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INDIANA DEPARTMENT OF TRANSPORTATION
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Statewide Screening of Signalized Intersections for Capacity Improvements

Saumabha Gayen, Enrique D. Saldivar-Carranza, Rahul Suryakant Sakhare, Jairaj Desai, Jijo K. Mathew, Nathan Shellhamer, Taylor Ruble, Dan McCoy, Jack Gallagher, Darcy M. Bullock

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16. Abstract

Identification of congested traffic signals that require capital investment to increase capacity has historically been a time-consuming process. Signalized intersections with congestion were analyzed to see if they could be improved through retiming, and capital investment was only considered if retiming is deemed infeasible. Automated Traffic Signal Performance Measures (ATSPMs), and more recently, signal performance measures (SPMs) derived from connected vehicle (CV) trajectory data, have already been used to streamline the process of identifying signalized intersections that can be improved through retiming. However, to date, similar efforts have not been used to identify intersections that may benefit from capital investment. This study developed a CV-based methodology to assess whether signal retiming could potentially be feasible for a given signalized intersection using the split failure percentage (SF) SPM. For intersections where retiming is not feasible, a ranking metric of critical path split failing trajectory counts (SfnCP) was developed for prioritization by capacity improvement necessity. This metric was implemented statewide to over 2,300 INDOT-managed signalized intersections over a 17-month timespan to demonstrate the effectiveness, efficiency, and scalability of the proposed approach. Additionally, the utility of CV data for similar ranking of unsignalized intersections and road segments was also discussed. To aid INDOT engineers with rapid identification and prioritization of intersections that can be considered for capital investments, performance reports containing various attributes were proposed and generated.

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EXECUTIVE SUMMARY

Motivation

Traffic signal management involves two distinct approaches to increase capacity at congested signalized intersections: signal retiming and capital investment. While retiming is less expensive and can alleviate many signal congestion problems, it is not always feasible. When retiming is infeasible, capital investment is typically considered. The traditional process for identifying such intersections in need of capacity improvements often requires a substantial investment of resources for obtaining turning movement counts and implementing engineering analysis.

Automated traffic signal performance measures (ATSPMs) and more recently, signal performance measures (SPMs) derived from connected vehicle (CV) trajectory data have already been used to streamline the process of identifying signalized intersections that can be improved through retiming. However, to date, similar efforts have not been used to identify intersections that may benefit from capital investments to increase capacity. This presents a significant need and opportunity to extend existing methodologies and develop a more efficient and effective approach for identifying and ranking signalized intersections in need of capital investments.

Study

This study developed a CV-based methodology that assesses whether signal retiming is feasible for a given signalized intersection using the split failure percentage (SF) SPM. For those intersections for which retiming is not feasible, a ranking metric of critical path split failing trajectory counts (Sfn_{CP}) was developed to prioritize intersections by capacity improvement necessity. This ranking metric was implemented statewide to over 2,300 INDOT-managed signalized intersections over a 17-month timespan to demonstrate the effectiveness, efficiency, and scalability of the proposed approach.

Using this metric, the top ranked intersections for the entire state are presented. Field visits to selected intersections within the top ten validate the ranked lists. Additionally, the utility of CV data for ranking unsignalized intersections and road segments by capital investment necessity is also discussed, with these locations requiring different SPMs and ranking metrics for analysis. To aid INDOT engineers with rapid identification and prioritization of locations that can be considered for capital investments, performance reports containing various attributes were generated and shared with INDOT.

Recommendations

It is recommended that the proposed ranking metric for signalized intersections, as well as the signal performance reports presented, be used as a screening tool. Intersections that may benefit from capital investment in the form of infrastructure upgrades can be quickly identified from these reports. Intersections identified from these reports or corresponding ranked lists must be further evaluated for proposed budget and infrastructure upgrade strategies before capital investment decisions are made.

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LIST OF ABBREVIATIONS

AOG	Arrivals on Green
ATSPM	Automated Traffic Signal Performance Measure
CV	Connected Vehicle
DSB	Downstream Blockage
EBL	Eastbound Left
EBT	Eastbound Through
FFT	Free Flow Trajectory
FHWA	Federal Highway Administration
GPS	Global Positioning System
GTR	Green Time Reallocation
HCM	Highway Capacity Manual
INDOT	Indiana Department of Transportation
IQR	Interquartile Range
MPR	Market Penetration Rate
NBL	Northbound Left
NBT	Northbound Through
NEMA	National Electrical Manufacturing Association
PPD	Purdue Probe Diagram
RPD	Relative Performance Diagram
SBL	Southbound Left
SBT	Southbound Through
SF	Split Failure Percentage
SPM	Signal Performance Measure
TOD	Time-of-Day
WBL	Westbound Left
WBT	Westbound Through

1. PROJECT OVERVIEW

1.1 Introduction

The Federal Highway Administration (FHWA) states that a key objective of a traffic signal is to serve operational efficiency at a roadway intersection (Koonce et al., 2008). It is particularly important for agencies to identify when a traffic signal is failing to adequately achieve this objective and subsequently strategize on whether signal retiming or capital investment should be considered.

Signal retiming involves adjustments to green times for different movements at an intersection with the aim to serve current traffic conditions as best as possible. Within the last two decades, the use of Automated Traffic Signal Performance Measures (ATSPMs) has drastically improved the effectiveness of retiming (Day et al., 2020; FHWA, n.d.). More recently, the emergence of commercially available connected vehicle (CV) trajectory data provides the potential to scale the collection of traffic signal performance measures (SPMs) to aid practitioners with signal retiming decisions Saldivar-Carranza, Li, Mathew, et al., 2023; Waddell, Remias, Kirsch, & Young, 2020).

While retiming is widely applicable and can improve overall congestion for many poorly performing signals, it is not always effective or feasible. An adequate retiming approach relies on the premise that movements with excess capacity can reallocate green time to more congested movements (Denney et al., 2008; Saldivar-Carranza, Li, Platte, et al., 2023). However, there are cases where several movements at a signalized intersection are operating below desired performance thresholds. For these cases, the reallocation of green time may not produce significant improvements and can even worsen congestion for an already busy movement.

Capital investment to upgrade infrastructure may be required to achieve capacity improvements at these intersections (Chandler et al., 2013; FHWA, 2004). The traditional procedure for identifying such locations that need infrastructure upgrades takes a significant amount of agency time and resources, as detailed in Section 2.1. Techniques that utilize CV-based SPMs could produce a more efficient, systematic process for identifying these intersections.

1.2 Objective and Scope

The objective of this report is to propose a scalable low-labor CV-based methodology to identify congested signalized intersections where retiming is infeasible and capacity improvement is needed. Furthermore, a metric is proposed to prioritize these intersections in the context of a limited capital investment budget. This metric, in combination with various SPMs and related attributes, is provided as signal performance reports for use by INDOT engineers. Additionally, alternative identification and ranking methodologies for unsignalized intersections and road segments are explored. It is important to note that the methods, metrics, and performance reports discussed in this paper are suggested solely as a screening tool; further investigation and cost analysis is required before making any capital investment decisions at specific locations.

In this study, performance measures are derived from CV trajectory data for 2,309 signalized intersections (Figure 1.1). These intersections represent almost the full population of INDOT-managed traffic signals with four or fewer legs maintained as of November 2023. A standard four-legged intersection with eight relevant movements is shown in Figure 1.2. The movements are abbreviated as shown in Table 1.1.

1.3 Connected Vehicle Trajectory Data

For all intersections shown in Figure 1.1, CV trajectory data has been collected from a third-party provider for a span of 17 months, from January 2022 through May 2023. The full extent of unique CV trajectories analyzed is shown in Appendix A. The analyses presented in this report use weekday (Monday through Friday) data for the following three time-of-day (TOD) periods.

- AM Peak Period: 7:00 AM–9:00 AM
- Midday Period: 10:00 AM–2:00 PM
- PM Peak Period: 4:00 PM–6:00 PM

CV data consists of Global Positioning System (GPS) points obtained for individual passenger vehicles equipped with necessary communication and transmission technology. The CV data used in this study

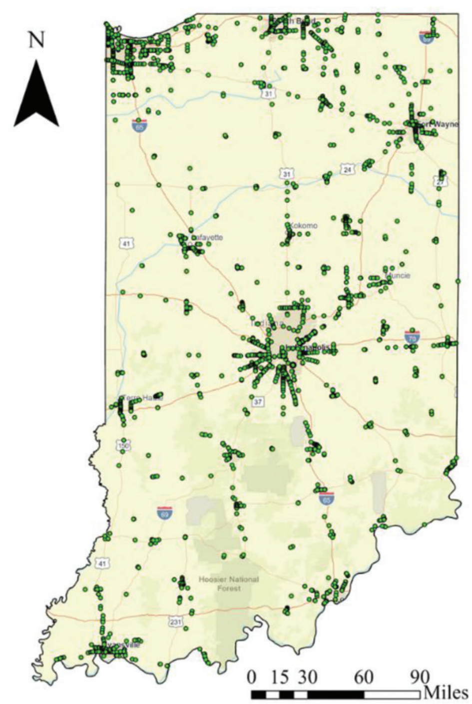


Figure 1.1 Analyzed INDOT-managed signalized intersections (n: 2,309).

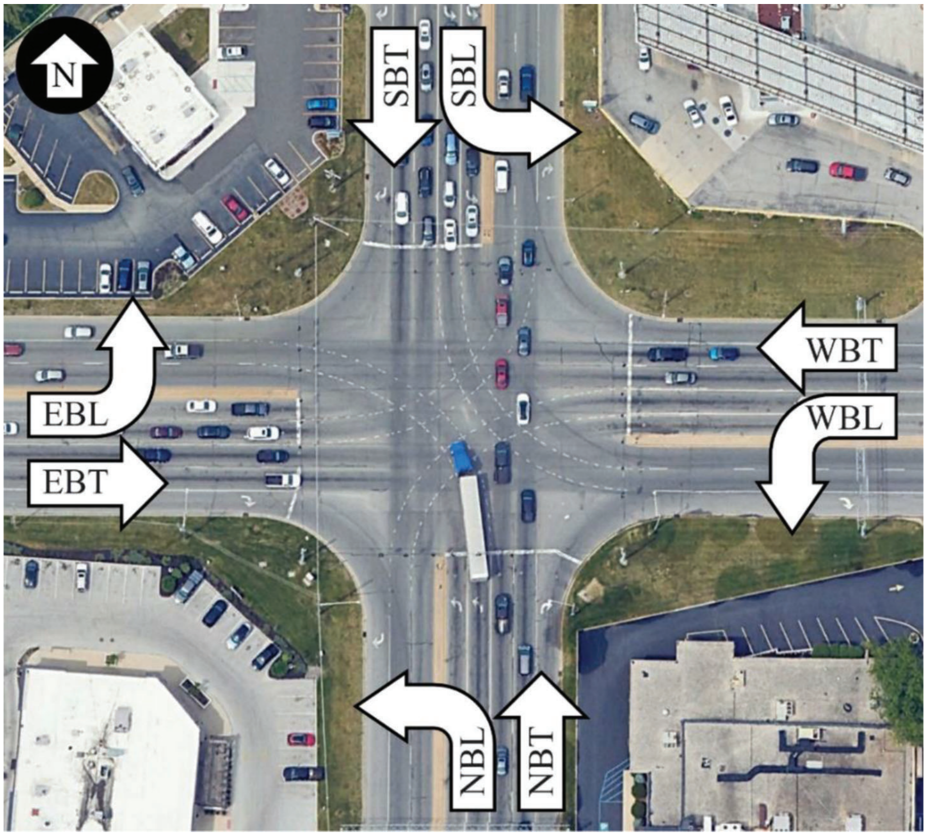


Figure 1.2 Standard four-legged signalized intersection with eight relevant movements.

TABLE 1.1
Abbreviations for relevant intersection movements

Movement	Through	Left
Northbound	NBT	NBL
Eastbound	EBT	EBL
Southbound	SBT	SBL
Westbound	WBT	WBL

consists of vehicle waypoints reported every three seconds with a spatial accuracy of three meters. These waypoints are provided with timestamp, latitude, longitude, speed, heading, and an anonymous unique journey identifier. For each unique journey, GPS points can be traced together and chronologically organized to obtain the vehicle's trajectory (Li et al., 2019; Saldivar-Carranza, Li, Mathew, et al., 2023).

An important consideration for CV trajectory data is its market penetration rate (MPR). CV MPR is defined as the ratio of sampled CVs to all vehicles on the road in a given area. This ratio indicates the representativeness of the dataset, as well as its level of confidence in estimating real-world conditions. Based on multiple studies, the current CV MPR for Indiana is estimated at around 5%, a level which can provide reliable real-world insights at traffic signal locations when data is aggregated over sufficiently large intervals (Hunter, 2022; Hunter et al., 2021; Sakhare, Hunter, et al., 2022; Wong et al., 2019).

1.4 Research Results

The aforementioned identification and ranking procedures have been used to obtain ten top-ranked capital investment candidate intersections for two analysis periods, as shown later in Chapter 6. Additional supporting analyses and results are presented in the appendices. Appendix A discusses the extent of all intersections and unique CV trajectories analyzed for this study. Appendix B presents findings from field visits to three top-ranked intersections, validating the rankings obtained from the employed methodology.

