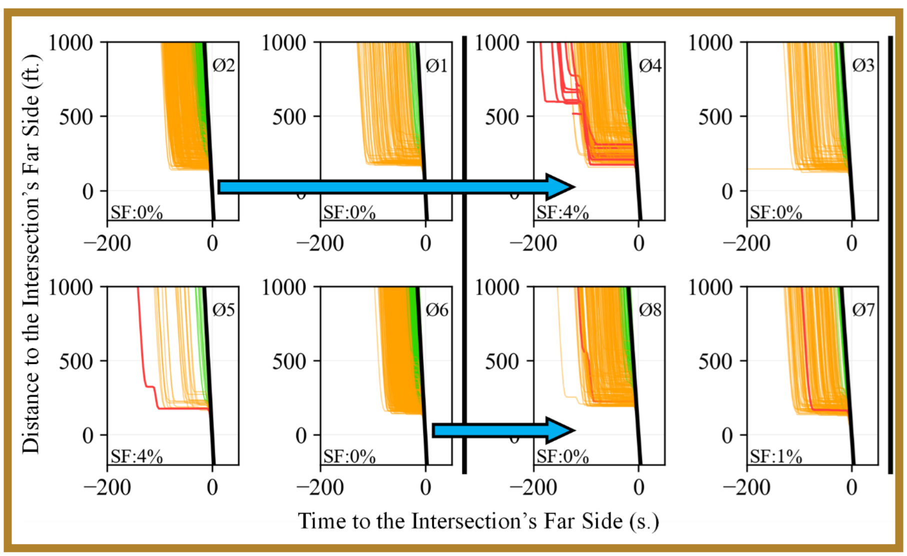
JOINT TRANSPORTATION
RESEARCH PROGRAM
INDIANA DEPARTMENT OF
TRANSPORTATION AND PURDUE UNIVERSITY

Business Processes to Prioritize Traffic Signal Retiming and Assess the Impact of Retiming Activities



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NOTICE

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16. Abstract

The Indiana Department of Transportation (INDOT) manages over 2,000 traffic signals in the State. It is unfeasible to identify systemwide improvement opportunities by evaluating the performance of thousands of traffic signals on monitoring dashboards. This report describes how a scalable technique based on connected vehicle (CV) trajectory data systematically evaluates performance at the movement level to prioritize retiming and maintenance activities. In total, eleven timing changes were implemented at nine traffic signals over various time-of-day (TOD) periods using the proposed approach. The method achieved average control delay and split failure reductions of up to 53 sec/veh and 30%, respectively. A before-after performance analysis is presented for each intersection and the business processes implemented to achieve these results are discussed. The business process analysis resulted in a companion study, SPR-4857, which identified signals with operational performance problems that should be further evaluated for potential capital investments, such as turn lane additions.

17. Key Words traffic signal, intersection, performance measure, connected vehicle, big data, retiming		**18. Distribution Statement** No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.	
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EXECUTIVE SUMMARY

Motivation

Traffic signal operations have a significant impact on road network operations. The Indiana Department of Transportation (INDOT) manages over 2,000 traffic signals in the State. It is therefore important for INDOT to identify locations that require additional operations improvements through signal retiming.

The traditional process of assigning limited resources to signal retiming practices was a 3- to 5-year cyclic schedule. However, this approach allows signals to operate inefficiently over long periods of time. Recently, Automated Traffic Signal Performance Measures (ATSPMs), which rely on intersection detection and communication equipment, have been used to systematically monitor intersection performance and locate retiming opportunities. Nevertheless, ATSPMs require significant capital investments in infrastructure and maintenance activities to accomplish statewide coverage.

In the last few years, commercial high-fidelity connected vehicle (CV) trajectory data has appeared as a scalable dataset that can be used to estimate actionable traffic signal performance measures. This approach provides important benefits, since agencies can proactively monitor operations without deploying a large amount of detection and communication equipment. However, no CV-derived methods have been developed to assess green redistribution potential at scale based on individual conflicting movements within and across ring diagram barriers at the intersection.

Study

This study presents a scalable methodology by which CV-based performance measures can identify critical split failing movements where additional green time could be provided from either within or across ring diagram barriers at the intersection. In addition, downstream blockage from adjacent intersections was considered to determine if the rebalancing would be effective.

To demonstrate the efficiency of the proposed technique, eleven timing changes over different time-of-day (TOD) periods at nine signalized intersections across the state were implemented. Reductions of up to 53 sec/veh and a 30% on average control delay and split failures, respectively, were achieved. A detailed before-and-after analysis is provided within this report for each modified intersection that presented overall positive changes, and the business processes used to achieve these results are discussed.

Using the proposed methodology, agencies can promptly identify systemwide capacity challenges and places where tactical deployment of retiming resources is likely to result in an improvement. The presented analysis also resulted in the development of a companion study, SPR-4857, which provides a method to screen for intersections that have capital investment opportunities where signal retiming is unfeasible.

Recommendations

It is recommended that the proposed screening technique be performed monthly, statewide, and by district. INDOT resources can then be allocated to verify the feasibility and accuracy of retiming suggestions and then implement the most promising revisions. Furthermore, this approach can help assess the efficiency of timing changes, since previously modified intersections should be placed lower in the rankings for subsequent iterations.

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LIST OF ABBREVIATIONS

AOG	Arrivals on Green
ATSPM	Automated Traffic Signal Performance Measures
CV	Connected Vehicle
DSB	Downstream Blockage
FFT	Free Flow Trajectory
FHWA	Federal Highway Administration
INDOT	Indiana Department of Transportation
PM	Performance Measure
PPD	Purdue Probe Diagram
RPD	Relative Performance Diagram
SF	Split Failure
Spat	Signal Phase and Timing
SR	Split Rebalance
TOD	Time-of-Day

1. INTRODUCTION

Traffic signal operations have a significant impact on road networks. They are estimated to contribute between 5% and 10% of all traffic delay and cost motorists over $22 billion annually in the United States (NOCoE, 2020). The state-of-the-practice traffic signal management had a national result of C+ in the *2019 Traffic Signal Benchmarking and State of the Practice Report* (NOCoE, 2020). With over 400,000 traffic signals in operation nationwide, it is crucial for agencies to monitor signal performance and identify locations where improvements could reduce congestion, enhance mobility, decrease delays, and reduce the number of vehicle stops (NOCoE, 2012).

Options to improve intersection operations at challenged locations include signal retiming and capital investments to upgrade infrastructure (Figure 1.1). The latter can come in the form of lane additions, intersection type change, added right-of-way, construction of alternative routes, or even the integration of public transportations modes (Chandler et al., 2013; Rodegerdts et al., 2004). However, whenever possible, signal retiming should be prioritized to improve intersection performance as it represents a less expensive alternative.

Signal retiming involves the implementation and modification of signal timing parameters, phasing sequences, and control techniques to better serve vehicle demand (Sunkari, 2004). To maximize benefits, the Federal Highway Administration (FHWA) recommends agencies to focus resources to maximize favorable measures such as progression and throughput and minimize unfavorable measures such as delay and split failures (Denney et al., 2008). The benefit-to-cost ratio of signal retiming has been estimated to be around 40:1 (Sunkari, 2004). There have been extensive efforts in the development of performance measures to identify locations where signal retiming opportunities can achieve these benefits (Day, Li, et al., 2015; Day, Remias et al., 2015; Day et al., 2018).

The *Traffic Signal Timing Manual* provides a summary of practices that aid practitioners in the timing of traffic signals (Koonce, 2008; Urbanik, 2015). Traditionally, agencies have retimed signals on a 3- to 5-year cycle where citizen complaints were often the main performance measure (FHWA, 2019; NCHRP, 2010). In the past two decades, several studies have investigated using detector-based Automated Traffic Signal Performance Measures (ATSPM) (Day et al., 2014) and probe data to develop movement, intersection, and system-level analyses. The resulting metrics enable practitioners to identify problem locations where performance can be improved sooner than with traditional approaches.

In the last few years, high-fidelity CV trajectory data, comprised of entire journey-based vehicle trajectories, has become commercially available. With over 400 billion vehicle position records generated each month in the United States (Mathew et al., 2024), this dataset has become a viable source to generate scalable traffic signal performance measures (Saldivar-Carranza, Li, Mathew, et al., 2021; Saldivar-Carranza et al., 2023; Waddell et al., 2020; Wolf et al., 2019).

