Deriving Operational Traffic Signal Performance Measures from Vehicle Trajectory Data

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Abstract

Operations-oriented traffic signal performance measures are important for identifying the need for retiming to improve traffic signal operations. Currently, most traffic signal performance measures are obtained from high-resolution traffic signal controller event data, which provides information on an intersection-by-intersection basis and requires significant initial capital investment. Over 400 billion vehicle trajectory points are generated each month in the United States. This paper proposes using high-fidelity vehicle trajectory data to produce traffic signal performance measures such as: split failure, downstream blockage, and quality of progression, as well as traditional Highway Capacity Manual level of service. Geo-fences are created at specific signalized intersections to filter vehicle waypoints that lie within the generated boundaries. These waypoints are then converted into trajectories that are relative to the intersection. A case study is presented that summarizes the performance of an eight-intersection corridor with four different timing plans using over 160,000 trajectories and 1.4 million GPS samples collected during weekdays in July 2019 between 5:00 a.m. and 10:00 p.m. The paper concludes by commenting on current probe data penetration rates, indicating that these techniques can be applied to corridors with annual average daily traffic of ~15,000 vehicles per day for the mainline approaches, and discussing cloud-based implementation opportunities.

Literature Review

Developments in ATSPMs since 2010 have equipped traffic signal practitioners with a robust set of tools to make proactive, data-driven maintenance and operational decisions across their systems (1, 2, 4, 6). The technology has been institutionalized in at least four U.S. states and is being assessed or demonstrated in 27 others (1), with additional deployments and pilots in at least 44 local jurisdictions around the United States. Key catalysts for adoption are having reliable communication links between the field cabinets and the traffic operations.
center (7), and having functional detection systems at the intersection (8).

Recently, performance measures developed from point-based probe GPS sources via smartphone applications, fleet telematics, and connected vehicles have emerged. This type of probe or “trajectory” data offered by commercial providers typically contains latitude, longitude, timestamp, speed, heading, and a unique obfuscated trip identifier. Studies have demonstrated that metrics such as travel time, delay, arrivals on green, and queue length can be produced using trajectories (9–13). A major benefit is that it leapfrogs the requirement to build and maintain communication and detection systems (4).

Each performance measure requires some reasonable level of penetration for the data to accurately represent on-the-ground conditions. Day et al. (9) concluded that a penetration rate between 0.09% and 0.80% was sufficient to optimize offsets with similar performance to data collected by physical loop detectors by aggregating data over multiple days. Waddell et al. (12) determined that even after extensive data cleaning, the remaining dataset with a penetration rate below 0.04% can still be used to identify offset adjustment opportunities. Zhao et al. (10) explored data with penetration rates as high as 15% to estimate queue lengths and volume, which approached the recommended rate proposed by Argote-Cabañero et al. (14) to estimate average delay in the oversaturated regime.

According to the Highway Capacity Manual (6th edition), the common methods to assess intersection performance are control delay and level of service (LOS) (15). As more states bring ATSPMs into their day-to-day workflows, it is important to identify and include both traditional delay based performance metrics as well as operational performance metrics that agencies can use to make timing adjustments. For example, according to the Utah Department of Transportation’s Chart Usage Report website (16), between January 1 and July 1, 2020, the most-used ATSPM was the Purdue Phase Termination diagram (7), followed by Approach Volume and Turning Movement Counts.

Tracking phase termination status by time of day (TOD) is essential for practitioners to determine whether specific movements at an intersection require more split time or if the intersection is at capacity (17–19). Freije et al. (18) proposed a method to estimate split failures using stop bar detection. Wu and Liu (20) used setback detector data to implement a shockwave-based queue estimation model to determine when an approach is at over-capacity. Emtenan and Day (21) concluded that detectors with a fixed setback closer to the stop bar typically underestimate the number of stops caused by queues. As the detector setback was increased, the accuracy of estimating the number of stops also increased (21). With a higher penetration of probes, there is an opportunity to leverage the data for estimating conventional Highway Capacity Manual metrics such as LOS and delay, as well as to develop new methodologies to overcome limitations of fixed-sensor systems that would work well in undersaturated and oversaturated regimes.

Proposed Approach

This paper develops scalable trajectory analysis techniques to compute:

- movement LOS,
- proportion of vehicles arriving on green,
- frequency of split failures and
- frequency of downstream blockage.