2. LITERATURE REVIEW

This chapter states the traditional process for identifying intersections needing capital investment and details existing research on using SPMs to potentially identify signal retiming opportunities. The recommended SPM for congestion screening is then suggested, and intersection infrastructure upgrade techniques are discussed.

2.1 Traditional Signal Capital Investment Opportunity Identification Process

Traditionally, a signalized intersection needing increased capacity through capital investments has been identified only after extensive retiming efforts are explored (Denney et al., 2009; FHWA, n.d.; Koonce et al., 2008). The process of identifying such a signal is as follows.

1. A triggering event occurs. This event is either a user complaint, or an intersection reaching its scheduled date for retiming, which is typically every 3–5 years.
2. For this intersection, field data collection is conducted to obtain traffic volumes and turning movement counts.
3. This data is then entered into a signal optimization model.
4. The model attempts to implement retiming to improve traffic flow at the intersection.
5. If the model fails to achieve adequate performance through retiming, the intersection is then considered for capital investments to upgrade infrastructure.

This process (Figure 2.1) is labor-intensive and reactive in nature.

2.1.1 Developments in Signal Retiming Opportunity Identification

Widespread adoption of ATSPMs, and more recently SPMs derived from CV trajectory data, have removed the need for a triggering event to begin the process of intersection assessment, allowing for quicker implementation of timing adjustments (Day et al., 2015). Several studies have used performance measures from either source of data to identify retiming opportunities and suggest possible retiming schemes.

Smaglik et al. (2011) has proposed ATSPM-based metrics to quantify oversaturation, while Dobrota et al. has developed measures for capacity utilization, both of which can be used to assess if an intersection should be considered for retiming (Dobrota et al., 2023; Smaglik et al., 2011). Day et al. has shown that ATSPMs can also be used to measure performance and guide maintenance and retiming operations at the corridor level (Day & Bullock, 2020; Day et al., 2018, 2021). ATSPMs have further been used to develop retiming schemes and rank intersections by retiming need and opportunity (Dunn et al., 2019; Guadamuz et al., 2022; Li et al., 2017).

CV data, sometimes referred as probe data, has been used by Zhao et al. to estimate queue lengths at intersections, and by Waddell et al. to quantify signalized corridor delay, both metrics which can potentially screen intersections needing retiming (Waddell et al., 2020; Zhao et al., 2019). Day et al. has used trajectory data to optimize signal timing offsets along a corridor (Day et al., 2017). Recent studies have also used CV trajectory data to identify and rank signals with retiming opportunity (Saldivar-Carranza, Li, Platte, et al., 2023; Winfrey et al., 2023).

2.1.2 Recommended Performance Measure for Congestion Screening

Various capacity and progression-oriented performance measures have been developed from high-resolution controller data (Day et al., 2014). Similar and new performance measures from CV trajectory data have also been derived (Saldivar-Carranza, Li, Mathew, Hunter, et al., 2021; Saldivar-Carranza, 2021; Saldivar-Carranza, Li, Mathew, et al., 2023). Among these performance measures, split failures, which indicate vehicles having to wait more than one cycle length to cross an intersection, provide the best indication that an intersection movement is congested and operates above capacity. Split failure occurrences can be predicted from both high-resolution controller events and CV trajectories, but studies have shown that such predictions are more reliable, albeit more conservative, when obtained from CV trajectory data (Emtenan & Day, 2020; Gayen et al., 2023; Saldivar-Carranza et al., 2024).

Furthermore, CV trajectory-based estimations of vehicle split failure percentage have already been used to successfully identify signal retiming opportunities by Saldivar-Carranza et al. (Saldivar-Carranza, Li, Platte, et al., 2023). For this reason, it remains the recommended performance measure for identifying intersections with congestion and capacity issues, and it is the fundamental SPM used for traffic signal capital investment analysis in this study.

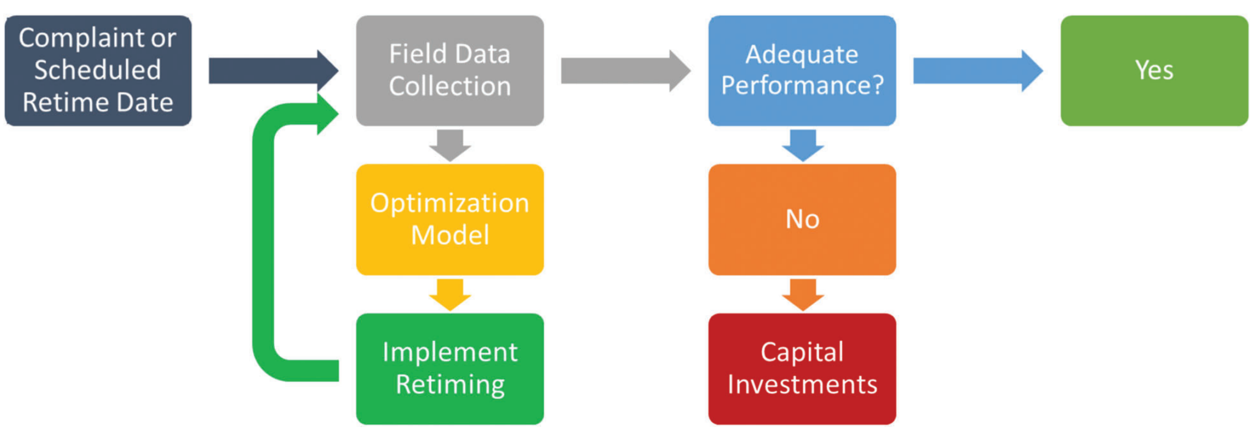


Figure 2.1 Traditional process for signal retiming and capital investment implementation.

2.2 Signalized Intersection Infrastructure Upgrade Techniques

For intersections selected to undergo a capital investment project to increase capacity, the most common infrastructure upgrade technique involves adding new lanes (Koonce et al., 2008). This can be the addition of through lanes or specific turn lanes, or even additional turn lane storage bays. Many historic studies have observed notable capacity increases caused by adding through lanes at an intersection approach (Dai et al., 1987; Musci & Khan, 2003; Zhao et al., 2016). Newer studies have also observed capacity improvement from adding left-turn or right-turn lanes, or even simply increasing the storage space provided for these exclusive turn lanes (Liu et al., 2019; Ma et al., 2017; Rahmani et al., 2023).

Another option to improve capacity or reduce congestion at an intersection is reconfiguration to an alternative design. Such designs include the displaced left-turn, median U-turn, restricted crossing U-turn, and quadrant roadway intersections, which can reduce conflict points and allow greater green time for congested movement groups. (Hughes et al., 2010). Several studies have examined the operational and safety improvements achieved by reconfiguring a traditional intersection to adopt one of these more innovative designs (Abdelrahman et al., 2020; El Esawey & Sayed, 2011; Mishra & Pulugurtha, 2022).

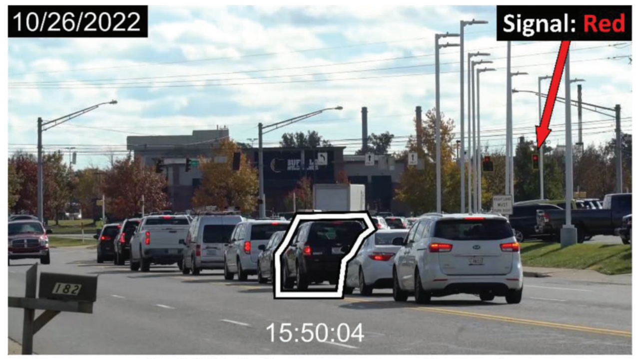
If it is predicted that demand at a signalized location cannot be adequately serviced by additional lanes, storage space, or even alternative configurations, more costly infrastructure upgrades may be necessary. This could include construction of alternate routes to divert traffic from a congested intersection, or even integration of public transportation modes with specialized upstream signals, with signal priority given to these modes. The FHWA has documented several examples of congestion reduction from constructing alternate routes (Dunn Engineering Associates, 2006). Other studies have observed capacity and congestion improvements from transit-focused upstream pre-signals or dedicated bus-only lanes at intersections (Hao et al., 2016; Xuan et al., 2012).

3. TRAJECTORY-BASED SPLIT FAILURE ESTIMATIONS

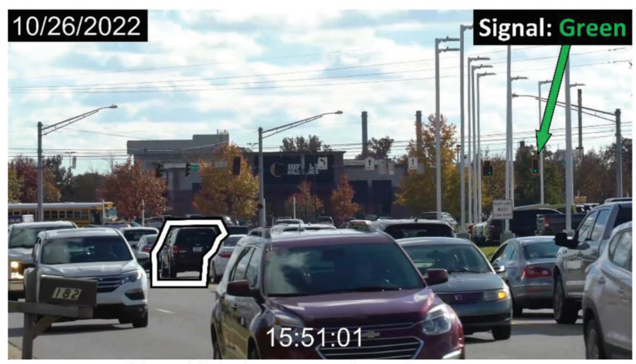
This chapter describes a split failure event. Subsequently, split failure event identification and split failure percentage estimation from CV trajectory data is explained.

A split failure event occurs when the allocated green time for a signal phase is insufficient to fully discharge all of the vehicles waiting in the queue just before the signal turns green (FHWA, n.d.; National Academies of Sciences, Engineering, & Medicine, 2020). This means that a vehicle must wait longer than the entire signal cycle length to cross the intersection. In doing so, it will have to make two or more stops on red. An example of this is shown in Figure 3.1. The contoured vehicle, a black SUV, is shown to be stopped on red in Figure 3.1a, advancing forward on green in Figure 3.1b, and then again stopped on red just ahead of the stop-bar in Figure 3.1c. Thus, this black SUV and the two vehicles behind it exhibit split failure since they all have made two separate stops on red.

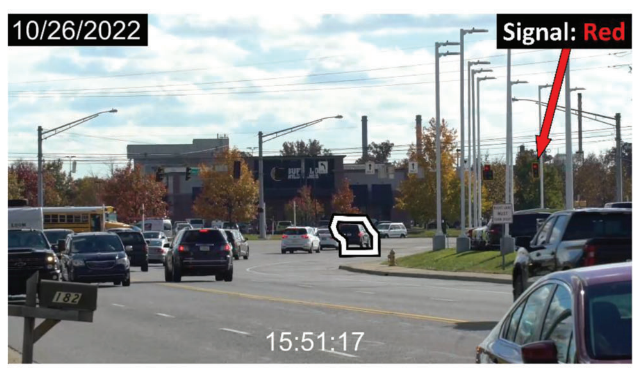
From the raw CV data used in this study, all waypoints near intersections are obtained, unique vehicle trajectories are reconstructed, and waypoint headings are used to identify the turning movement executed by each vehicle (Saldivar-Carranza, Li, & Bullock, 2021; Saldivar-Carranza, Li, Mathew, et al., 2023). A Purdue Probe Diagram (PPD) can then be generated for each relevant movement at an intersection, where each



(a) Vehicle in queue stopped on red



(b) Vehicle in queue advancing on green



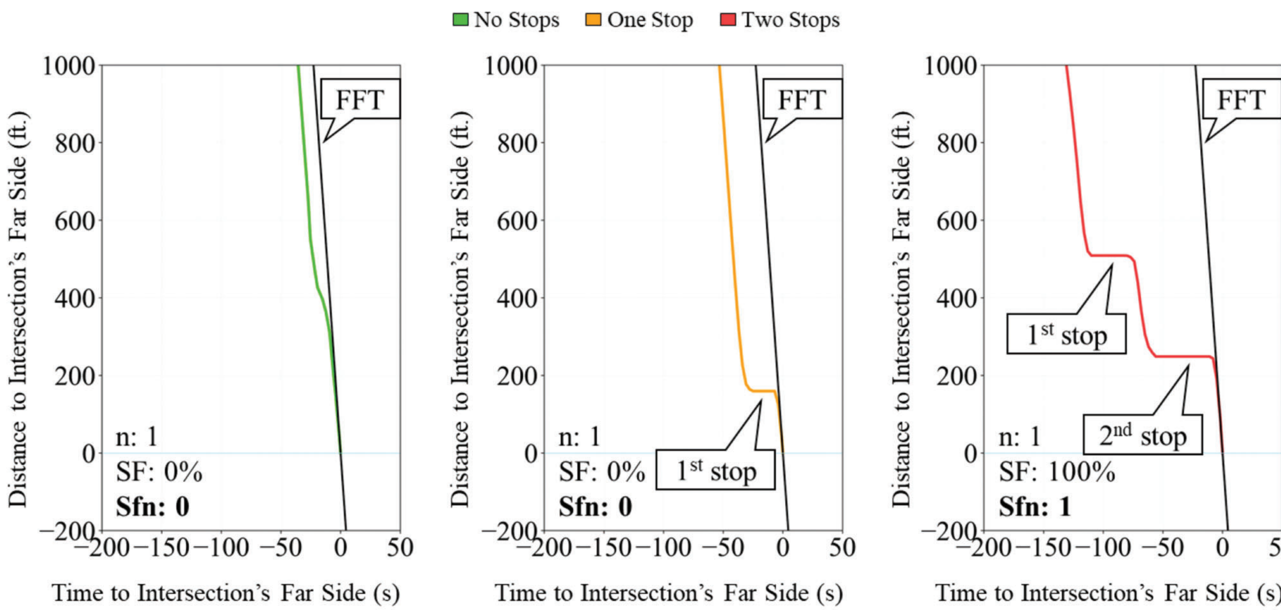
(c) Vehicle in queue stopped for a second time on red

Figure 3.1 Occurrence of a SF event at a signalized intersection movement.

unique trajectory is plotted on a time-space diagram relative to the intersection's far side stop-bar and color-coded based on the number of stops (Saldivar-Carranza, Li, Mathew, et al., 2023).