1.1 Connected Vehicle Trajectory Data

Commercial CV trajectory data, currently with estimated penetration rates around 5% (Sakhare et al., 2022), consists of individual passenger vehicle trajectory waypoints with a 3-sec reporting interval and nominal 3-meter spatial accuracy. Each waypoint has the following information: latitude, longitude, speed, heading, and an anonymous vehicle identifier. The data is obtained from multiple automotive manufacturers and no aggregation is performed. The dataset does not include any infrastructure information, such as signal phase and timing (SPaT) or MAP messages (Abernethy et al., 2012; SAE International, 2016). By chronologically linking individual waypoints with the same trajectory identifier, the estimated trip of an equipped vehicle can be obtained. Therefore, a CV trajectory *T* is

(a) Signal retiming (b) Infrastructure upgrades

Figure 1.1 Different approaches to improve operations at challenging locations.

defined as the set of its waypoints W_i, with $i = 1, 2, \ldots, k$, where $i = 1$ is the first and $i = k$ is the last sampled waypoints of the vehicle. That is:

$$T = \{W_i\}_{i=1}^{k} \quad \text{(Eq. 1.1)}$$

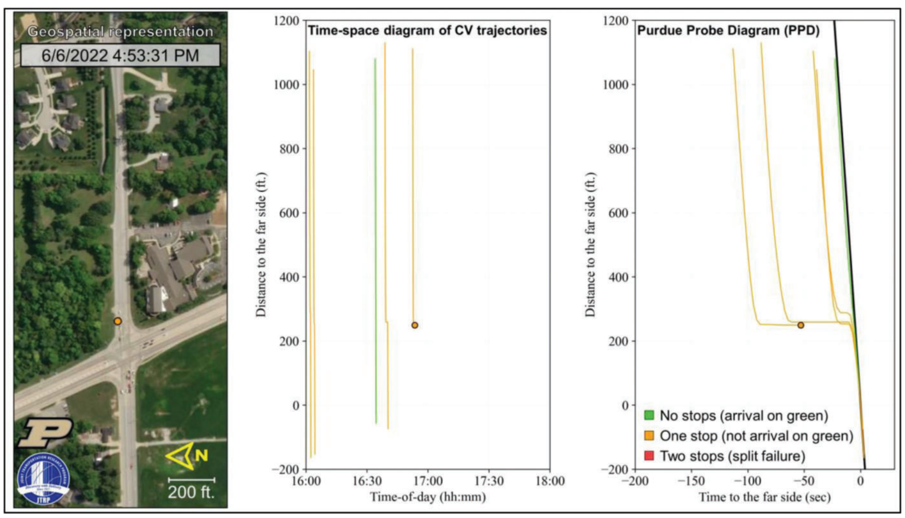
$$W_i = \{identifier, longitude_i, latitude_i, timestamp_i, speed_i, heading_i\} \quad \text{(Eq. 1.2)}$$

Figure 1.2 shows examples of times-space trajectories along the US-421 at W 116th St. intersections (Figure 1.2a) and the SR-37 corridor (Figure 1.2b).

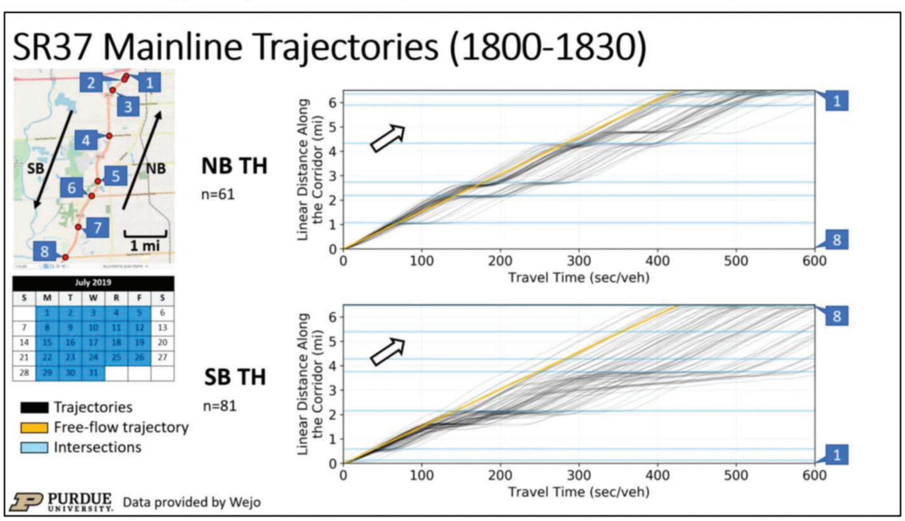
1.2 Motivation

The identification of oversaturated movements and whether green time can be redistributed has previously been studied using ATSPM, probe data, and aggregated data (Campbell & Skabardonis, 2014; Day et al., 2018; Denney et al., 2008; Li et al., 2017); however, these methods do not assess green redistribution potential at scale based on individual conflicting movements within and across barriers in the ring diagram. Achieving this analysis agency-wide using infrastructure detector methods typically require robust and accurate detection (Emtenan, & Day, 2020), which can be costly to install and maintain (NCHRP, 2010). Previous studies using probe data have looked at corridor-level operational conditions to identify congested intersections, but do not distinguish between localized capacity concerns and blockage by adjacent intersections (Li et al., 2017). The limited spatial and temporal fidelity of segments have also constrained practitioners.

CV trajectory data has emerged as a scalable dataset for determining road network performance because it does not depend on detection and communication equipment and is not aggregated by road segments. Consequently, CV-based traffic signal analytics easily



(a) Along an intersection (Saldivar-Carranza & Bullock, 2024)



(b) Along a corridor (Saldivar-Carranza, 2024)

Figure 1.2 Examples of time-space trajectories.

TABLE 1.1
Meetings held throughout the project

Date	Topic
July 11, 2022	Vincennes traffic signals discussion
September 8, 2022	Signal retiming opportunities in Vincennes
October 19, 2022	Signal retiming opportunities by district
March 29, 2023	Signal retiming opportunities in Fort Wayne
May 23, 2023	Progress discussion, training, and peer exchange
December 11, 2023	Update on INDOT signals coverage and reporting approach
January 17, 2024	Review of signal systems engineers on reporting approach
June 13, 2024	Update on data acquisition and progress on the technical report

scale to provide performance measures for all movements of every intersection without detection (Day, Li et al., 2015; Day, Remias, et al., 2015; Day et al., 2018).

This report presents a scalable methodology by which CV-based performance measures can be used to identify critical split failing movements where additional green time could be provided from either within or across ring diagram barriers at the intersection. In addition, downstream blockage from adjacent intersections is considered to determine if the rebalancing will be effective. Using the proposed methodology, agencies can promptly identify systemwide where there are not only capacity challenges, but where tactical deployment of retiming resources is likely to result in an improvement. Furthermore, this report discusses the business processes to prioritize signal retiming and assess the impact of retiming activities.

1.3 Dissemination and Research Results

Significant efforts have been made by Purdue University and INDOT to disseminate research results and converge on an implementation approach. Table 1.1 lists different meetings held by both teams to discuss progress, reporting techniques, and signal retiming results at different locations in the state.

The following is a list of related publications that provide background, methodology, or were derived because of SPR-4737 research tasks.