Subsequently, a comparison between a traditional Purdue coordination diagram and a crowdsourced performance measure is made. The paper concludes with proposed corridor-wide graphical summary techniques that can quite efficiently be scaled to several hundred intersections.

Study Corridor

In this study, crowdsourced performance measures are computed for a corridor located south of Indianapolis, IN (Figure 1a, callout i). The corridor is comprised of eight signalized intersections (Figure 1b). The first intersection when traveling southbound (SB) is Thompson Rd, followed by Harding St, Epler Ave, Southport Rd, Wicker Rd, County Line Rd, Fairview Rd and Smith Valley Rd. These intersections have four different TOD timing plans:

- Morning peak (AM): 05:00–09:15
- Midday (MD): 09:15–14:30
- Afternoon peak (PM): 14:30–19:00
- Evening (EV): 19:00–22:00.

Trip counts were calculated for each intersection to assess the penetration level of the third-party crowdsourced trajectory data utilized in this study. Figure 1c shows a summary of the trip counts by TOD timing plans for July 2019 weekdays. For this time period, over 1.4 million GPS points in 160,000 trips were analyzed during the TOD timing plans. All trips in the dataset have a frequency of 3 s between pings. The median penetration of the trajectory data in the corridor is 2% for weekdays in July 2019 during the TOD analyzed. From the available data, the median corridor travel time was calculated to be 522 s.
Trajectory Data

The third-party crowdsourced trajectory data used in this study is comprised of individual waypoints with a reporting interval of 3 s. Each waypoint has the following information: GPS location, measured-on-vehicle speed, heading, timestamp, and an anonymous trajectory identification number. By linking individual waypoints by their trajectory identification number, a vehicle’s trajectory can be obtained.

To reference trajectories to the study locations geo-fences were created. By filtering trajectories that lie within the boundaries of the geo-fences, and by taking into consideration the position of the initial and final waypoints, trajectories that crossed a specific intersection with a particular movement can be obtained.

Delay Based Performance Measures Concepts

The two most popular delay definitions used to evaluate intersections are stopped delay and control delay (Figure 2) (2, 22). Stopped delay is defined as the amount of time that a vehicle has a speed of zero \( t_3 - t_2 \) at an intersection. Control delay includes the delay caused by deceleration, the stopped delay, and the delay caused by acceleration.

\[
\text{Control Delay} = t_4 - t_1 - \text{Free Flow Trajectory Travel Time},
\]

Figure 1. SR-37 study corridor and trip count summary: (a) SR-37 in Indianapolis, IN (ESRI, data available under the Attribution-ShareAlike 2.0 Generic license), (b) SR-37 and intersection IDs (ESRI, data available under the Attribution-ShareAlike 2.0 Generic license), and (c) SR-37 trip counts in all directions, by intersection, on July 2019 weekdays for the different time of day timing plans. Note: AM = 05:00–09:15; MD = 09:15–14:30; PM = 14:30–19:00; EV = 19:00–22:00.
where

\[
\text{Free Flow Trajectory Travel Time} = \frac{L_1 - L_4}{\text{Speed Limit}} \quad (2)
\]

\(t_1\) is the time when the vehicle started decelerating (s), \(t_4\) is the time when the vehicle stopped accelerating (s), \(L_1\) is the distance where deceleration started (ft.), \(L_4\) is the distance where acceleration ended (ft.), and \text{Speed Limit} is the segment’s speed limit in feet per second.

**Control Delay LOS**

LOS is a qualitative description of the operating conditions at an intersection. It is based on the control delay experienced by vehicles (23). Table 1 shows the different LOS ratings with qualitative descriptions and their respective range of control delay.

By utilizing Equations 1 and 2 and Table 1 criteria, individual trajectories can be assigned a LOS rating. Figure 3a depicts a time–space diagram where the vertical axis is the distance in feet to the intersection’s stop bar (callout ix) and the horizontal axis is the time in seconds relative to when the vehicle crosses the far side (callout x) of the intersection. Callout viii is a free-flow trajectory (FFT), which is the trajectory of a vehicle traveling at the posted speed limit without stopping. Callouts i–vi are a series of trajectories of vehicles traveling northbound (NB) through, at SR-37 and Southport Rd, color coded by their LOS rating, during the MD timing plan between July 22 and July 26, 2019. The farther away a trajectory approaches the stop bar from the FFT, the greater its delay will be.