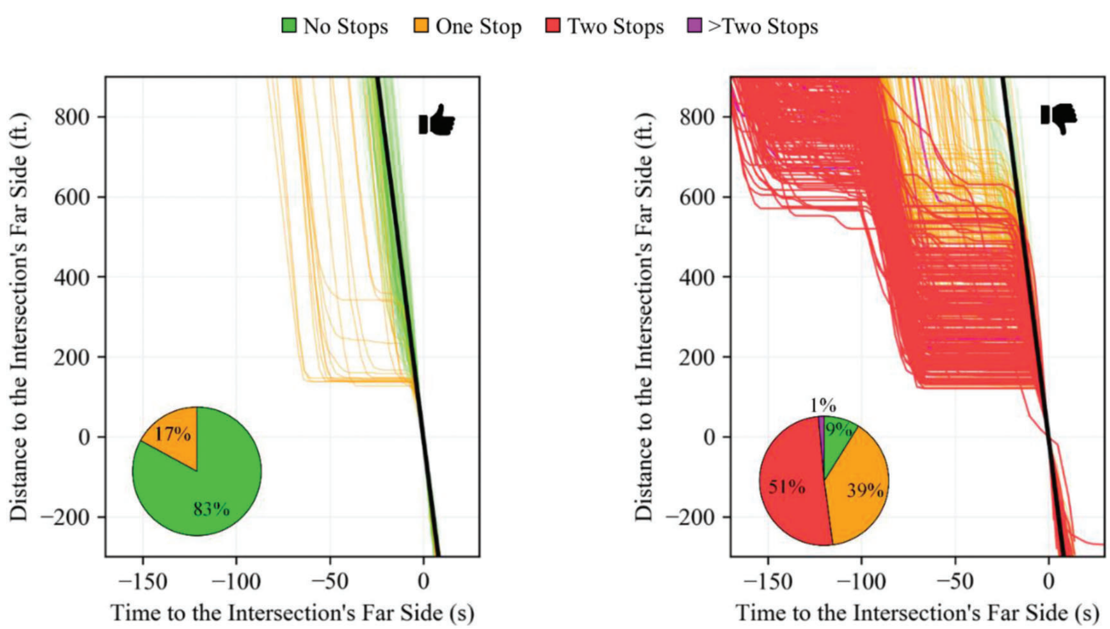
On a PPD, a split failure event is identified by a trajectory that stops at least twice, color-coded in red or purple (Saldivar-Carranza, Li, Mathew, Hunter, et al., 2021). Figure 3.2 shows three examples of individual trajectories on a PPD: a trajectory that arrives on green and does not stop (Figure 3.2a), a trajectory that arrives on red and stops once (Figure 3.2b), and a trajectory that arrives on red and stops twice (Figure 3.2c), exhibiting a split failure event. The black line represents the free flow trajectory (FFT) of the movement, approximated as the approach speed limit (Saldivar-Carranza, Li, Mathew, Hunter, et al., 2021).

To assess overall split failure percentage (SF) for a movement over a specific time interval, all CV



(a) No stops (b) One stop (c) Two stops

Figure 3.2 PPDs of individual vehicle trajectories with different stop counts.



(a) Movement with 0% SF (b) Movement with 52% SF

Figure 3.3 PPDs with aggregated vehicle trajectories.

trajectories that executed that movement within that time interval can be aggregated onto a single PPD. Figure 3.3 shows two examples of aggregated CV trajectories on a PPD for a sample intersection movement. Figure 3.3a shows an uncongested movement with 0% SF, while Figure 3.3b shows a congested movement with 52% SF (51% of trajectories making two stops and 1% making more than two stops). For all PPDs in this thesis, performance measures are notated as follows.

- n: sampled CV trajectory count.
- SF: percentage of sampled trajectories identified as split failing.
- Sfn: number of sampled trajectories identified as split failing.

The percentage of sampled trajectories that exhibit split failure, SF, is obtained by Equation 3.1 (Saldivar-Carranza, Li, Mathew, et al., 2023):

$$SF = 100 * \frac{1}{n}\sum_{i=1}^{n}\varphi(\tau_i) \qquad \text{(Eq. 3.1)}$$

where τ_i is the *i-th* trajectory out of n sampled trajectories and φ is a function that indicates whether the evaluated trajectory exhibits two or more stops, as seen by Equation 3.2 (Saldivar-Carranza, Li, Mathew, et al., 2023):

$$\varphi(\tau_i) = \begin{cases} 0, \text{ if } \tau_i \text{ experiences one or fewer stops} \\ 1, \text{ if } \tau_i \text{ experiences two or more stops} \end{cases} \qquad \text{(Eq. 3.2)}$$

If SF is desired as a ratio instead of a percentage, a value obtained from Equation 3.1 can be divided by 100. The number of sampled trajectories that exhibit split failure, Sfn, is given by Equation 3.3.

$$Sfn = \sum_{i=1}^{n}\varphi(\tau_i) \qquad \text{(Eq. 3.3)}$$

4. SIGNAL RETIMING FEASIBILITY

This chapter explains how signal retiming feasibility is determined using relative movement SF values. Two existing methods for signal retiming are discussed and extended to propose a new method to identify if a signal has no opportunity for improvements through retiming.

4.1 Signals with Retiming Opportunities

A technique to determine potential signal retiming opportunities with trajectory-based SF estimations is presented in (Saldivar-Carranza, Li, Platte, et al., 2023). This methodology relies on the standard National Electrical Manufacturing Association (NEMA) signal phasing dual-barrier, dual-ring diagram (Koonce et al., 2008) (Figure 4.1).

Among the eight relevant movements at an intersection, the movement with the highest SF value is denoted as the critical movement, which could benefit from green time reallocation (GTR) (i.e., the practice of transferring green time from donor movements to the critical movement) (Saldivar-Carranza, Li, Platte, et al., 2023). For standard NEMA signal phasing, GTR is governed by two rules (Koonce et al., 2008; Saldivar-Carranza, Li, Platte, et al., 2023).

- Green time given to the critical movement must be taken from another movement in its own ring, as these green times will sum to the total available green time in one cycle.
- The sum of green time for an adjacent pair of movements in a barrier must be consistent with that of the other pair within the same barrier.

Based on these rules, GTR to the critical movement can be provided from a conflicting movement or from the opposite barrier.

The movement adjacent to the critical movement in the same barrier is defined as the conflicting movement. When the conflicting (donor) movement is not congested, green time can potentially be reallocated from this movement to the congested critical movement. An example of this retiming scheme with accompanying PPDs for an intersection is shown in Figure 4.2, with the blue arrow representing GTR between movements (Saldivar-Carranza, Li, Platte, et al., 2023).

The movement with maximum SF value from the barrier not containing the critical movement is defined as the opposite barrier maximum movement. If this movement is not significantly congested, green time could potentially be reallocated from a donor movement in this barrier and in the same ring as the critical movement. Additionally, the same reallocation of green time must occur on the opposite ring. An example of this retiming scheme with accompanying PPDs for an intersection is shown in Figure 4.3 (Saldivar-Carranza, Li, Platte, et al., 2023).

The blue trajectories to the bottom-right of the origin on the PPDs represent downstream blockage (DSB) events. DSB occurs when queues at an adjacent intersection significantly affect the progression of vehicles upon exiting the intersection of interest. Trajectories are defined to exhibit a DSB event if they have at least 10 seconds of delay compared to the free flow trajectory after they exit the intersection (Saldivar-Carranza et al., 2021; Saldivar-Carranza, 2021; Saldivar-Carranza, Li, Mathew, et al., 2023).

DSB is an important SPM depicted on PPDs because it can suggest whether a signal congestion problem is independent or dependent on adjacent intersections. High DSB for certain movements at an intersection could indicate congestion problems along an entire corridor segment.

4.2 Signals without Retiming Opportunities

Effective signal retiming is only possible when certain movements are not congested. This ensures that operations can be improved for the critical movement

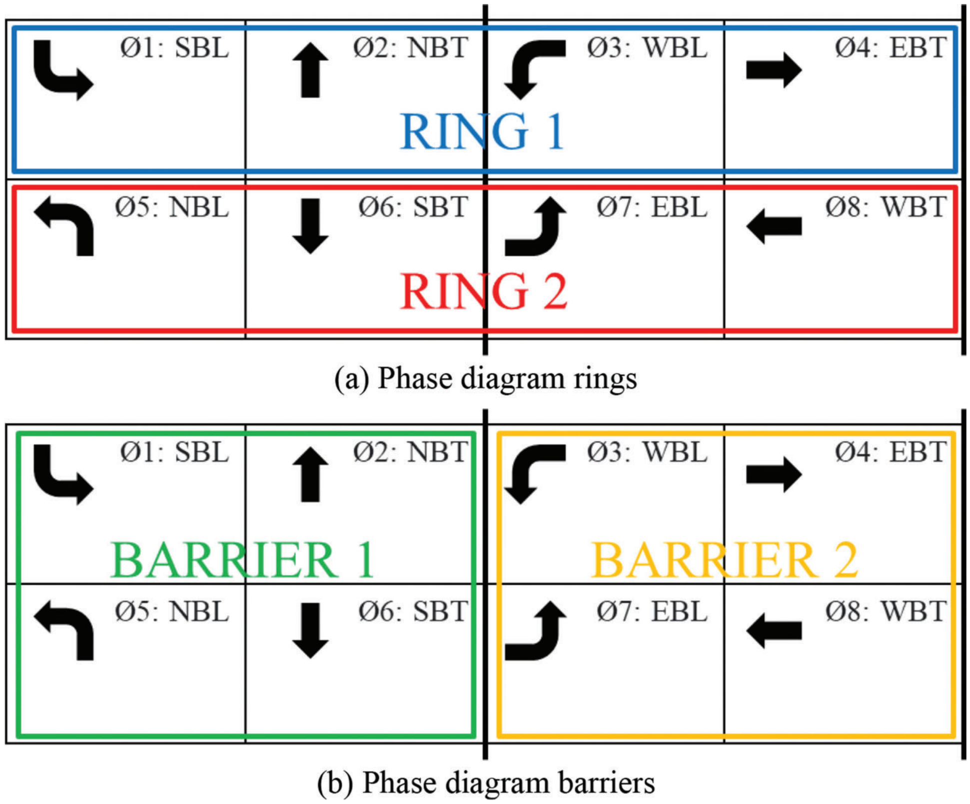


Figure 4.1 Standard NEMA phase diagram with ring and barrier separation.

without negatively affecting the donor movements (Saldivar-Carranza, Li, Platte, et al., 2023). However, some signals have multiple congested movements such that signal retiming would be ineffective. A hypothetical example of such a signal is shown in Figure 4.4, where four of the eight movements are congested. For this example, the NBT critical movement (Ø2) cannot receive any green time from the SBL conflicting movement (Ø1), as this movement is also congested. The critical movement also cannot receive any green time from the WBL or EBT movements (Ø3 or Ø4), as any green time taken from these movements must also be taken from either the EBL or WBT movements (Ø7 or Ø8), which are also congested. Thus, GTR, by conflicting or opposite barrier movements, is rendered ineffective.

The congested movements depicted in Figure 4.4 represent a critical path of movements. A critical path on a standard NEMA phase diagram of a four-legged bidirectional intersection is a group of four movements which include (TRB, 1985, 2010, 2016).

- One pair of adjacent movements from the same ring within the left-side barrier.
- Another pair of adjacent movements from the same ring within the right-side barrier.

It is proposed that the identification of a critical path of congested movements should be the approach to identify intersections with no retiming opportunity.

The critical path idea has been developed previously in the Highway Capacity Manual (HCM) and emphasized by Day et al. (Day et al., 2013, 2014; TRB, 1985). Checking for the existence of a critical path of congested movements can filter out cases where retiming alone could reduce overall intersection SF.

The four possible critical paths for a standard bidirectional four-legged intersection are shown in red in Figure 4.5 (Day et al., 2013). In order to establish whether a movement has sufficient CV trajectory samples to be considered in critical path analysis, a trajectory count threshold of 30 is proposed. For movements with at least 30 sampled CV trajectories, a SF threshold of 1% is used to determine whether that movement is congested. These proposed thresholds for trajectory sample size and SF are only recommendations and can be modified if desired.

If congestion (i.e., SF $\geq$ 1%) is observed on all four movements of a possible critical path, then it is established that a congested critical path exists. Intersections with existence of a critical path of congested movements for a given analysis period can then be flagged as a candidate for capacity improvement by means of a capital investment project.