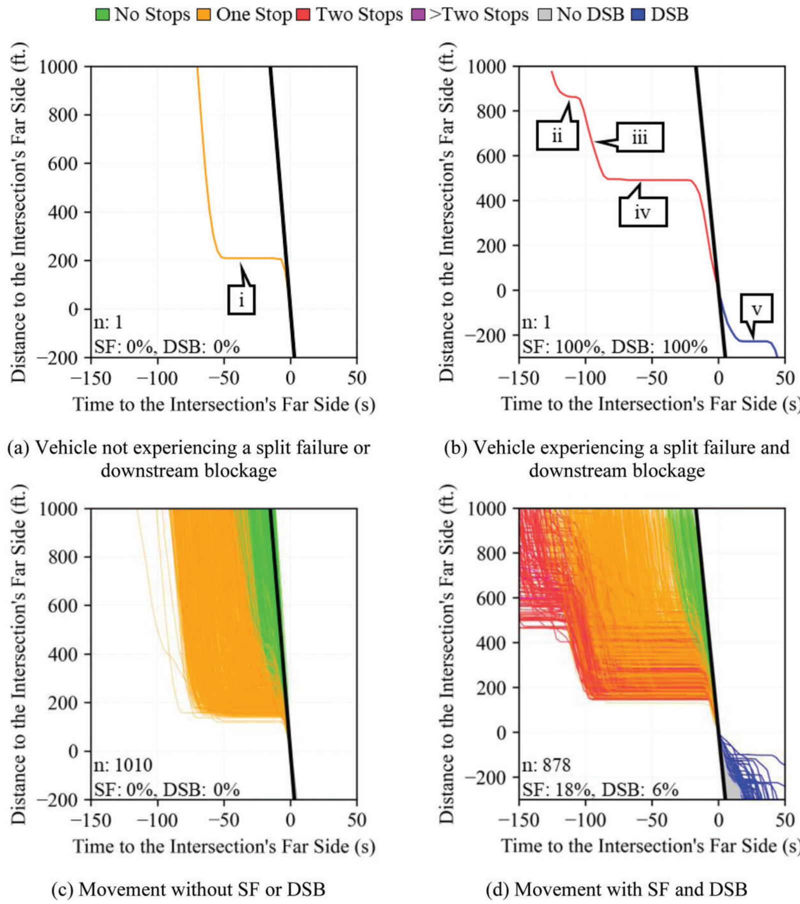
- Saldivar-Carranza, E., Li, H., Mathew, J., Fisher, C., & Bullock, D. M. (2022). Signalized corridor timing plan change assessment using connected vehicle data. *Journal of Transportation Technologies*, *12*(3), 310–322. https://doi.org/10.4236/jtts.2022.123019
- Saldivar-Carranza, E., Rogers, S., Li, H., & Bullock, D. M. (2022). Diamond interchange performance measures using connected vehicle data. *Journal of Transportation Technologies*, *12*(3), 475–497. https://doi.org/10.4236/jtts.2022.123029
- Saldivar-Carranza, E., Li, H., Taylor, M., & Bullock, D. M. (2022). Continuous flow intersection performance measures using connected vehicle data. *Journal of Transportation Technologies*, *12*(4), 861–875. https://doi.org/10.4236/jtts.2022.124047
- Saldivar-Carranza, E. D., Li, H., Gayen, S., Taylor, M., Sturdevant, J., & Bullock, D. M. (2023). Comparison of arrivals on green estimations from vehicle detection and connected vehicle data. *Transportation Research Record*, *2677*(12), 328–342. https://doi.org/10.1177/03611981231168116
- Saldivar-Carranza, E. D., Li, H., Platte, T., & Bullock, D. M. (2023). Systemwide identification of signal retiming opportunities with connected vehicle data to reduce split failures. *Transportation Research Record*, *2677*(12), 587–603. https://doi.org/10.1177/03611981231168844
- Saldivar-Carranza, E. D., Li, H., Mathew, J. K., Desai, J., Platte, T., Gayen, S., Sturdevant, J., Taylor, M., Fisher, C., & Bullock, D. M. (2023). *Next generation traffic signal performance measures: Leveraging connected vehicle data*. West Lafayette, IN: Purdue University. https://doi.org/10.5703/1288284317625
- Gayen, S., Saldivar-Carranza, E. D., & Bullock, D. M. (2023). Comparison of estimated cycle split failures from high-resolution controller event and connected vehicle trajectory data. *Journal of Transportation Technologies*, *13*(4), 689–707. https://doi.org/10.4236/jtts.2023.134032
- Saldivar-Carranza, E. D., Gayen, S., Li, H., & Bullock, D. M. (2024). Comparison at scale of traffic signal cycle split failure identification from high-resolution controller and connected vehicle trajectory data. *Future Transportation*, *4*(1), 236–256. https://doi.org/10.3390/futuretransp4010012

In general, the foundation of all these papers has been linear referencing the trajectories and pivoting those trajectories on a point a few hundred feet past the movement stop bar for a particular time-of-day (TOD) period (Saldivar-Carranza et al., 2023). This allows delay, arrivals on green, split failure, and downstream blockage trends to be observed at the movement level (Saldivar-Carranza et al., 2023). Figure 1.2a shows a screen scrape of pivoted trajectories and the corresponding intersection geometry. Saldivar-Carranza and Bullock, 2024 provides a link that illustrates how pivoting works in that figure.

2. IDENTIFICATION OF SIGNAL RETIMING OPPORTUNITIES

This section describes the proposed CV-based techniques to identify systemwide locations with signal retiming opportunities (Saldivar-Carranza et al., 2023) and is organized as follows.

- First, split failure and downstream blockage events and estimations, which are the foundation of the signal



(a) Vehicle not experiencing a split failure or downstream blockage

(b) Vehicle experiencing a split failure and downstream blockage

(c) Movement without SF or DSB

(d) Movement with SF and DSB

Figure 2.1 CV-based SF and DSB concepts from Purdue Probe Diagrams.

retiming opportunities identification technique, are explained.

- Then, a methodology that uses relative split failure and downstream blockage measurements of different movements on an intersection to identify if a movement is a good candidate for timing adjustments is covered.
- Finally, a use case is presented to demonstrate the real-world impact of the technique.

2.1 Split Failure and Downstream Blockage Estimations

A vehicle experiencing a split failure (SF) is identified from CV data when its trajectory stops two or more times before crossing the intersection (Saldivar-Carranza, Li, Mathew, et al., 2021). The first stop indicates the arrival of the vehicle at the back of the queue, and the second and subsequent stops indicate insufficient green to service the vehicle.

Downstream blockage (DSB) occurs when a queue at a downstream intersection obstructs the progression of vehicles at the upstream intersection. DSB is identified when a trajectory has a least 10 sec of delay compared to a free flow trajectory (FFT) after crossing the far side of the intersection (Saldivar-Carranza, Li, Mathew, et al., 2021). Reducing the occurrence of SF at an intersection may not be possible locally if the same movement also experiences DSB, as the source of congestion is likely at the downstream intersection.

Figure 2.1 shows the SF and DSB concepts with Purdue Probe Diagrams (PPDs). On a PPD, vehicle trajectories for a particular movement are linear-referenced to the far-side of an intersection and color-coded based on the number of stops (Saldivar-Carranza, Li, Mathew, et al., 2021). The movement a trajectory follows is identified by evaluating its entry and exit heading in relation to the intersection (Saldivar-Carranza, Li, & Bullock, 2021).

Figure 2.1a shows a vehicle that only stops once during its approach (callout i). Since it stops less than two times before crossing through the intersection and it does not have significant delay after, it is not categorized as having experienced a SF or DSB. In contrast, Figure 2.1b displays a vehicle that stops two times before crossing through the intersection and experiences delay after. It first stops at the back of a queue (callout ii). Then, the vehicle starts moving as the queue is being discharged (callout iii). However, as the split time for this movement is not long enough to discharge the entire queue, the vehicle stops again (callout iv), making it experience a SF. After it crosses the intersection, it must stop again soon after due to a downstream queue (callout v).

To normalize by sampled demand, the occurrence of SF and DSB events are presented as a ratio or percentage. The indicator function X is used to denote whether the i-th trajectory (T_i), out of n trajectories analyzed, experienced a SF, and the indicator function Y is used to denote whether T_i experienced DSB. That is:

$$X(T_i) = \begin{cases} 0, if\ T_i\ does\ not\ experience\ a\ SF \\ 1, if\ T_i\ experiences\ a\ SF \end{cases} \quad \text{(Eq. 2.1)}$$

$$Y(T_i) = \begin{cases} 0, if\ T_i\ does\ not\ experience\ DSB \\ 1, if\ T_i\ experiences\ DSB \end{cases} \quad \text{(Eq. 2.2)}$$

Then, the SF and DSB ratios can be calculated as:

$$SF\ Ratio = \frac{\sum_{i=1}^{n} X(T_i)}{n} \quad \text{(Eq. 2.3)}$$

$$DSB\ Ratio = \frac{\sum_{i=1}^{n} Y(T_i)}{n} \quad \text{(Eq. 2.4)}$$

By multiplying the ratios by 100, the percentage of analyzed vehicles experiencing SF or DSB is obtained.

Figure 2.1c shows all the 1,010 sampled vehicles that follow the same movement as Figure 2.1a during a given period. No vehicles experienced SF or DSB. Using Equations 2.3 and 2.4, 0% SF and DSB is calculated. Figure 2.1d shows all the 878 sampled vehicles that follow the same movement as Figure 2.1b during a given period. On this movement, 158 vehicles experienced SF and 53 DSB. Using Equations 2.3 and 2.4, 18% SF and 6% DSB is calculated.

2.2 Relative Performance Diagrams

This subsection describes the approach to identify locations where signal timing modifications could potentially reduce split failures at a particular movement. The technique is demonstrated by evaluating traffic signal performance at 112 INDOT managed intersections in central and west Indiana (Figure 2.2). Figure 2.2b callout ii points to the intersection chosen for retiming and presented as a use case, which will be discussed on detail on a subsequent subsection.

The identification of signals where potential retiming opportunities exists is based on two essential points (Li et al., 2017).

