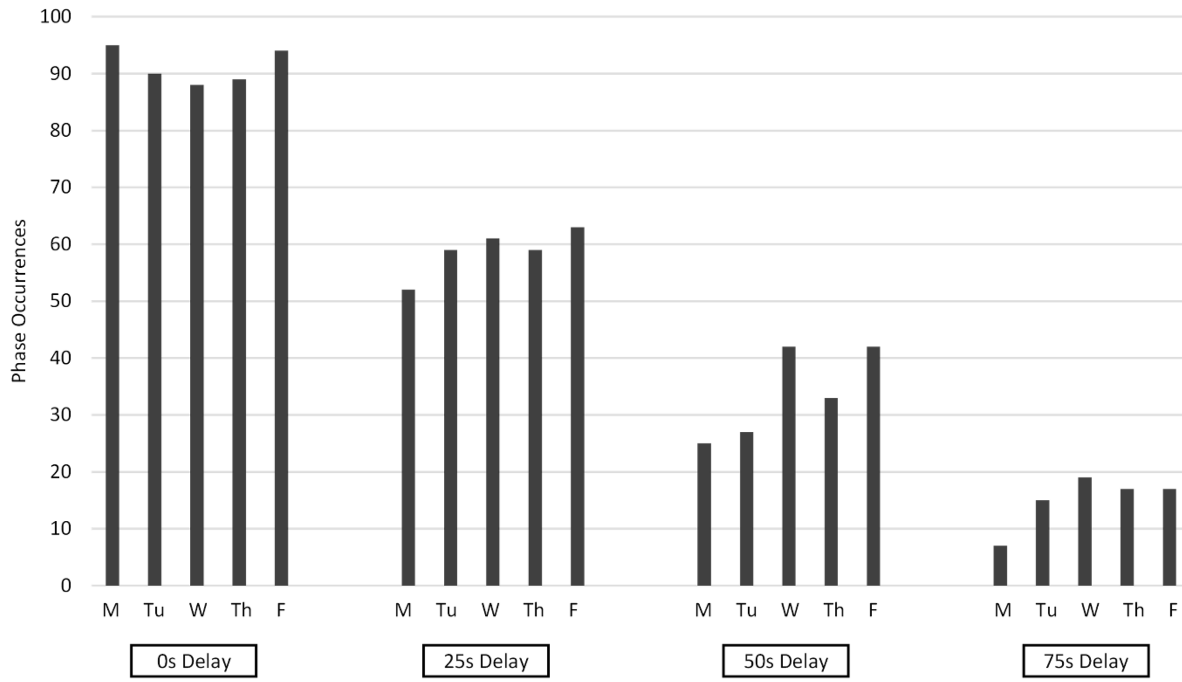


FIGURE 10 Total number of phase occurrences during the 15:00 - 18:00 study period on Phase 1 (westbound protected left) for 0s, 25s, 50s, and 75s detector delay parameters.

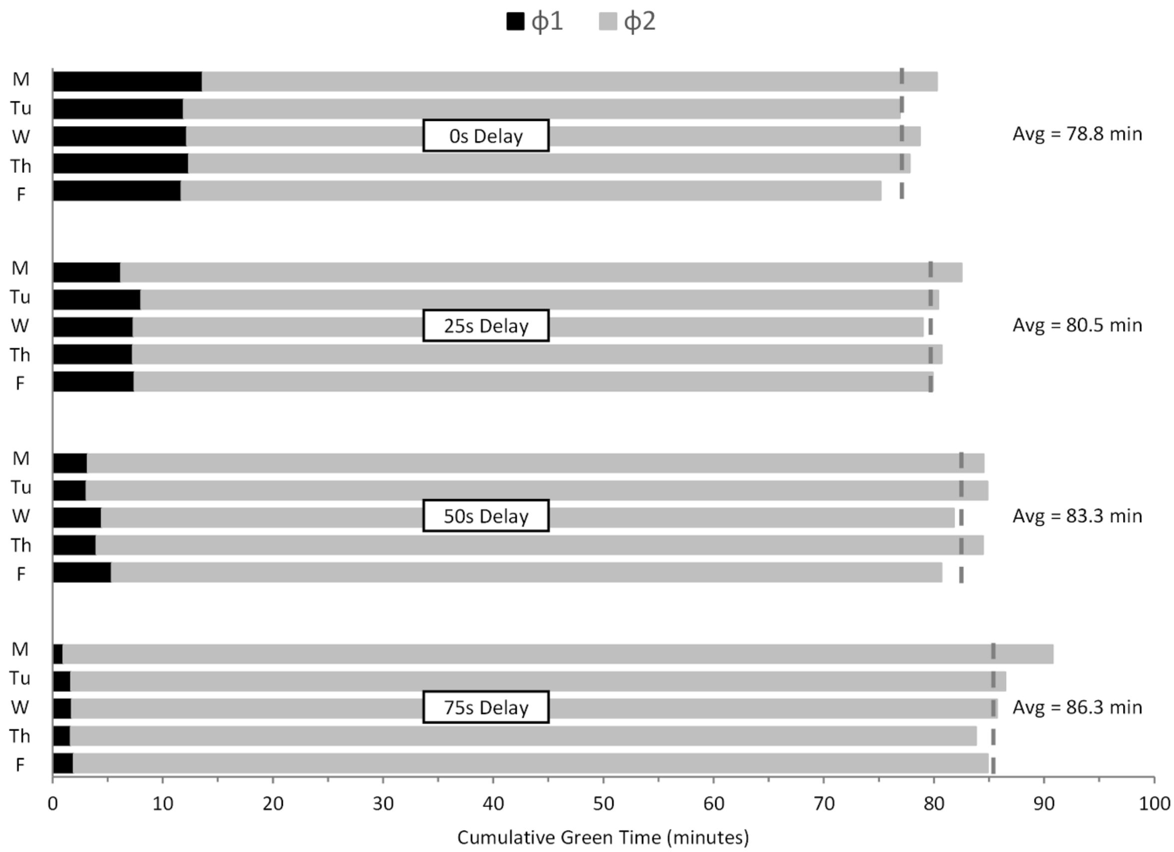


FIGURE 11 Cumulative green time of opposing Phase 1 (westbound protected left) and Phase 2 (eastbound through) split movements for 0s, 25s, 50s, and 75s detector delay parameters.