The utility of this critical path technique is evident when analyzing the two intersections for which ring diagram PPDs of the same analysis period are provided in Figure 4.6. Both intersections are highly congested and may appear to have no retiming opportunity. However, critical path analysis reveals that the

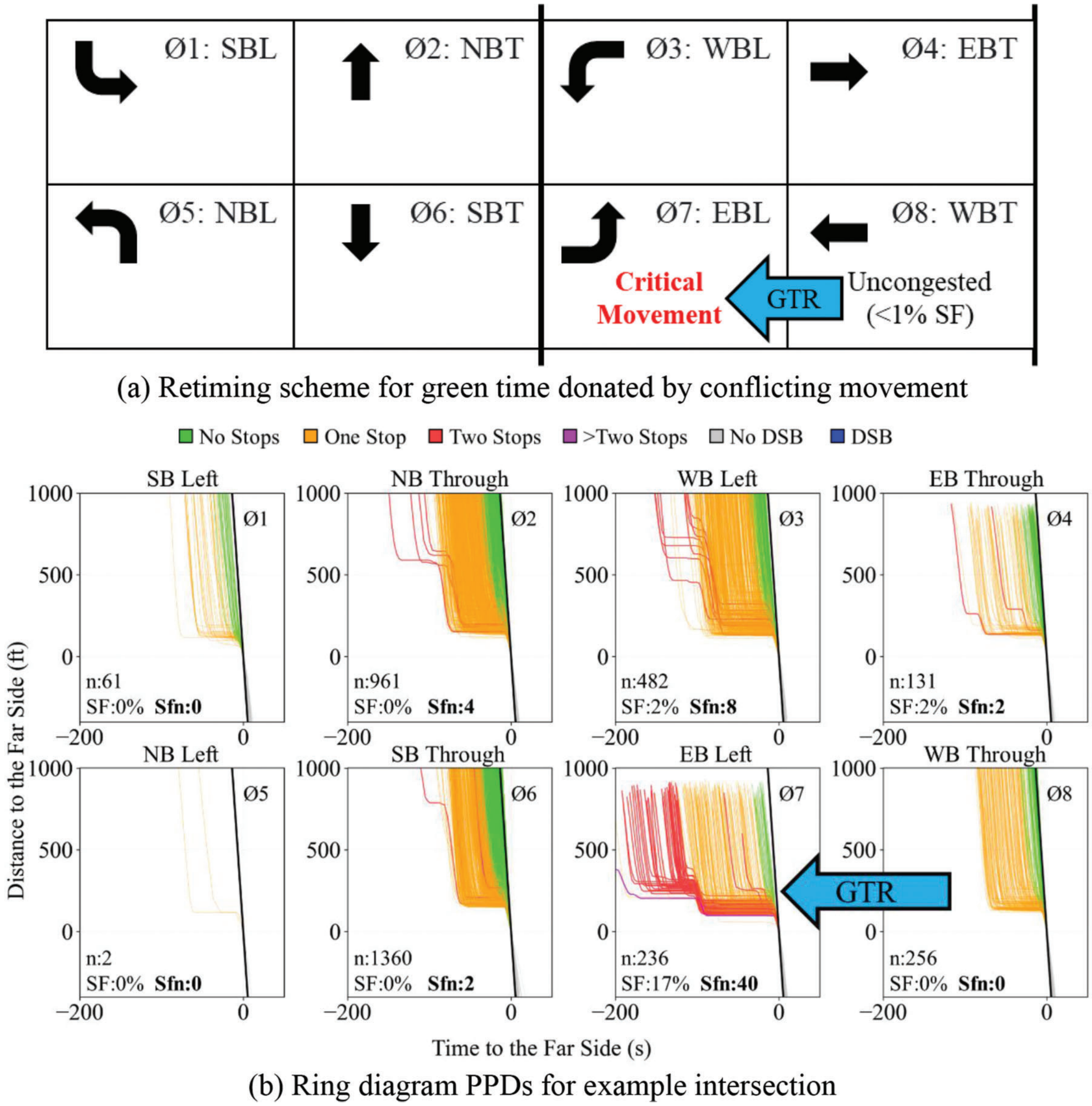


Figure 4.2 Example of conflicting movement retiming opportunity.

intersection in Figure 4.6a has a critical path of congested movements (Path 5678), while the intersection in Figure 4.6b does not have congestion along a critical path, since the NBT and NBL movements (Ø2 and Ø5) are uncongested.

A green thumbs up indicates a movement with SF less than 1%, a red thumbs down indicates a movement with SF greater than or equal to 1%, and a white thumbs down indicates a movement that does not meet the established trajectory count threshold. Thus, these two intersections can be differentiated; the intersection in Figure 4.6a can only be improved with infrastructure upgrades, while the intersection in Figure 4.6b can be addressed with retiming.

It is important to note that this critical path technique assumes that intersections are independent, isolated locations. However, when agencies consider GTR or infrastructure upgrades for an intersection, they must account for DSB for specific movements. Additional green time given to a movement already experiencing high DSB could worsen DSB for that movement and even exacerbate congestion for movements at nearby intersections. High DSB could suggest the need for infrastructure upgrades along an entire corridor of signalized intersections. Addressing capital investment needs along corridor segments is discussed separately in Section 7.2.

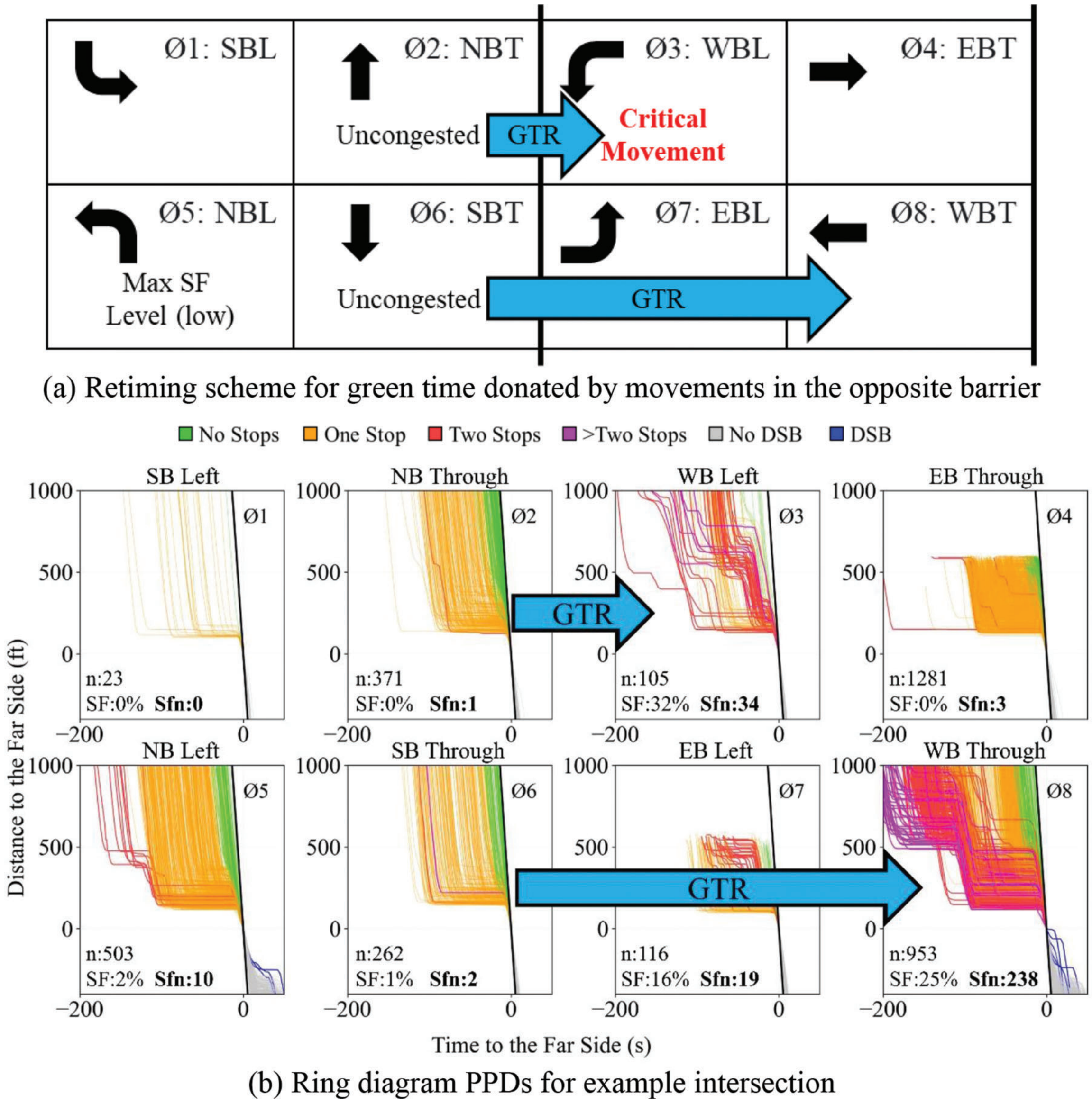


Figure 4.3 Example of opposite barrier maximum movement retiming opportunity.

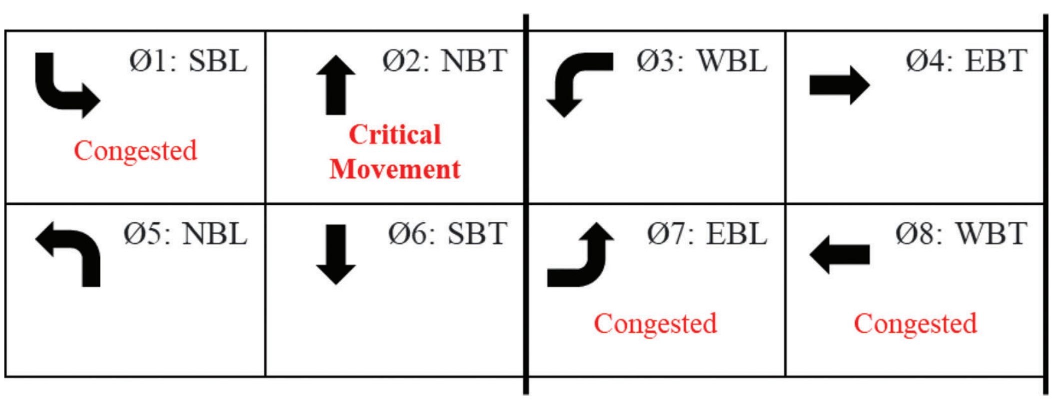


Figure 4.4 Phase diagram for signal with no retiming opportunity.

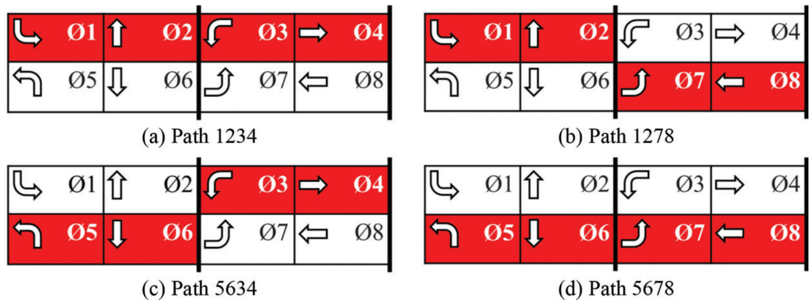


Figure 4.5 Possible critical paths for standard eight-phase signal controller sequence.

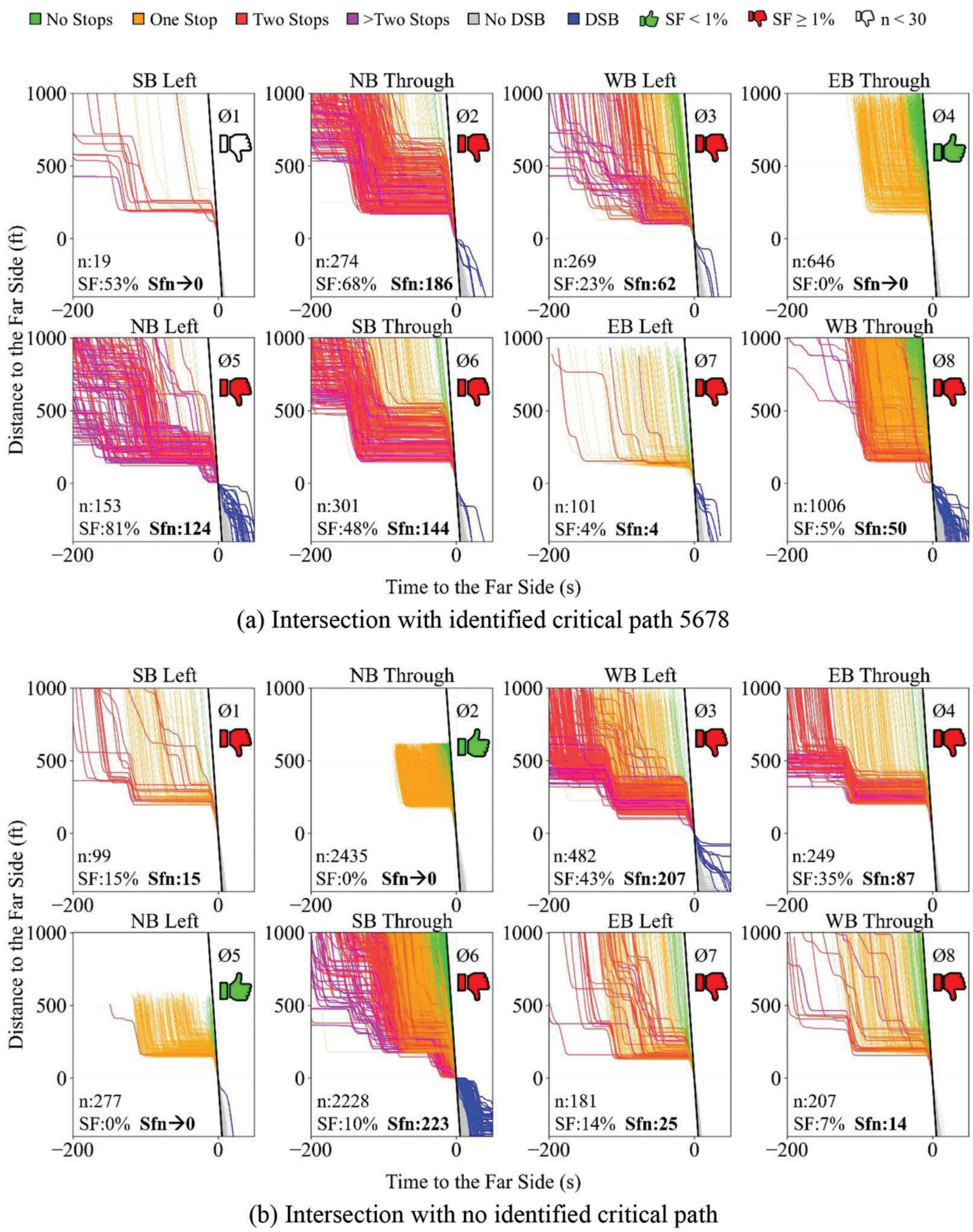


Figure 4.6 Ring diagram PPDs for two intersections with different critical path identification.