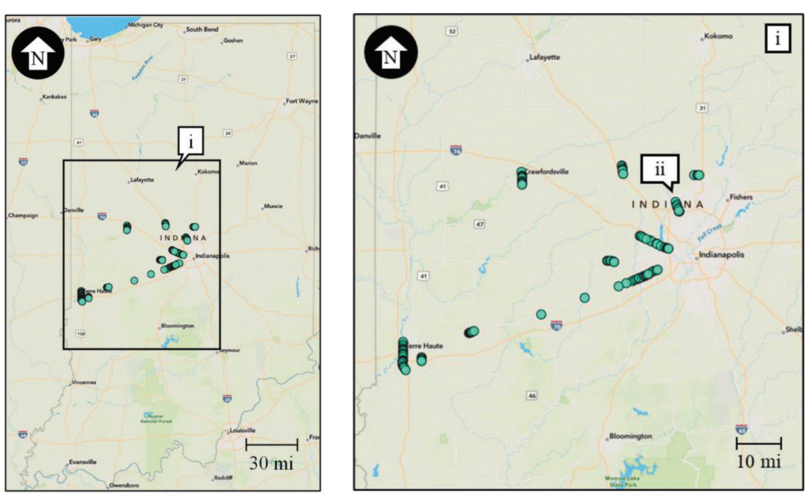
- First, the movement on the signal that has the highest level of SF needs to be identified. This movement will be referred as "critical movement," and it is the target where additional split is desired.
- Then, movements that could distribute split to the critical movement need to be evaluated. These movements will be referred as "donor movement(s)." If the donor movements are also saturated, then split rebalance (i.e., the practice of taking split from one phase and giving it to another) cannot be performed. On the other hand, if the donor movements are undersaturated, there is potential to reduce split failures by reallocation split from the donor movement to the critical movement.

There are two types of donor movements. The first is the conflicting movement of the critical movement within the same barriers and ring. The second considers movements on the opposite barrier of the ring diagram. Depending on which donor is used to identify retiming candidates, different signals may appear as options.

Relative Performance Diagrams (RPDs), which are a visualization tool based on the points discussed above to identify retiming candidates, are described below. RPDs differ depending on which donor movements are evaluated.

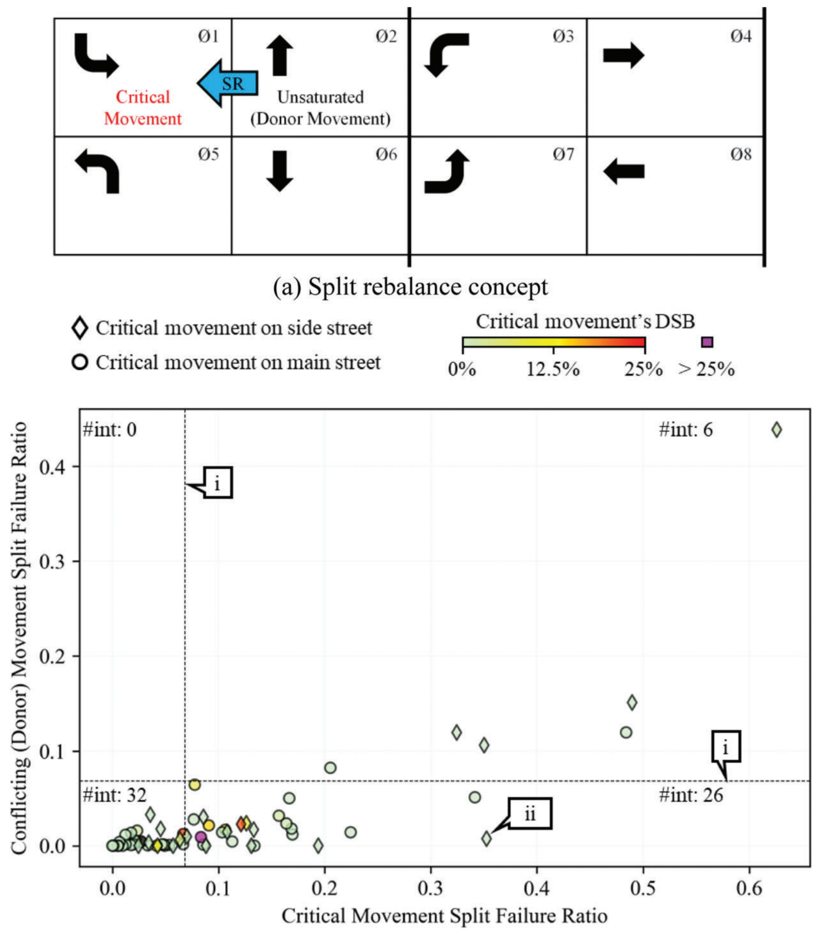
2.2.1 Conflicting Movement RPD

Conflicting Movement RPDs are based on the analysis of conflicting movements as donor movements. After identifying the critical movement, the conflicting movement is evaluated to assess split rebalance (SR) opportunities.



(a) Indiana (b) Central and west Indiana

Figure 2.2 Analyzed intersections (map data: Esri, HERE, Garmin, FAO, NOAA, USGS, EPA, NPS).



(a) Split rebalance concept

(b) May 2022 weekdays system RPD from 16:00 to 18:00 hrs.

Figure 2.3 Conflicting movement RPD.

The conflicting movement is easily identifiable as it is located next to the critical movement within the same barrier in the ring diagram. Figure 2.3a shows how this concept works on a standard dual ring diagram. In this hypothetical case, the southbound-left movement (phase 1) is identified as having the highest level of SF in the intersection; hence, becoming the critical movement. Then, the northbound-through movement (phase 2) is the donor as it is next to the critical movement and is located within the same barrier and ring. Therefore, if phase 2 is undersaturated there might be opportunities for split rebalance.

Figure 2.3b shows the Conflicting Movement RPD for the analyzed locations. Each marker represents an evaluated intersection. The horizontal axis represents the split failure ratio of the critical movement. The vertical axis shows the split failure ratio of the conflicting (donor) movement. Only intersections where at least 30 trajectories were sampled for the donor and critical movement are plotted. Dashed lines located at the global split failure ratio (i.e., total number of split failures divided by the total number of sampled trajectories on the analyzed movements) are plotted for reference (callout i). These dashed lines divide the RPD in four quadrants.

1. *Top-left (0 intersections):* this quadrant is always empty as there is no case in which the donor movement has a higher split failure value than the critical movement.
2. *Bottom-left (32 intersections)*: this quadrant shows the intersections where both the critical and donor movements have relatively small split failure ratios; hence, no concerns are raised.
3. *Top-right (6 intersections):* this quadrant shows the intersections were both movements have significant split failures, and split rebalancing is not feasible. Nonetheless, these intersections could potentially be good candidates to evaluate for capital investments that would increase capacity (Gayen, 2024).
4. *Bottom-right (26 intersections):* this quadrant shows the intersections where the critical movement has significant spit failures while the donor movement has values below global average. Here is where the locations with retiming opportunities are found. The closer the donor movement is to zero, the more likely it will be that it can provide split time to the critical phase with no detrimental impact to itself.

Additionally, each marker is color-coded based on the level of DSB of the critical movement Saldivar-

Carranza, Li, Mathew, et al., 2021. This is done because even if an intersection seems like a good candidate for retiming, if progression of vehicles is being blocked by a downstream intersection, then the source of split failures might not be the analyzed location and split rebalance would not alleviate congestion (Li et al., 2017).

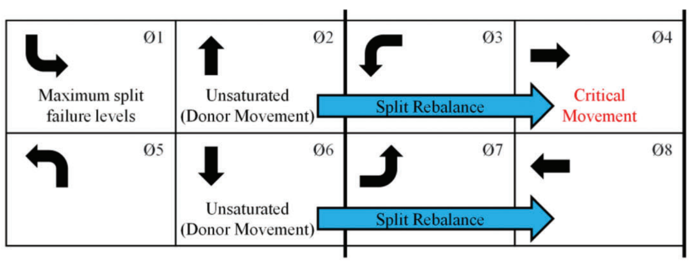
An intersection identified as being a good candidate for signal retiming from Figure 2.3b is indicated by callout ii, US-421 at W 116th St. This intersection has a critical and donor movement with 35% and 1% split failures, respectively and was selected for its significant difference on split failure levels between both movements. Additionally, no DSB on the critical movement was estimated at the location, which indicates that the source of congestion is not a downstream intersection and signal retiming may improve operations.