### Table 1. Highway Capacity Manual Level of Service Criteria for Signalized Intersections (23)

| Level of service | Average control delay (seconds/vehicle) | Description |
|------------------|----------------------------------------|-------------|
| A                | \(\leq 10\)                             | Free flow   |
| B                | >10–20                                 | Stable flow (slight delay) |
| C                | >20–35                                 | Stable flow (acceptable delays) |
| D                | >35–55                                 | Approaching unstable flow (tolerable delay) |
| E                | >55–80                                 | Unstable flow (intolerable delay) |
| F                | >80                                    | Forced flow (congested and queues fail to clear) |

**Figure 2.** Delay definitions (22).

**Figure 3.** Vehicle trajectories traveling northbound (NB) through during the midday period at SR-37 and Southport Rd from July 22 to July 26, 2019: (a) six trajectories with different level of service (LOS) ratings, (b) all 452 trajectories available for the time of day and analysis period, and (c) percentage of trajectories by their LOS.

*Note: FFT = free-flow trajectory.*
Callout vii is a segregation line that helps to visually separate trajectories by their LOS, in this case the boundary between LOS E and LOS F. It is important to note that the objective of the segregation lines is merely to help set visual boundaries, since they are only based on the deceleration and stopped delay components of control delay.

Figure 3a is a subset of Figure 3b, in which all the 452 trajectories of vehicles traveling NB through, during the MD TOD timing plan between July 22 and July 26, 2019, are shown. Figure 3c is a pie chart of what percentage of the trajectories in Figure 3b were characterized with the different LOS ratings. It is worth noting that because of the 3 s period between waypoints, some individual vehicle trajectories may be misclassified by one LOS. Nevertheless, the distribution of this error is uniform; therefore, on average, no statistical bias is introduced.

From Figure 3c, 38% of the trajectories during the analysis period were classified as LOS A, but a considerable amount of trajectories were in LOS E or LOS F (10% and 7% respectively).

Numerical Comparison on Estimated Control Delay and Stopped Delay

Table 2 shows the estimated control delay and stopped delay values for the trajectories presented in Figure 3a. The difference between these two delay definitions becomes clearer when we have trajectories that do not stop at the intersection, nonetheless they have to slow down or travel at slower speeds due to the intersection (callouts i and ii). The last column shows the corresponding LOS using the estimated control delay and the LOS thresholds shown in Table 1.

Operational Based Performance Measures

Motorists’ general expectations of traffic signals are:

1. Well synchronized signals such that motorists arrive during the green interval and do not have to stop upstream of the signal,
2. Sufficient green time so they can proceed through in one cycle,
3. Sufficient coordination with adjacent signal so they can proceed through an intersection unimpeded by downstream queues.

In the past, arrivals on green have been evaluated using the Purdue coordination diagram (PCD) (2, 24, 25) and diagnosis of sufficient green time has been made using the Purdue split failures (18, 26). Downstream blockage has been quite difficult to differentiate from split failures using traditional high-resolution data.

The use of trajectory-based data provides an opportunity to look holistically at these three operational performance measures from the perspective of individual vehicles. This section introduces a new visualization tool called the Purdue probe diagram (PPD).

Arrivals on Green: Purdue Probe Diagram. Arrivals on green (AOG) is a performance measure that indicates the percentage of vehicles that arrive at a signalized intersection during the green phase of the cycle. This measurement provides an indication of the performance of coordinated intersections. Low AOG values indicate that vehicle platoons are not progressing through the corridor as intended.

Since crowdsourced trajectory data do not directly provide information on the state of signalized intersections, methods have to be developed to infer the signal condition at arrival. For this reason, a new trajectory-based performance measure graphic, capable of providing AOG, is proposed, the Purdue probe diagram.

A PPD for the PM timing plan for vehicles traveling NB at SR-37 and Southport Rd between July 22 and July 26, 2019 is presented in Figure 4a. The graphic is similar to the one shown in Figure 3b, with the main difference being that trajectories in Figure 4a are color coded by the number of stops during the approach.

The first time a vehicle’s speed goes to zero when approaching an intersection, the trajectory is attributed one stop. After this, every time a vehicle’s speed goes from non-zero to zero, after traveling for at least 100 ft following the previous stop, it is categorized with an additional stop. The 100 ft filtering is done to avoid counting extra stops when vehicles are just inching forward when waiting for green in the queue. AOG is then calculated as the ratio between trajectories that had no stops during the approach and the total number of trajectories.