5. CAPITAL INVESTMENT NECESSITY RANKING

This chapter develops a ranking metric for intersections without retiming opportunity that can be evaluated for any individual analysis period. Furthermore, statewide signal performance reports, which contain various attributes, including this ranking metric, are discussed. Finally, aggregation of this metric across the entire study timespan is explained, as this can produce ordered lists of intersections ranked by capital investment necessity.

5.1 Ranking Metric Evaluation

Originally, a ranking metric called *crit_conf_opp_sum*- (the sum of SF for the critical, conflicting, and opposite barrier maximum movements) was proposed as a ranking metric for capital investment opportunities. However, this metric was discarded for two reasons: a high value for this metric does not necessarily indicate that retiming is infeasible, and this metric does not factor in trajectory volumes for different movements. For these reasons, a metric that considers movement volumes and retiming feasibility (using critical path analysis) was proposed as a better alternative.

If a congested critical path exists for a given intersection and analysis period, one specific path is selected, and a ranking metric for this selected path is evaluated. This metric is the sum of split failing trajectory counts (Sfn) on the selected critical path, and it is denoted as $\mathrm{Sfn_{CP}}$. After obtaining n, SF, and Sfn values for all relevant movements at an intersection, critical path selection (using $n \geq 30$ and $SF \geq 1\%$ thresholds) and $\mathrm{Sfn_{CP}}$ values are algorithmically estimated for different scenarios as follows.

- If a critical path with congestion does not exist, no path is selected, and the associated $\mathrm{Sfn_{CP}}$ is set to 0.
- If exactly one congested critical path exists, this path is selected, and the sum of Sfn for all movements on this path is recorded as the associated $\mathrm{Sfn_{CP}}$ value.
- If more than one congested critical path exists, the path with the greatest Sfn sum is selected, and this corresponding sum is recorded as the associated $\mathrm{Sfn_{CP}}$ value.

For an intersection with existence of congestion on all four possible critical paths for a given analysis period, $\mathrm{Sfn_{CP}}$ evaluation can be explained by Equation 5.1, where each $Sfn_{\text{Ø}i}$ corresponds to the number of split failing trajectories for the *i-th* phase with *i* being any relevant integer value between 1 and 8. The phases (or corresponding movements) that contribute to this derived sum make up the selected critical path.

$$Sfn_{CP} = \max\{(Sfn_{\text{Ø}1} + Sfn_{\text{Ø}2} + Sfn_{\text{Ø}5} + Sfn_{\text{Ø}6})\} + \max\{(Sfn_{\text{Ø}3} + Sfn_{\text{Ø}4},\ Sfn_{\text{Ø}7} + Sfn_{\text{Ø}8})\} \quad \text{(Eq. 5.1)}$$

An example of such an intersection with congestion on all four possible critical paths is shown in Figure 5.1a. In this case, the critical path selection algorithm identifies Path 5634 as having the largest Sfn sum, 760, which is recorded as the associated $\mathrm{Sfn_{CP}}$. A graphical depiction of critical path selection and $\mathrm{Sfn_{CP}}$ evaluation for this intersection is shown in Figure 5.1b.

5.2 Statewide Reporting of Performance Challenges

The $\mathrm{Sfn_{CP}}$ value is obtained for all intersections by month by TOD period entries that have CV trajectory data for at least two movements. For the 2,309 intersections by 17 months by three TOD periods, 108,487 of the possible 117,759 entry combinations have data for at least two movements. For each entry, 93 attributes, including the obtained $\mathrm{Sfn_{CP}}$ value, are recorded and tabulated as performance reports to be used by INDOT engineers. These attributes are summarized as follows.

- *5 Key Attributes:* These attributes together make up each unique entry combination and consist of the internal intersection ID, month, year, TOD lower boundary, and TOD upper boundary of the analysis period.
- *4 Location Identifiers:* These attributes consist of the intersection name, latitude, longitude, and INDOT district in which it is located.
- *10 RPD-based Statistics*: These attributes are performance measures and indicators derived from relative performance diagrams (RPDs) that are used for signal retiming identification (Saldivar-Carranza, Li, Mathew, et al., 2023; Saldivar-Carranza, Li, Platte, et al., 2023).
- *39 Detailed SPMs*: These attributes are intersection and movement level performance measures, including SF, control delay, DSB, and arrivals on green (AOG).
- *17 Trajectory Counts:* These attributes consist of the sampled CV trajectory count for the entire intersection and its eight possible movements, as well as the split failing trajectory count for each movement.
- *17 Critical Path Attributes:* These are all the attributes involved in the algorithm used to determine critical path existence and selection, except for the ranking attribute.
- *1 Capacity Improvement Ranking Attribute:* This is the associated $\mathrm{Sfn_{CP}}$ value for each unique entry, named as *CP_Sfn* in the performance reports.

To rank the entire statewide list of INDOT-managed intersections by capacity improvement necessity, the $\mathrm{Sfn_{CP}}$ value must be aggregated across all 51 possible analysis periods (17 months by 3 TOD periods) for each intersection. This is done with pivot tables that group each unique entry by internal intersection ID. Doing so produces a ranked list of intersections with capacity improvement necessity across the entire 17-month span of January 2022 through May 2023.

Filtering can be used to produce ranked lists for any subset of the 51 total analysis periods. Months can be filtered to identify capacity improvement candidates within specific timespans, such as the latest 5 months from January through May 2023. This time period was considered in isolation to obtain rankings that do not factor in 2022 data and only account for the most recent 5 months of data availability. Similarly, TOD periods can be filtered if only AM peak, midday, or PM

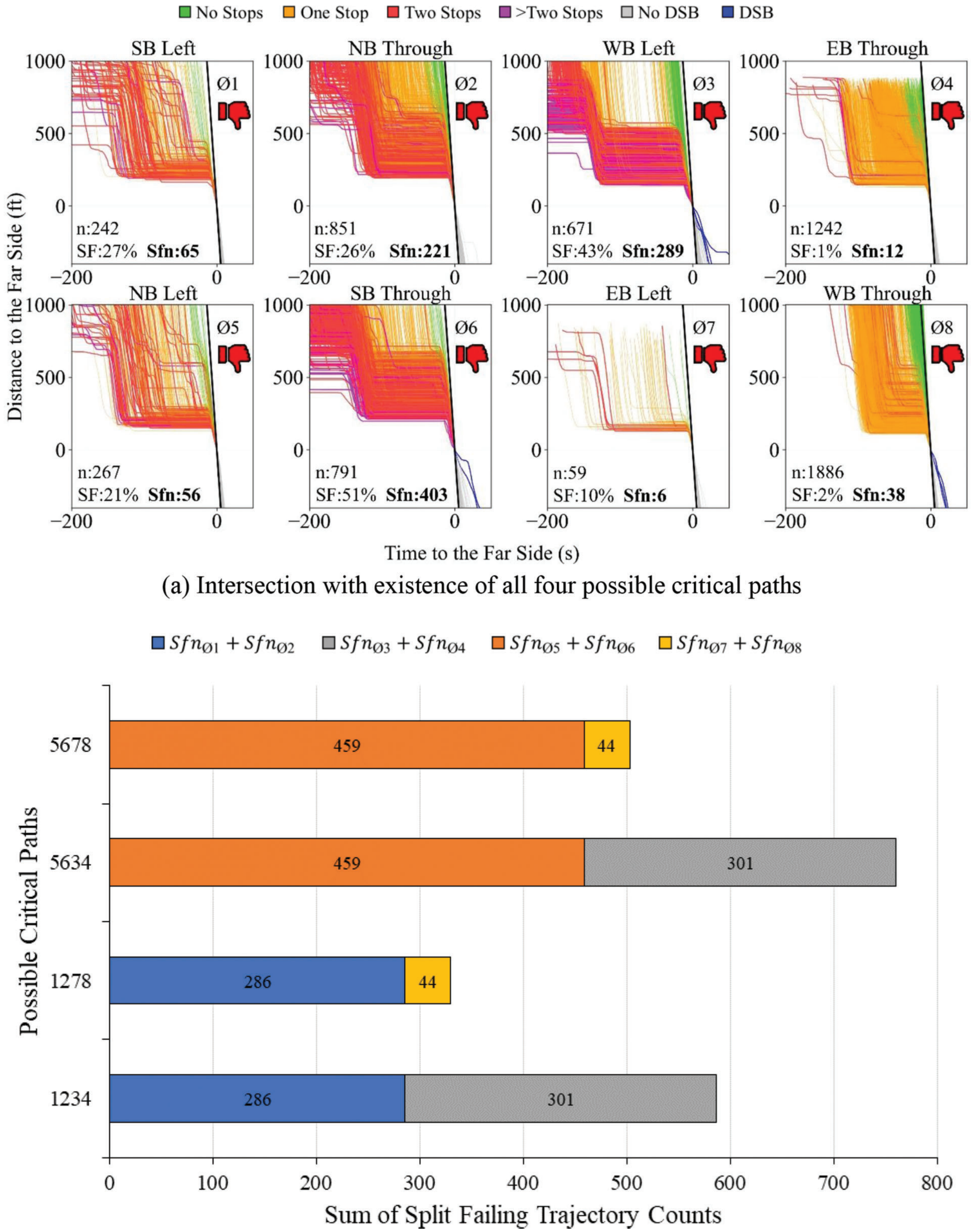


Figure 5.1 Example of critical path selection and ranking metric evaluation.

peak candidates are desired. Additionally, intersection rankings for any available analysis period can be filtered by any of the six INDOT districts (Crawfordsville, Fort Wayne, Greenfield, LaPorte, Seymour, or Vincennes).

6. RESULTS

This chapter lists the ten top-ranked capital investment candidate intersections both the entire study timespan as well as the latest 5 months of data availability and compared these two lists. Additionally, the limitations and assumptions made to produce these ranked lists are discussed.

6.1 Top-Ranked Capital Investment Candidates

For the entire analysis period of January 2022 through May 2023, the top ten intersections by total Sfn_{CP} are provided in Table 6.1 with Sfn_{CP} by TOD period shown. This is followed up by the top ten intersections for only the January 2023 through May 2023 period in Table 6.2, as these rankings consider only the most recent 5 months of the available data. From both tables, it is observed that most intersections experience the greatest volume of split failure in the PM peak period between 4:00 PM to 6:00 PM. The following seven of the top ten intersections are common for both timespans.

- SR 930 @ US 27, Fort Wayne
- US 30 @ Hart, Dyer
- SR 135 @ Smith Valley, Greenwood
- US 30 @ US 41, Schererville
- US 36 @ Dan Jones, Avon
- SR 46 @ Walnut, Bloomington
- US 30 @ Cline, Schererville

The intersection locations within Indiana for top ten lists are shown in Figure 6.1. The intersections listed above are marked in pink and can be seen for both the entire 17-month period and the latest 5-month period. Additionally, these intersections were all considered as candidates for field visit validation, which is discussed in Appendix B.

6.2 Limitations

The Sfn_{CP} metric also poses certain assumptions and limitations. This metric is developed with the assumption that CV MPR is uniform across the state of Indiana. However, studies have shown that the MPR has some variation by road type, TOD, and region (Hunter, 2022; Hunter et al., 2021; Sakhare, Hunter, et al., 2022). As such, for two intersections with the same traffic volume and critical path split failure events but different MPR, the Sfn_{CP} metric would be higher for the intersection with greater MPR. Nevertheless, MPR variation is small enough that Sfn_{CP} values can be used for screening purposes. Further, Sfn_{CP} can be normalized based on the total number of unique vehicle trajectories used to derive the metric to reduce potential biases induced by varying CV MPR values.