2.2.2 Opposite Barrier RPD

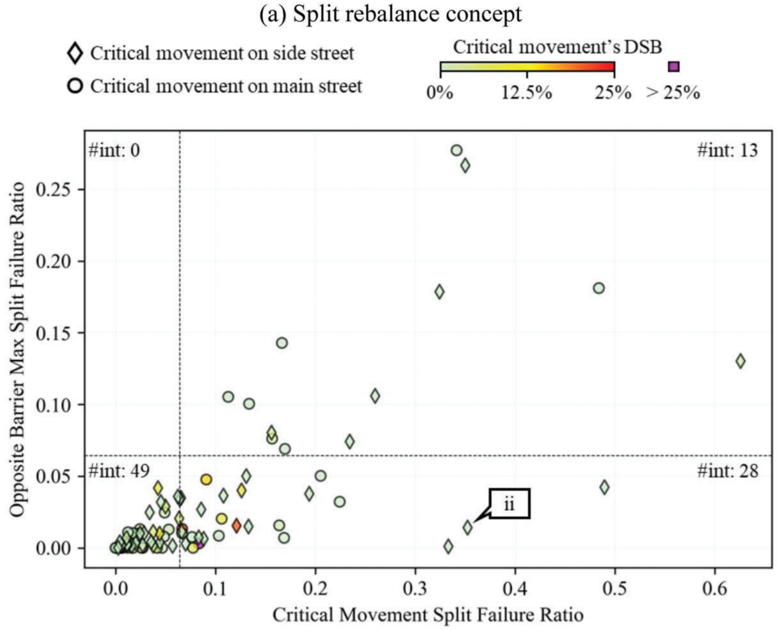
Opposite Barrier and Conflicting Movement RPDs are similar, with the only difference being that the vertical axis on the former is based on the maximum split failure value from the movements on the opposite barrier.

Figure 2.4a shows how this concept works. In this hypothetical case, the eastbound-through movement (phase 4) is identified as having the highest level of SF in the intersection; hence, becoming the critical movement. Then, all the split failure values of the movements on the opposite barrier (phases 1, 2, 5, and 6) are evaluated and the maximum is plotted on the RPD. The maximum is used because any other combination would underestimate the level of congestion at a movement within that barrier. In the example, the southbound-left movement (phase 1) has the maximum split failure value. If the maximum is low, the critical movement's opposite barrier is a viable option for further analysis. In this case, phases 2 and 6 are undersaturated and opportunities for split rebalance are available. Since this technique requires inter-barrier split distribution, the same amount of time modified on one ring must be modified on the other.

Figure 2.4b shows the Opposite Barrier RPD of the signals analyzed. An intersection identified as being a good candidate for signal retiming from Figure 2.4b, that was also identified as having improvement opportunities in Figure 2.3b, is indicated by callout ii. This intersection has a critical movement and opposite maximum with 35% and 1% split failures, respectively.

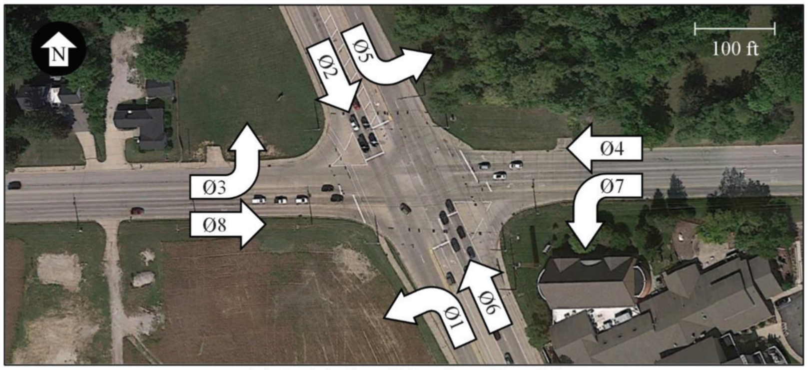


(a) Split rebalance concept

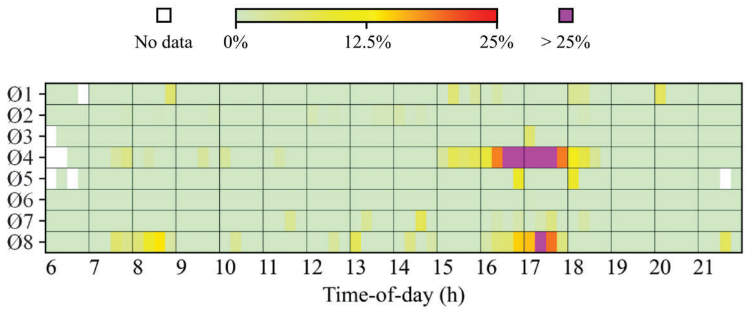


(b) May 2022 weekdays system RPD from 16:00 to 18:00 hrs.

Figure 2.4 Opposite barrier RPD.



(a) Aerial view (Map data: Google)



(b) May 2022 weekdays SF by movement

Figure 2.5 US-421 at W 116th St.

The following subsection further investigates the case of the intersection identified as having retiming opportunities in Figure 2.3b and Figure 2.3b (callout ii).

2.3 Use Case: US-421 at W 116th St.

This subsection provides a deeper analysis of the operational state of the different movements at the intersection based on PPDs (Saldivar-Carranza, Li, Mathew, et al., 2021). Then, from the PPDs and insights gained from site-visits, signal timing modifications were implemented. Finally, a before-after analysis is provided.

Figure 2.5a shows an aerial view of the intersection with its respective movements and phases. The coordinated phases are 2 (southbound-through) and 6 (northbound-through). Figure 2.5b shows a heatmap with the SF estimations for all movements by TOD.

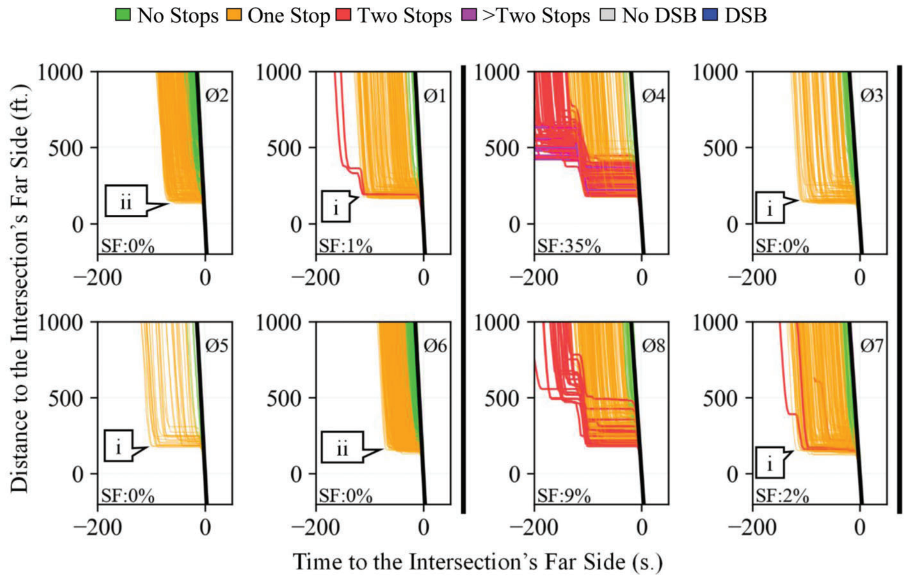
The critical movement is westbound-through (phase 4). However, the eastbound-through movement (phase 8) also experiences significant levels of SF. Both phases have lagging left-turns and do not inherit time from previous phases in the sequence due to floating force-offs. Therefore, it is desired to provide both phases (4 and 8) additional split time and adjust the force-off option to allow them to receive unused green.

Since this intersection appears as a good candidate on both RPDs (Figure 2.3b and Figure 2.4b), time could potentially be rebalanced from either conflicting movements (phases 3 and 7) or the opposite barrier (phases 1, 2, 5, and 6). However, since phases 1, 3, 5, and 7 already have delays close to the cycle length of 120 sec (Figure 2.6a, callout i), it is decided to use phase 2 and 6 as donor movements as those vehicles have significantly shorter delays (Figure 2.6a, callout ii). Thus, the changes implemented for the PM peak period based on the performance estimations, field visits, and engineering judgment are the following.