TABLE 6.1
Top 10 capacity improvement candidates for January 2022–May 2023 (17 months)

			Sfn_{CP} for January 2022–May 2023			
Rank	**Intersection, City**	**INDOT District**	**AM**	**Midday**	**PM**	**Total**
1	SR 930 @ US 27, Fort Wayne	Fort Wayne	1,884	17,285	14,435	33,604
2	US 30 @ Hart, Dyer	La Porte	1,393	6,165	26,038	33,596
3	SR 135 @ Smith Valley, Greenwood	Seymour	425	13,182	15,954	29,561
4	US 30 @ US 41, Schererville	La Porte	907	10,143	17,838	28,888
5	US 36 @ Shiloh Crossing, Avon	Crawfordsville	0	13,679	10,247	23,926
6	US 36 @ Ronald Reagan, Avon	Crawfordsville	911	8,500	14,496	23,907
7	US 30 @ Taft, Merrillville	La Porte	71	1,762	15,763	17,596
8	US 36 @ Dan Jones, Avon	Crawfordsville	1,535	6,192	9,693	17,420
9	SR 45 @ Walnut, Bloomington	Seymour	152	1,010	15,170	16,332
10	US 30 @ Cline, Schererville	La Porte	1,358	1,418	12,543	15,319

TABLE 6.2
Top 10 capacity improvement candidates for January 2023–May 2023 (5 months)

			Sfn_{CP} for January 2023–May 2023			
Rank	**Intersection, City**	**INDOT District**	**AM**	**Midday**	**PM**	**Total**
1	US 30 @ Hart, Dyer	La Porte	15	932	8,689	9,636
2	SR 135 @ Smith Valley, Greenwood	Seymour	94	3,087	5,190	8,371
3	SR 930 @ US 27, Fort Wayne	Fort Wayne	570	3,695	3,956	8,221
4	US 30 @ US 41, Schererville	La Porte	0	2,497	5,004	7,501
5	SR 37 @ Greenfield, Noblesville	Greenfield	299	89	6,214	6,602
6	US 30 @ Cline, Schererville	La Porte	570	263	4,571	5,404
7	SR 45 @ Walnut, Bloomington	Seymour	46	267	4,896	5,209
8	US 36 @ Post, Indianapolis	Greenfield	1,307	578	3,228	5,113
9	US 36 @ Dan Jones, Avon	Crawfordsville	536	1,445	3,073	5,054
10	SR 135 @ County Line, Indianapolis	Seymour	310	436	3,737	4,483

Figure 6.1 Top 10 capacity improvement candidates by analysis period.

Another important consideration is that the Sfn_{CP} metric weights by sampled trajectory counts (volume). For two intersections with the same MPR but different traffic volumes, the Sfn_{CP} metric would be higher for the intersection with greater volume. Thus, the top-ranked candidates will probably require the costliest capital investment projects among all intersections identified as needing capacity improvement. If unweighted results are desired to identify low-cost projects, average vehicle delay or SF (as percentage) on the critical path movements should be calculated as a new metric for ranking the statewide list of intersections.

7. RANKING OF UNSIGNALIZED INTERSECTIONS AND ROAD SEGMENTS

This chapter explores how CV data can also be used to potentially identify and rank unsignalized intersections and road segments needing capital investments. Alternative methods and metrics for screening these locations are introduced.

7.1 Unsignalized Intersections

In addition to the ranking of signalized intersections to identify capital investment opportunities, CV data can be used to rank unsignalized intersections with the same purpose. At the time of this study, and to the best of the authors' knowledge, INDOT manages 300 all-way stops, over 20,000 intersections with one uninterrupted road (i.e., uninterrupted main), and over 30 roundabouts (Figure 7.1). A systematic approach to estimate which of these intersections have the most need for capacity improvements is of significant value to transportation agencies.

In contrast with the ranking of signalized intersections, split failure events do not occur at unsignalized intersections since there is no split and this SPM cannot be used to estimate capacity needs. A viable ranking alternative is control delay. Intersection level control delay (i.e., delay induced by any traffic control device), calculated as the sum of all control delay experienced by all traversing vehicles divided by the number of all traversing vehicles, can be used to estimate the locations where added capacity could significantly reduce travel times and alleviate potential congestion. Figure 7.2 shows all intersections shown in Figure 7.1 ranked by their estimated control delay. The locations found on the left of the graphs, that depict large values of sampled trajectories, may be good candidates for further study.

(a) All-way stops (n: 300) (b) Uninterrupted main (n: 22,820) (c) Roundabouts (n: 33)

Figure 7.1 INDOT-managed unsignalized intersections (map data: Esri, TomTom, Garmin, FAO, NOAA, USGS, EPA, NPS, USFWS).

A comprehensive approach to reporting capital investment opportunities for unsignalized intersections should not only include intersection level control delay, but also control delay estimations for each movement at the intersection. Additional information on the number of sampled vehicles and downstream blockage events by movement can provide practitioners with tools to further prioritize analysis efforts.

Reports on the analysis of uninterrupted main intersections (such as two-way stop-controlled intersections) should further provide control delay, sampled trajectory counts, and downstream blockage events counts by turn type (i.e., right, through, and left) and by road type (i.e., uninterrupted main and interrupted side). This is because the traffic control approach at these intersections results in different travel experiences for these groups, and having their estimated performance can provide valuable insights on an intersection's operational conditions.

7.2 Road Segments

CV data can also be used to evaluate operating traffic speeds on the entire roadway system (Sakhare et al., 2024; Sakhare, Li, et al., 2023). Traditionally, speed studies have involved a site visit. Speeds are manually counted or collected via a traffic counter tube. This method can only collect one site at a time and is not easily scalable.

With 5% of the traffic stream being sampled with CV data (Sakhare, 2023; Sakhare, Hunter, et al., 2022), multiple days or a month can be combined to calculate mean and percentile speeds for road segments. This data would be extremely useful in locating areas of modified geometrics and/or increased enforcement efforts (Sakhare, Desai, et al., 2022, 2023). This section showcases the usability and scalability of CV data for evaluating speeds using the sample roadway of US 30 in Indiana (Figure 7.3). The roadway is segmented into 0.1-mile sections by direction.

A month of CV data from May 2023 was combined to evaluate this roadway. Performance measures gathered for each of the segments were as follows.

- 25th percentile speed
- 50th percentile speed
- 75th percentile speed
- 15th percentile speed
- 85th percentile speed
- Trajectory count
- Interquartile range (IQR) speed
- Average travel time

Each of these metrics were also categorized by TOD. These TOD categories were different from those used for signalized intersections and are as follows.

- AM: 6:00 AM–9:00 AM
- Midday: 9:00 AM–4:00 PM
- PM: 4:00 PM–7:00 PM
- Evening Time: 7:00 PM–10:00 PM
- Nighttime: 10:00 PM–6:00 AM

Figure 7.4 summarizes 15th percentile (light red), 25th percentile (red), median (black), 75th percentile (green) and 85th percentile (light green) traffic speeds during weekday AM hours for 0.1-mile segments along US 30 EB for May 2023. The sudden drops correspond to signalized intersection locations along the route. Sample intersection locations are highlighted by vertical blue dotted lines for location insights. They are named as the town name followed by the intersection minor street.

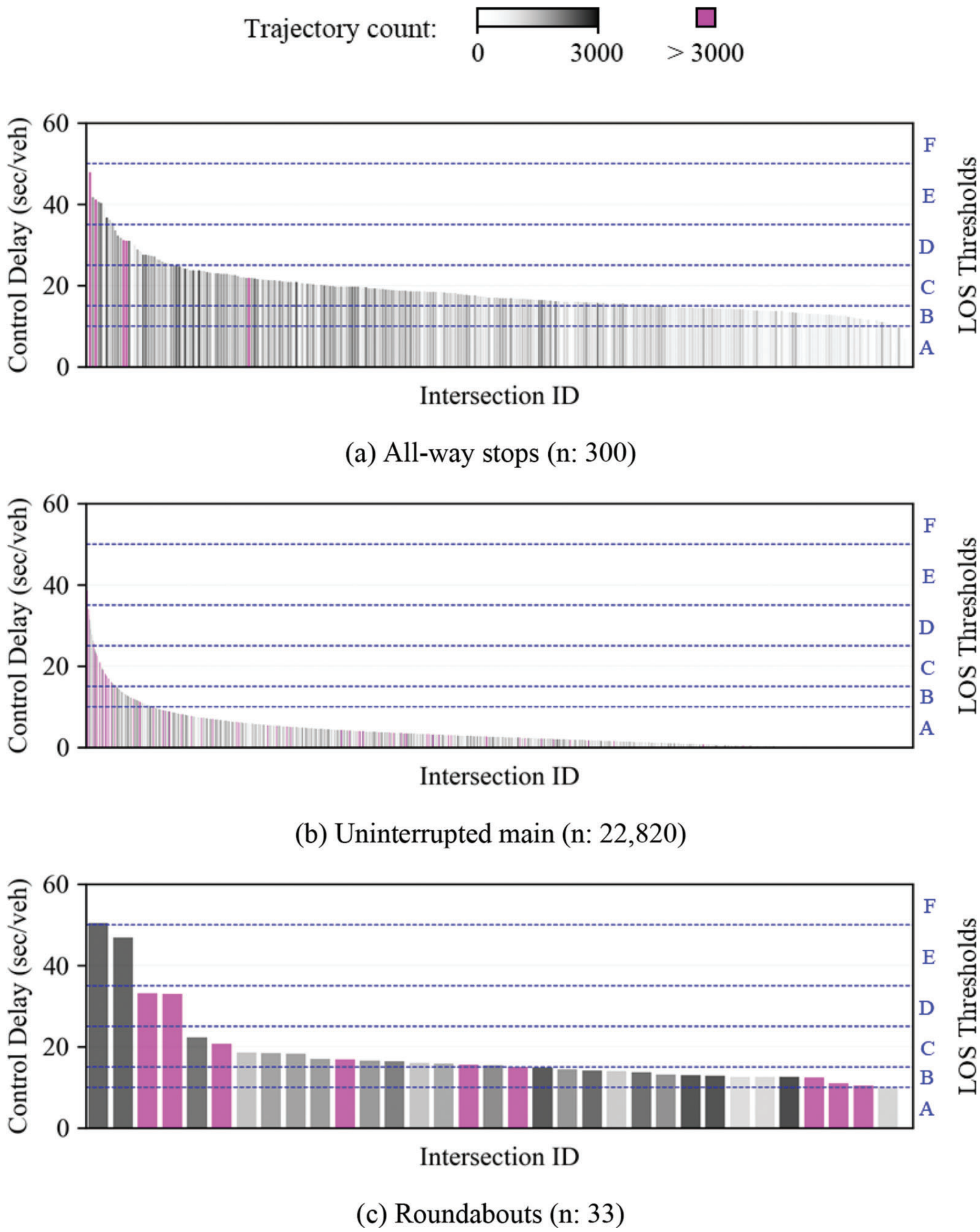


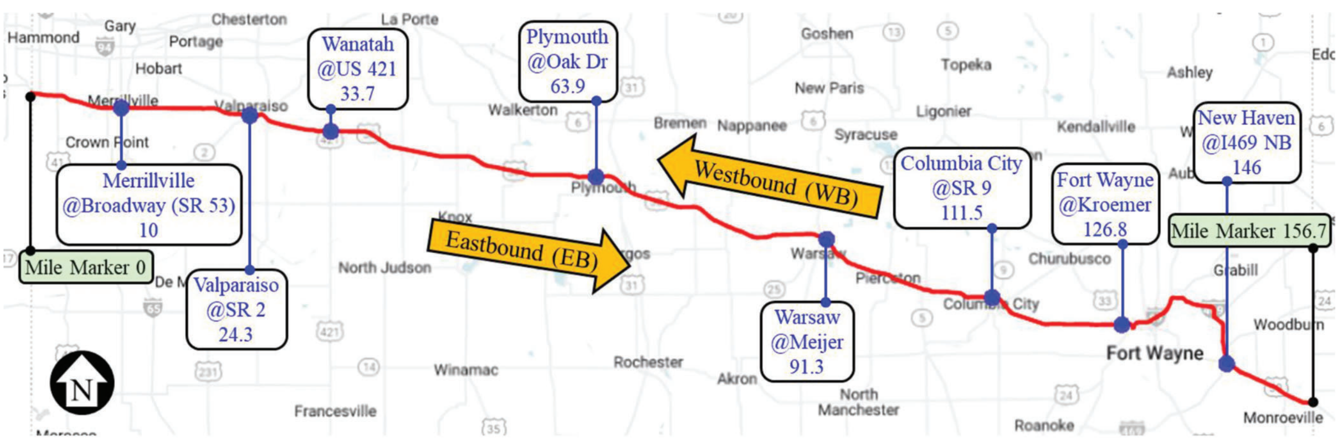
Figure 7.2 Ranking by intersection level control delay based on May 2023 weekday data from 4:00 PM to 6:00 PM with LOS thresholds (TRB, 2010).