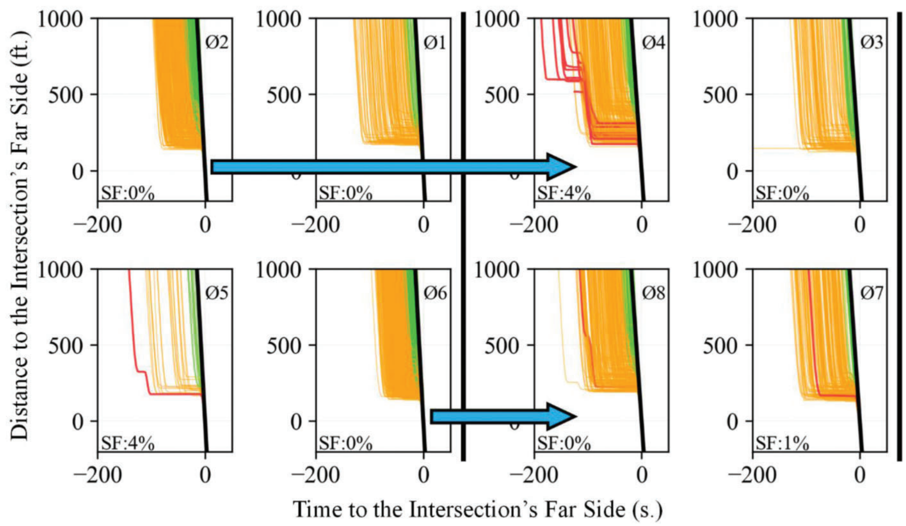
- *Donor phases (2 and 6):* 4.8 sec reduction of split time and 1.8 sec reduction of minimum gap time. Further, set actuated-coordinated (split extension) to 7% and 10%, respectively, to allow the phases to gap out.
- *Critical phases (4 and 8):* additional 4.8 sec of split time and receive any additional unused time from phases 2 and 6 by changing operations to simulate fixed force-offs.
- *Left-turn phases (1, 3, 5, and 7):* changed maximum selection to be limited to the split time to allow phases 4 and 8 to inherit all unused time by 2 and 6.

Figure 2.6 shows the ring diagrams representing the sequence and barriers of this intersection with the PPDs of each movement before and after the timing changes. Figure 2.6b shows blue arrows indicating from which phases time is taken and which phases time is given. The benefits of the implemented changes can be qualitatively observed.

Table 2.1 shows the aggregated change in performance at US-421 and W 116th St. from 2 weeks before and after timing modifications were implemented. Levels of SF, arrivals on green (AOG), and weighted average control delay are assessed for each movement.



(a) Before signal retiming: May 27th to June 9th, 2022, weekdays



(b) After signal retiming: June 10th to June 23rd, 2022, weekdays

Figure 2.6 PPDs ring diagrams at US-421 and W 116th St. from 16:00 to 18:00 hrs.

TABLE 2.1
Performance measure (PM) change at US-421 at W 116th St.

		Phase							
PM	**Period**	**1**	**↓ 2[a]**	**3**	**↑ 4**	**5**	**↓ 6[a]**	**7**	**↑ 8**
SF (%)	Before	1	0	0	35	0	0	2	9
	After	0	0	0	4	4	0	0	0
	Difference	-1	0	0	-30	4	0	-2	-9
AOG (%)	Before	7	49	21	3	11	57	13	12
	After	12	42	23	18	29	54	12	20
	Difference	5	-7	2	15	17	-3	-1	8
Avg. Delay (s/veh)	Before	67	37	52	113	63	34	64	73
	After	62	44	57	60	54	36	56	55
	Difference	-5	7	5	-53	-9	3	-8	-19

[a] Coordinated phases.
↑ Additional green time.
↓ Reduced green time.

Significant SF reductions were accomplished for the critical phases (4 and 8) with no changes for the donors (phases 2 and 6). There were 30% and 9% reductions in split failures, 15% and 8% increase in AOG, and 53 and 19 sec/veh reduction in delay for the benefited target phases 4 and 8, respectively. Simultaneously, the donor phases 2 and 6 experienced no change in split failures, 7% and 3% decrease on AOG, and 7 and 3 sec/veh growth in delay, respectively. Additionally, from field observations, it is found that queues at the critical movement went from having up to 20 vehicles during the before period to only up to 8 vehicles during the after period.

At the intersection level, 6 additional vehicles were sampled in the after period, there was a 3.7% reduction in the occurrence of SF, AOG increased 1.3%, and the average delay reduced by 5.5 sec/veh. This indicates that the implementation of the presented technique resulted in an overall positive impact. The following section discusses how the methodology can be implemented statewide.

3. IMPLEMENTATION

The successful statewide implementation of the presented technique to identify signal retiming opportunities requires of the following:

- movement level performance estimation of all signalized intersections,
- a reporting approach to communicate identified opportunities to practitioners, and
- a business process to prioritize retiming and assess the impact of the modifications.

These points are elaborated in the following sections.

3.1 Coverage of INDOT Signals

To derive movement level PPDs for calculating SF and DSB estimations (Figure 2.1), which is needed to identify retiming opportunities from RPDs (Figure 2.3 and Figure 2.4), intersection geometric features need to be defined. These features include the intersection's

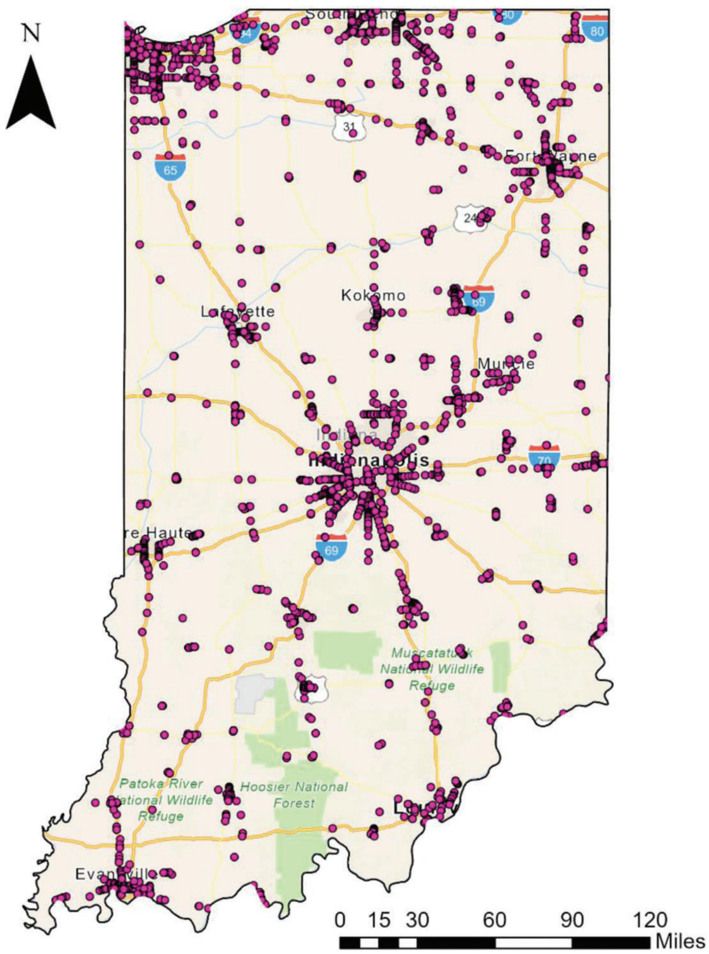


Figure 3.1 Analyzed INDOT intersections (n: 2,346) (map data: Esri, TomTom, Garmin, FAO, NOAA, USGS, EPA, NPS, USFWS).

TABLE 3.1
Attribute summary included in INDOT signal retiming opportunities report

Name	No. Attributes	Description
District	1	INDOT district where the intersection is located
County	1	Indiana county where the intersection is located
ID	1	Internal intersection ID
Name	1	Intersection name
Lat	1	Latitude
Lon	1	Longitude
Direction	1	Direction of travel being reported (i.e., SB, EB, NB, WB)
Movement	1	Turn type being reported (i.e., through, left)
Trajectory Count	1	Number of unique vehicle trajectories analyzed to generate results
SF Ratio (hh:mm:ss)	96	SF estimations by 15-min periods from 00:00 to 23:45 hrs
AM	1	Estimated SF for the AM peak (07:00–09:00 hrs) period
MID	1	Estimated SF for the midday (09:00–16:00 hrs) period
PM	1	Estimated SF for the PM peak (16:00–18:00 hrs) period
DAY	1	Estimated SF for the entire day
Conflicting Opportunity	1	TOD periods identified as having retiming opportunities based on the conflicting movement RPD
Opposite Max Opportunity	1	TOD periods identified as having retiming opportunities based on the opposite maximum RPD