Traffic speeds are observed to be on the lower side around the Merrillville area (nearly 30 miles on the west end of the roadway). Speeds were observed to be 60–70 mph in remote, uninterrupted areas. Corridors with several intersections in towns such as Plymouth, Warsaw, Columbia City, and Fort Wayne also see a drop in speeds. Between Fort Wayne and New Haven, the speeds were observed to go above 70 mph and, in some cases, more than 75 mph. This section of US 30 is routed along I-69 and I-469, which contributes to the increase in the observed speeds.

Figure 7.5 shows the trajectory counts for each of the segments used to evaluate the speeds as shown in Figure 7.4. All the segments had more than 500 trajectories used for determining the speeds. The peaks also represent the sections of the roadway with high volumes. This forms a measure for representativeness of the traffic. Average travel times can be computed using the median speed for the segments as all the segment lengths are 0.1 miles.

The future scope will cover the scaling of these performance measures across all routes of interest in Indiana and ranking road segments by these performance measures.

(a) US 30



(b) Mile-marker and highlighted sample intersection locations

Figure 7.3 Roadway US 30 in Indiana.

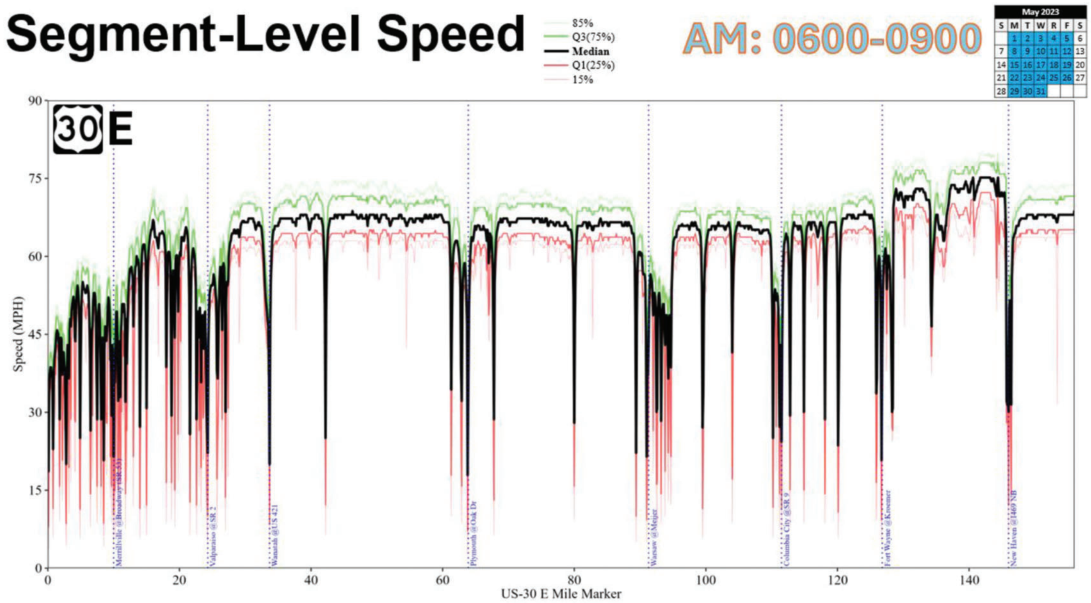


Figure 7.4 Traffic speeds by 0.1-mile segments during weekday AM hours along US 30 EB.

Figure 7.5 CV trajectory count by 0.1-mile segments during weekday AM hours along US 30 EB.

8. SUMMARY AND RECOMMENDATIONS

This report presented a methodology for identifying and ranking signalized intersections for capacity improvement. This methodology was applied to a statewide list of over 2,300 intersections with CV trajectory data collected across a 17-month span to identify intersections with the most severe capacity problems and no scope for effective retiming.

A new performance measure of critical path split failing trajectory counts (Sfn_{CP}) was developed to rank intersections with the greatest need for capacity improvement. This metric, along with 92 other attributes, is provided as a table for all intersections to produce functional signal performance reports for INDOT engineers. This table, and the included Sfn_{CP} metric, can be used as an agency screening tool to obtain intersections that should be considered for capital investment projects. Additionally, alternative methodologies and metrics to rank unsignalized intersections and roadway sections were briefly introduced, and these topics should be covered more extensively in future studies and reports.

It is important to note that the performance reports and ranked intersection lists generated for this project are recommended to be used as a screening tool only. Capacity improvement candidates identified from the reports and ranked lists must be further evaluated on a case-by-case basis to determine if a capital investment project is feasible, if it should be prioritized, and if so, the strategy and budget that will be adopted.

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APPENDICES

Appendix A. Extent of Signalized Intersections and Trajectories Analyzed

Appendix B. Field Visit for Result Validation

APPENDIX A. EXTENT OF SIGNALIZED INTERSECTIONS AND TRAJECTORIES ANALYZED

Altogether, for the three weekday TOD periods across 17 months for the 2,309 signalized intersections, 277,465,934 unique CV trajectories are evaluated. Table A.1 shows the number of intersections with existing CV data and the number of unique CV trajectories for each month within the analysis duration.

A majority of intersections have CV data for every month. The few intersections without CV data for each month consist of intersections that underwent construction within the analysis period. Examples include locations that were newly constructed, upgraded to become signalized, downgraded to become stop-controlled, or experiencing a temporary closure.

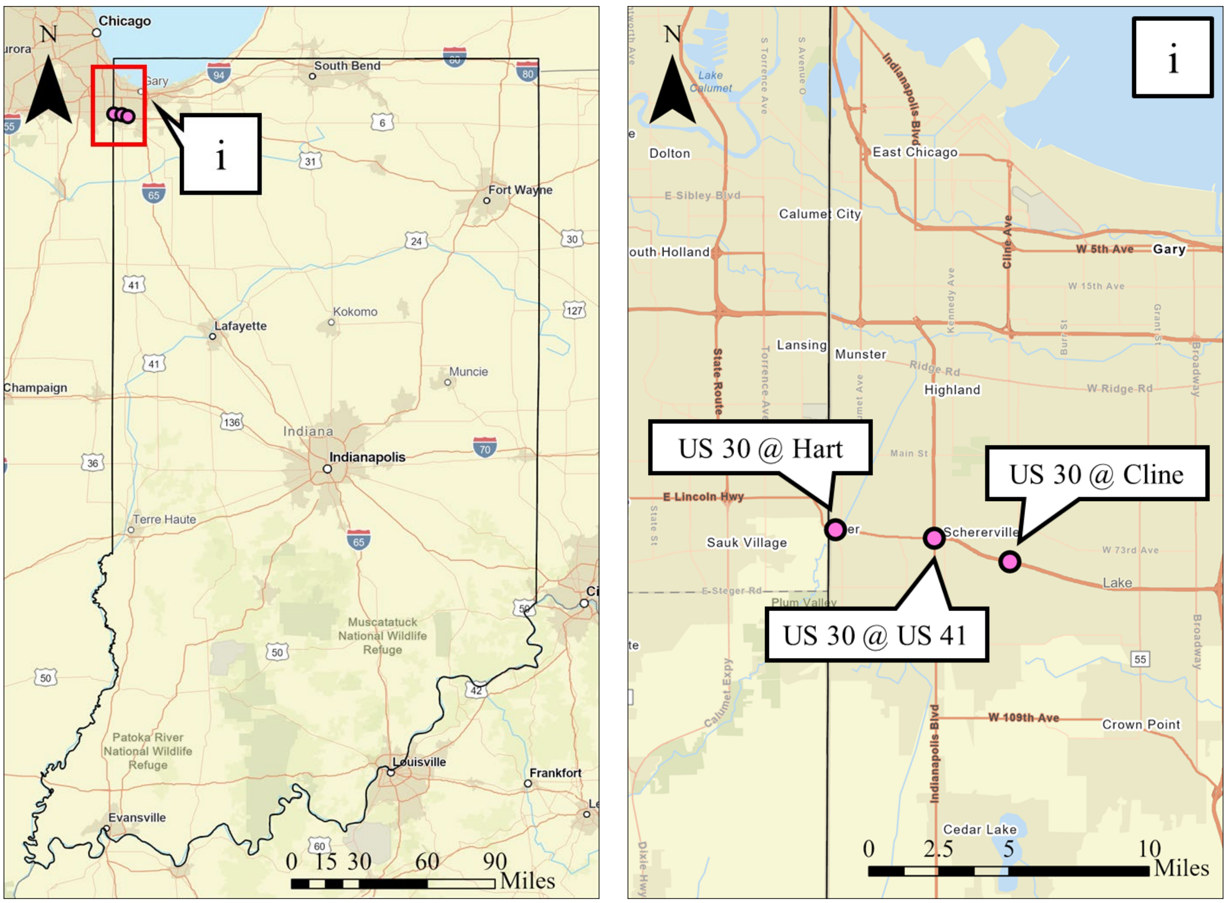
The number of unique CV trajectories per month ranges between 12 and 20 million, with the lowest number occurring for February 2022, and the highest number occurring for May 2023. This variation is caused by many changing factors, such as overall traffic, weather impacts, newly constructed or deconstructed signals, and increasing CV MPR.

Table A.1 Number of INDOT signalized intersections with existing CV data by month

Month	Intersections with CV Data	Intersections without CV Data	Unique CV Trajectories
Jan 2022	2,307	2	13,450,040
Feb 2022	2,307	2	12,670,937
Mar 2022	2,307	2	15,737,245
Apr 2022	2,308	1	14,803,163
May 2022	2,308	1	17,445,044
Jun 2022	2,308	1	17,693,234
Jul 2022	2,307	2	15,727,087
Aug 2022	2,305	4	18,303,324
Sep 2022	2,304	5	17,504,741
Oct 2022	2,305	4	16,402,925
Nov 2022	2,306	3	16,899,206
Dec 2022	2,304	5	16,301,917
Jan 2023	2,306	3	14,836,174
Feb 2023	2,309	0	15,718,808
Mar 2023	2,309	0	18,472,691
Apr 2023	2,308	1	16,093,526
May 2023	2,309	0	19,405,872

APPENDIX B. FIELD VISIT FOR RESULT VALIDATION

It is crucial to validate the methodologies used to obtain the ranked lists of capacity improvement candidates. For this reason, a field visit was performed on November 15, 2023 to verify the occurrence of split failure events at three signalized intersections within close proximity appearing in both top ten lists (Table B.1 and Figure B.5): US 30 @ Hart, US 30 @ US 41, and US 30 @ Cline. These intersections are all located within a 10-mile corridor of US 30 near the northwest corner of Indiana, as seen in Figure B.1.

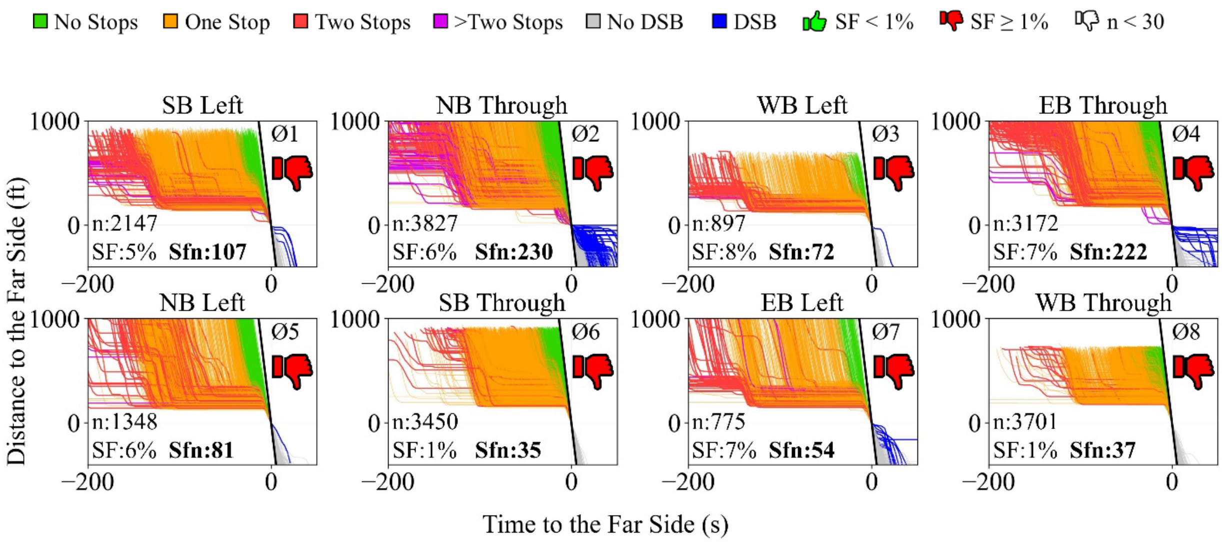


(a) Field visit intersections in northwest Indiana

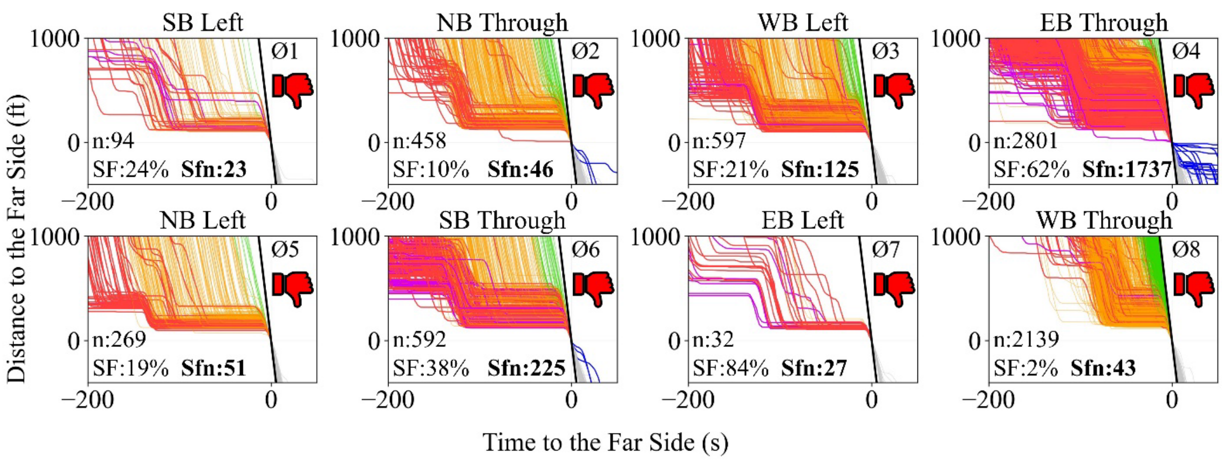
(b) Field visit intersections on US 30 corridor near Schererville, IN

Figure B.1 Intersections selected for field visit validation.