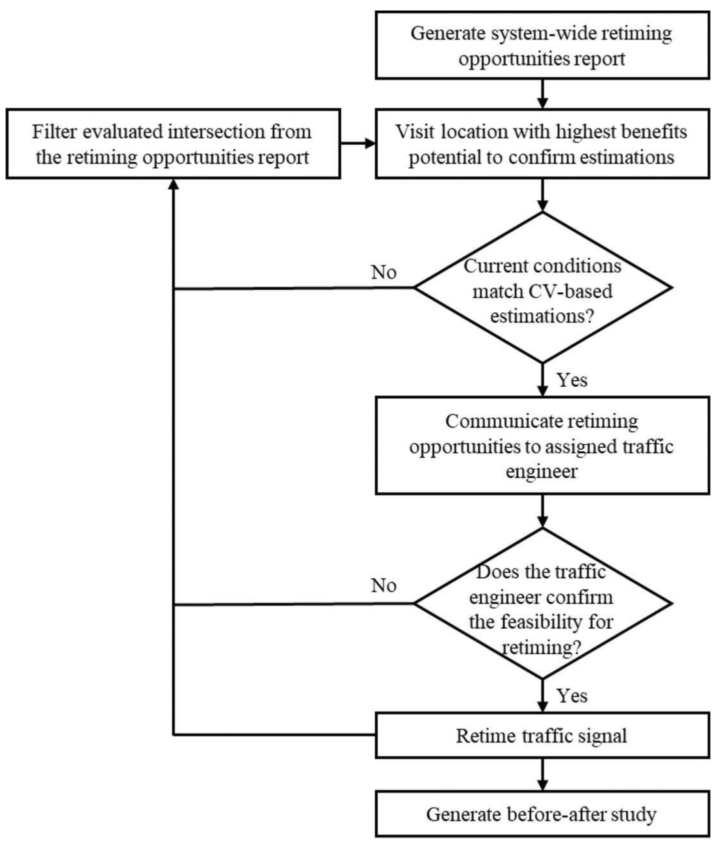


Figure 3.2 Approach to implementing signal timing changes.

center and how far upstream from the intersection vehicle progression is mainly affected just by the evaluated signal (Saldivar-Carranza, Li, & Bullock, 2021). This information usually takes 5 min to record and is used to linear reference and assign intersection movements to traversing vehicles (Saldivar-Carranza et al., 2023).

To accomplish coverage of all INDOT-managed signals, all intersection geometric features need to be defined in all districts. Figure 3.1 shows all 2,346

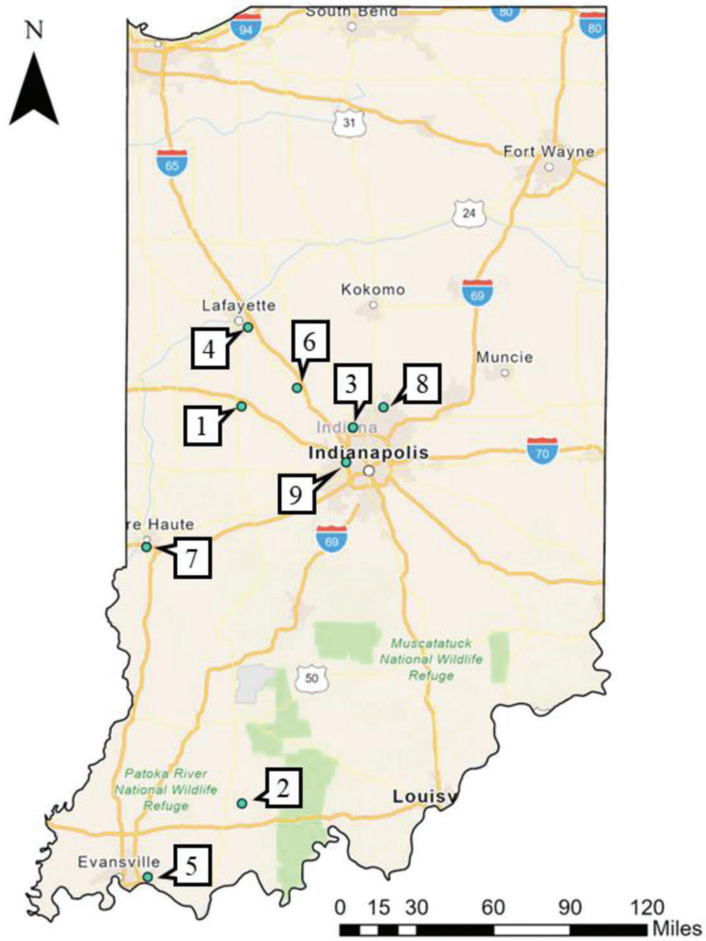


Figure 3.3 Retimed intersections identified with the proposed technique (n: 9) (map data: Esri, TomTom, Garmin, FAO, NOAA, USGS, EPA, NPS, USFWS).

manually defined intersections for performance analysis. Approximately, 200 hours of labor were required to accomplish statewide coverage (as of January 2024). However, once an intersection is defined, no further manual work is needed unless the intersection's geometry changes. Once definitions are completed, trajectory-based performance can be calculated and used to identify signal retiming opportunities.

3.2 Reporting Approach

Even though RPDs (Figures 2.3 and 2.4) provide at-a-glance identification of intersections with potential retiming opportunities, the visualizations can become difficult to assess when thousands of intersections are included for different TOD periods. For this reason, a movement level reporting approach in table format is designed to provide practitioners operational context and suggestions on locations that could potentially benefit from signal retiming.

The columns included in the reporting approach are summarize in Table 3.1 and contain the following.

- *Location information:* district, county, intersection ID, name, latitude, and longitude.
- *Movement information*: direction of travel and turn type.
- *Performance information:* number of trajectories analyzed, calculated SF ratios by 15-min periods, during the AM, MID, and PM periods, and over the entire day.
- *Opportunities identification:* whether the movement has opportunities for retiming as indicated by the conflicting movement and opposite barrier RPDs during the analyzed periods.

The most relevant columns of the report are "conflicting opportunity" and "opposite max opportunity." These columns indicate if the analyzed movement has retiming opportunities during the AM, MID, PM, or DAY periods based on each type of RPD plot. With this approach, the 13,420 movements of the 2,346 signalized intersections (Figure 3.1) that count with enough sampled trajectory data for analysis can be screened and prioritized for retiming efforts. Locations with retiming suggestions can be further filtered based on location, severity of SF estimations, and based on the number of sampled trajectories.

TABLE 3.2
Overview of challenges and modifications

ID	Name	TOD	Description
1	SR 32 at SR 47	14:45–16:00 hrs (MID)	Congestion caused by shift changes prompted green time reallocation to most affected movements.
1	SR 32 at SR 47	06:45–08:00 hrs (AM)	Congestion caused by shift changes prompted green time reallocation to most affected movements.
2	SR 64 at SR 162	16:00–18:00 hrs (PM)	Broken detection was fixed.
3	US-421 at W 116th St.	16:00–18:00 hrs (PM)	Green time was reallocated from uncongested to congested movements.
3	US-421 at W 116th St.	07:00–09:00 hrs (AM)	Green time was reallocated from uncongested to congested movements.
4	SR 38 at Creasy Ln	14:00–18:00 hrs (PM)	Green time was reallocated from an uncongested to a congested movement.
5	SR 66 at Bell	15:00–19:00 hrs (PM)	Green time was reallocated from an uncongested to a congested movement.
6	US-52 at SR 47	15:00–17:00 hrs (PM)	Maximum green was extended for a congested movement.
7	US-41 at Margaret Ave	14:00–20:00 hrs (PM)	Green time was reallocated from an uncongested to a congested movement.
8	SR 32 at Little Chicago Rd	15:00–19:00 hrs (PM)	Green time was reallocated from an uncongested to a congested movement.
9	US-136 at Waterfront Pkwy W	16:00–18:00 hrs (PM)	Gap out time was extended to compensate for a shorter detection area due to broken detection.