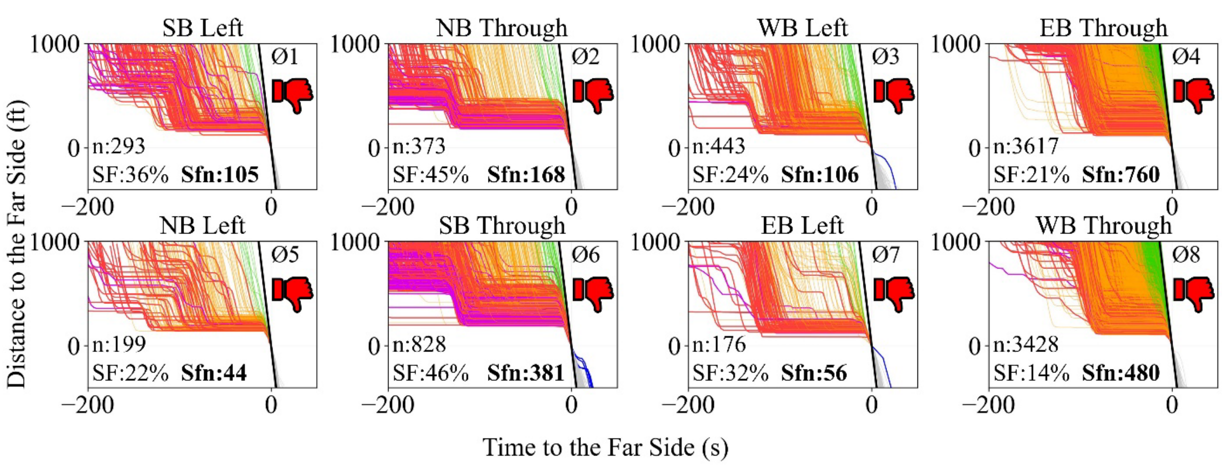
For all three intersections, Sfn_{CP} values were highest for the PM peak period, but among the entire statewide list, US 30 @ US 41 was also seen to have relatively high midday Sfn_{CP} values. For this reason, and due to time constraints, video footage for US 30 @ US 41 was obtained within the midday period (9:00 AM–1:00 PM CT), and footage for US 30 @ Hart and US 30 @ Cline were obtained in the PM peak period (3:00 PM–5:00 PM CT). It is important to note that the TOD periods used for statewide ranking correspond to the US Eastern Time Zone, and thus these periods occur one hour earlier for the visited intersections, as they are all in the US Central Time Zone. May 2023 PPDs for these intersections and their respective TOD periods for video logging are shown in Figure B.2.



(a) US 30 @ US 41, 9:00 AM – 1:00 PM CT



(b) US 30 @ Hart, 3:00 PM – 5:00 PM CT



(c) US 30 @ Cline, 3:00 PM – 5:00 PM CT

Figure B.2 May 2023 ring diagram PPDs for field visit intersections.

Based on these PPDs, video footage was obtained for the following directional approaches expected to have high SF for each intersection (Table B.1).

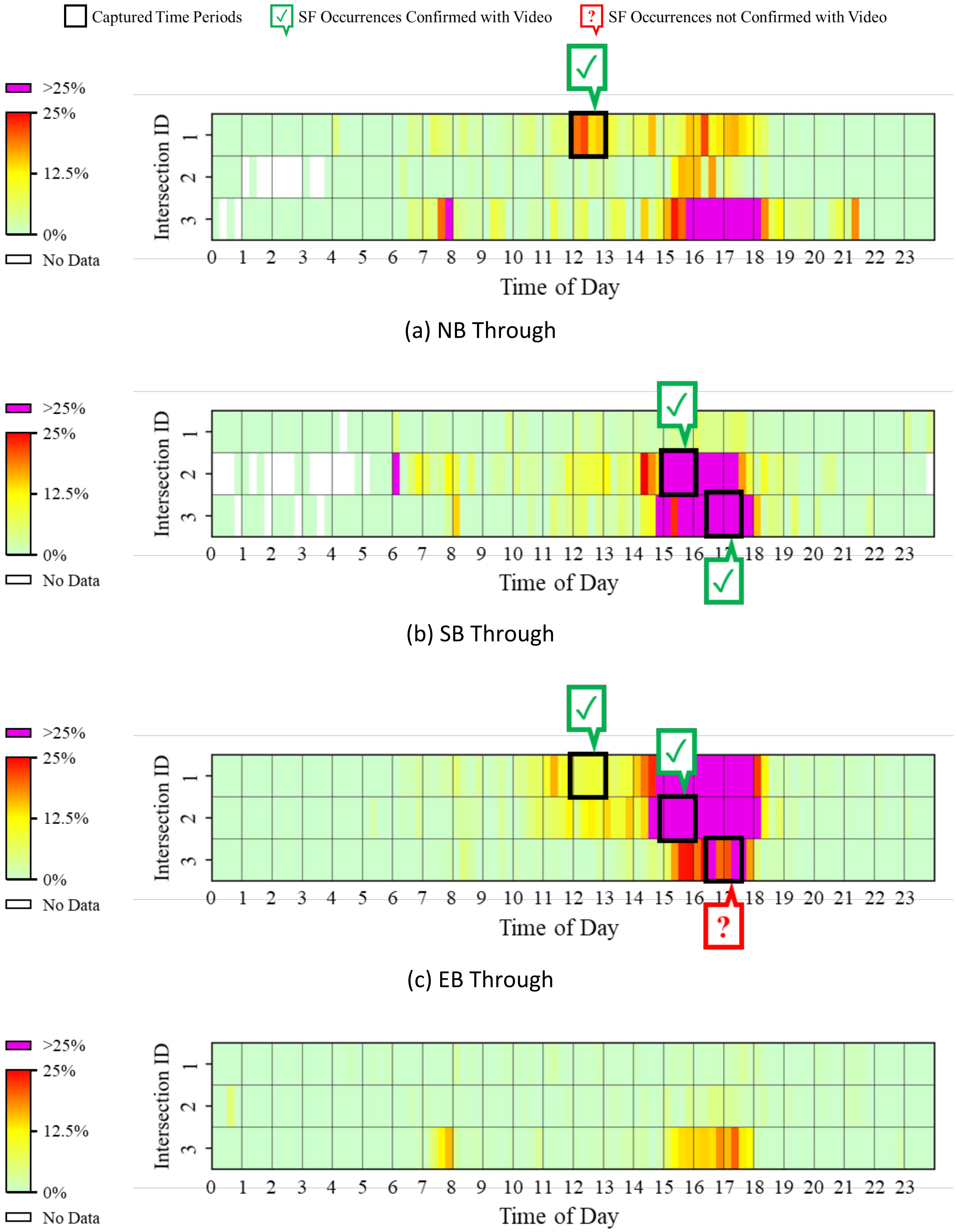
Table B.1 Videos of congestion and split failure events at field visit intersections

Intersection	Approach	Video Link	Video QR Code
US 30 @ US 41	NB on US 41	https://tinyurl.com/US30-US41-NB-Midday	
	EB on US 30	https://tinyurl.com/US30-US41-EB-Midday	
US 30 @ Hart	EB on US 30	https://tinyurl.com/US30-Hart-EB-PMpeak	
	SB on Hart	https://tinyurl.com/US30-Hart-SB-PMpeak	
US 30 @ Cline	EB on US 30	https://tinyurl.com/US30-Cline-EB-PMpeak	
	SB on Cline	https://tinyurl.com/US30-Cline-SB-PMpeak	

Several split failure event occurrences were verified in all, but one of the six videos taken, with the exception being the EB approach for US 30 @ Cline. However, it was visually confirmed that

SF events occurred for this approach just before and after the video was taken. Unfortunately, these events were not captured on video. Nevertheless, as the majority of approaches were confirmed to exhibit high SF, the field visits gave a strong indication that the methodology used for statewide capacity improvement identification and ranking provided reasonable results.

Figure B.3 shows aggregated May 2023 24-hour SF heatmaps on the through movements for these three visited intersections. Each 15-minute period is color-coded based on total SF for all sampled CV trajectories executing that movement in May 2023. US 30 @ US 41, US 30 @ Hart, and US 30 @ Cline have been given IDs 1, 2, and 3 respectively. Callouts for captured time periods and SF event confirmation, as seen from the field visits on November 15, 2023, are also included.



(a) NB Through

(b) SB Through

(c) EB Through

(d) WB Through

Figure B.3 May 2023 SF heatmaps for field visit intersections.

Examples of split failure events captured for the EBT (Ø4) and SBT (Ø6) movements at US 30 @ Hart (outlined in red in Figure B.4), are shown in Figure B.5. Figure B.5a–c shows a semi-truck with an orange trailer split failing on the EB approach, while Figure B.5d–f shows a silver truck split failing on the SB approach.

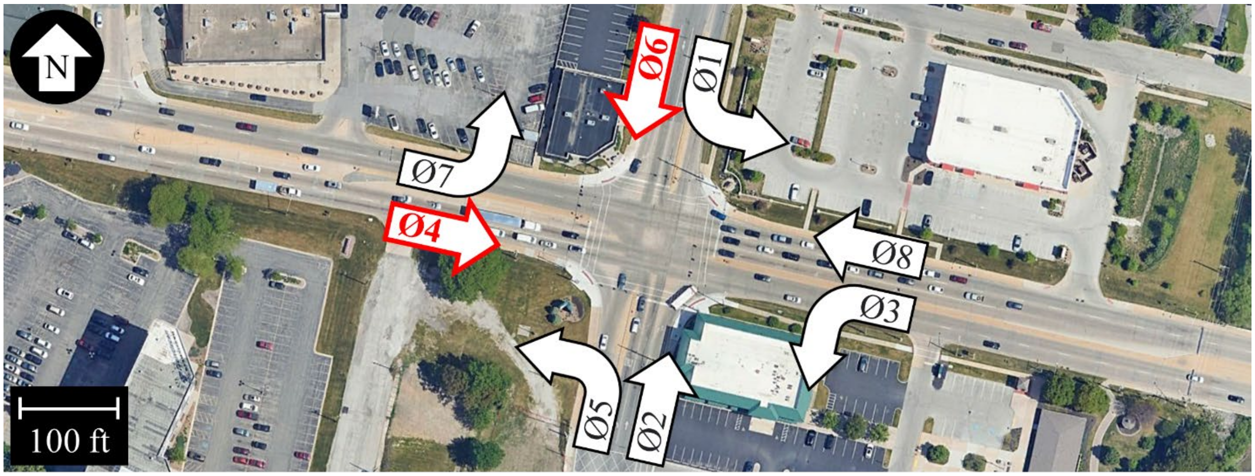


Figure B.4 US 30 @ Hart aerial view with movements.

EBT (Ø4) SF Event

(a) Semi-truck in queue stopped on red

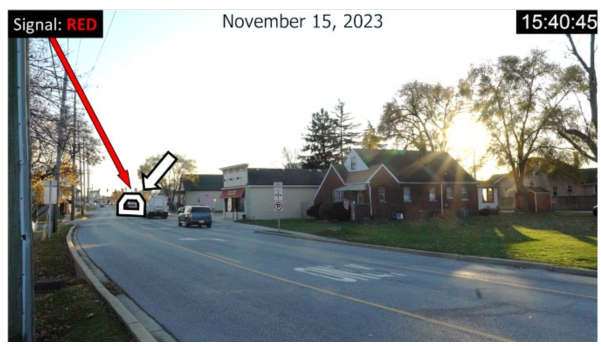
(b) Semi-truck in queue advancing on green

(c) Semi-truck in queue stopped for a second time on red

SBT (Ø6) SF Event

(d) Truck in queue stopped on red

(e) Truck in queue advancing on green



(f) Truck in queue stopped for a second time on red

Figure B.5 Captured split failure events on US 30 @ Hart.

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at http://docs.lib.purdue.edu/jtrp.

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