TABLE 3.3
Performance change at directly affected movements

		Beneficiary Movement(s) Performance Difference				Donor Movement(s) Performance Difference			
ID	**TOD**	**n**	**SF (%)**	**AOG (%)**	**Delay (s/veh)**	**n**	**SF (%)**	**AOG (%)**	**Delay (s/veh)**
1	MID	-18	-13.4	+3.8	-19.9	-67	+1.9	-7.6	+2.6
1	AM	-5	-10.6	+16.5	-13.0	+9	0.0	-0.6	-3.6
2	PM	+92	-6.8	+14.7	-12.0	–	–	–	–
3	PM	+28	-19.4	+11.4	-35.6	+47	0.0	-4.7	+4.5
3	AM	+19	-3.5	+9.0	-9.8	+88	+0.2	-10.0	+7.4
4	PM	+31	-5.5	+3.6	-8.7	-13	+0.2	-2.8	-1.7
5	PM	+1	-14.9	+4.0	-25.9	+15	+3.1	-1.6	-1.6
6	PM	+2	-9.0	+21.2	-26.9	–	–	–	–
7	PM	-27	-6.8	+7.2	-13.6	+508	0.0	-5.1	+3.3
8	PM	+9	-5.0	+8.9	-13.1	-58	-0.5	-4.4	+7.8
9	PM	+2	-25.0	+17.5	-40.1	–	–	–	–

TABLE 3.4
Intersection level change in performance

ID	TOD	n	SF (%)	AOG (%)	Delay (s/veh)
1	MID	-92	-4.7	-2.7	-7.1
2	PM	+160	-4.7	+8.4	-5.8
1	AM	+6	-4.0	+6.5	-8.1
3	PM	+6	-3.7	+1.3	-5.5
4	PM	+5	-1.7	+0.7	-3.6
5	PM	-62	-1.2	-2.7	-0.3
6	PM	-97	-0.8	+0.6	-2.6
7	PM	+52	-0.7	+4.5	-3.6
3	AM	+155	-0.5	-5.0	+3.5
8	PM	-498	-0.3	-0.8	+2.6
9	PM	-349	-0.2	-4.8	+4.5

3.3 Signalized Intersection Retiming

Once a trajectory-based signal retiming opportunities report is generated (Table 3.1), various steps need to be followed to implement and assess suggested changes. First, the location with highest benefits potential, as indicated by agency objectives, needs to be visited to confirm estimated operations. If operations are as expected, and retiming appears as a viable solution, the traffic signal engineer that manages the evaluated location needs to confirm the feasibility for timing modifications. If that is the case, signal retiming can be implemented, and a before-after evaluation of performance should be performed to assess the impact of the changes. These steps are graphically described in Figure 3.2.

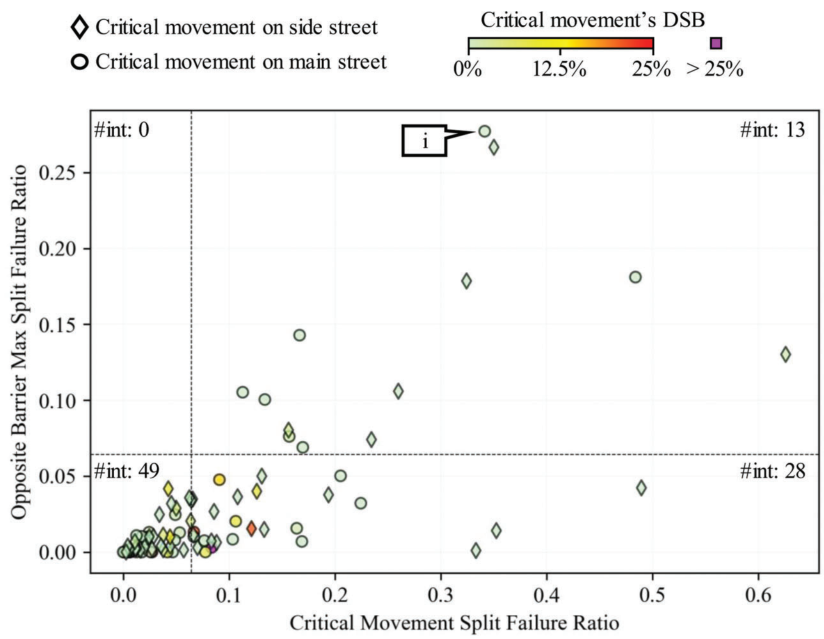
Following this approach, a total of eleven timing changes have been implemented at nine signalized intersections in central, west, and south Indiana over various TOD periods. The location of these intersections is shown in Figure 3.3.

Table 3.2 provides an overview of the challenges at each intersection and the high-level timing changes that were made to attempt to improve operations. It is important to note that the focus was weekday performance and weekends were no considered for this analysis. Most challenges originated from congestion; however, the problems at few locations (intersection IDs 2 and 9) were caused by broken detection that created split failure events at the critical movements.

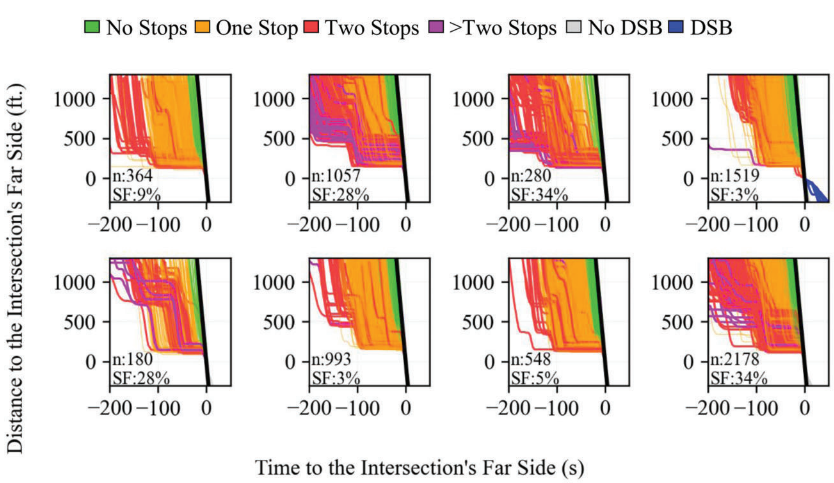
The effects that the changes described on Table 3.2 had on performance is discussed below.

3.3.1 Before-After Assessments

Table 3.3 presents the change in sampled trajectories (n), SF percentage, AOG percentage, and average control delay at the beneficiary and donor movements between 2 weeks before and 2 weeks after the changes described in Table 3.2 took place. A general increase in AOG, and reductions in SF and average delay at the benefited movements indicate that mobility at critical movements improved. However, as expected, donor



(a) May 2022 weekdays system RPD from 16:00 to 18:00 hrs.



(b) PPDs ring diagram at US-40 and Ronald Reagan from 16:00 to 18:00 hrs. (Figure 12a, callout i)

Figure 4.1 Opposite barrier RPD and relevant PPD ring diagram with no opportunities for retiming.

movements experienced moderate degradation of signal performance.

To take into consideration the effects that retiming changes may have on all movements at a location, intersection level performance needs to be calculated. Table 3.4 shows the intersection level performance change at all modified intersections. Since the signal retiming identification technique inherently aims at reducing the occurrence of split failure events at critical movements, a general reduction in the percentage of SF was accomplished. However, since the benefited movements were seldom coordinated, AOG results are mixed, with some locations improving and others deteriorating this performance measure. Regarding intersection delay, most locations saw reduced wait times as split failing events, which decreased, usually significantly contribute to this measurement.

4. DISCUSSION

Signal performance can be improved (Table 3.3 and Table 3.4) following the techniques (Figure 2.3 and Figure 2.4) and business processes (Figure 3.2) presented in this document. Since the methodology is based on scalable CV trajectory data that provides coverage of virtually any intersection, no detection or communication infrastructure needs to me installed or maintained. Furthermore, the reporting approach presented (Table 3.1) provides agencies with capabilities to assess and prioritize thousands of signal retiming efforts statewide.

The RPD approach to identify signal retiming opportunities proved capable of not only identifying capacity challenges produced by congestion, but also due to broken detection. This is because the technique identifies critical movements that have the highest ratio of split failure events at an intersection that also have possible donors of green time, without regarding the cause of congestion. Therefore, the methodology provides flexibility as it highlights challenges even when detection or communication equipment at the signal is not operational.

Additionally, the objective of the retiming opportunities identification technique could be changed to target other performance measures, such as increasing AOG or decreasing delay. During this project, the technique focused on reducing the occurrence of split failure events; hence, split failures were lowered (Table 3.3 and Table 3.4) at the modified intersections.

Even though the proposed technique provides significant scalable benefits, some limitations exist. The RPD-based identification of retiming opportunities assumes a sequence at each intersection and that signals use fixed force-offs (i.e., every movement can receive unused time from previous phases). For the first point, it is important to distinguish leading phases that have been identified as donors but may already be running efficiently because of gap out. In addition, timing plans that run floating force-offs do not allow non-coordinated movements to inherit unused green time and may be preventing the controller from efficiently allocating additional green to split-failing movements. Confirmation of timing plans remotely or via field visits is necessary before any adjustments are made. Furthermore, it is important to maintain constant communication with the traffic signal engineer managing the intersection to identify other challenges, such as the existence of pedestrian phases that would limit split rebalance (Figure 3.2).

4.1 Concept Extension to Identify Capital Projects

In some cases where all movements along one or more critical paths are over saturated, there is no feasible opportunity to reallocate green time (Figure 4.1). In those cases, the intersections are candidate for capital projects. A companion project, SPR-4857, was initiated to adapt these concepts to identifying those opportunities.

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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.

Further information about JTRP and its current research program is available at http://www.purdue.edu/jtrp.

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