Figure 4a depicts trajectories that experienced zero, one, two, and more than two stops. Trajectories that did not stop during the approach (green) are closer to the FFT, and therefore have a smaller delay than trajectories with one or more stops. Additionally, some no-stop trajectories appear to the right of the FFT, which is an indication of vehicles traveling above the speed limit.

Table 2. Delays for Trajectories in Figure 3a

| Callout | Estimated control delay (s) | Estimated stopped delay (s) | Level of service |
|---------|-----------------------------|-----------------------------|------------------|
| i       | 3                           | 0                           | A                |
| ii      | 18                          | 0                           | B                |
| iii     | 34                          | 12                          | C                |
| iv      | 49                          | 18                          | D                |
| v       | 74                          | 54                          | E                |
| vi      | 113                         | 60                          | F                |

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Figure 4 is a pie chart of the percentage of trajectories in Figure 4a that were categorized with different numbers of stops. The percentage of vehicles that had no stops is the same as the AOG value. In this case, 65% of vehicles arrived at the intersection during green, 34% experienced one stop and only 0.4% had two stops or more.

Split Failures. A split failure is when a traffic signal does not provide enough green time to allow vehicles in a particular movement to cross the intersection, thus making them wait for longer than one cycle length. Split failures occurring on an approach are an indicator of that approach operating at overcapacity. Being able to locate where and when split failures occur is important for agencies to identify opportunities to reallocate green time to improve system operation (18).

Using the PPD, a vehicle trajectory is categorized as having experienced a split failure when it stops two times, or more, when approaching an intersection. In the PPD shown in Figure 4a, two vehicles experienced split failures. Focusing on the trajectory that stopped twice (callout i), it can be observed how the vehicle stopped for the first time around 650 ft away from the stop bar (callout ii) and a second time right before the stop bar (callout iii). From Figure 4b, it is observed that only 0.4% of vehicles experienced a split failure for the analyzed time period at the specified location.

Downstream Blockage. Downstream blockage is when there is a queue at the downstream intersection that obstructs the progression of vehicles. Identifying downstream blockage is important as a means to pinpoint locations where an oversaturated intersection is having an effect on an adjacent intersection. In some cases, an adjustment of the downstream green may address the problem, in other cases an agency must make a policy decision on how to manage those oversaturated conditions and the impact on the overall network.

In this study, downstream blockage has been defined as any trajectory that after crossing the far side of the intersection has at least a 10 s delay compared with the FFT. A 10 s threshold is utilized since, in the worst non-blocked scenario, a vehicle would take about 7 s to reach free-flow speed after crossing the far side. The previous calculation is based on the geometry at County Line Rd (narrowest intersection) and on a constant acceleration of 6.6 ft/s² as suggested by Long (27). Figure 5 shows a PPD with 735 trajectories traveling NB during the AM period from July 22 to July 26, 2019 at SR-37 and Thompson Rd. All the trajectories that are located to the right of a line offset by 10 s from the FFT (callout i) were categorized as having experienced downstream blockage (callout ii). In this example, 22 of the trajectories, or 3%, were classified as experiencing downstream blockage.

Visualizing Coordinated Movements by TOD

Now that PPDs have been introduced, a more thorough analysis of an intersection can be made. Figures 6 and 7 show PPDs of vehicle trajectories traveling SB and NB through, respectively, at SR-37 and Southport Rd on July 2019 weekdays during all the TOD timing plans. Figures 6a and 7a depict all the trajectories crossing the intersection by TOD, color coded by the number of stops. The variation on progression quality can be qualitatively viewed by looking for changes between green (good progression) and orange, red, or purple (poor progression).
For this corridor, the peak flows are NB (Figure 7) in the morning and SB (Figure 6) in the evening. Looking at the NB morning PPD (Figure 7b), there are 1,358 trajectories depicted, and 63% of the vehicles arrived on green with no stops. Throughout the day, the percentage of vehicles with no stops ranges between 57% and 73%. The number split failures (two or more stops) is around 1% for the AM and PM peak periods.

For the SB trajectories (Figure 6), the percent of vehicles arriving on green with no stops ranges from 49% to 79%. The southbound PM (Figure 6d) period has the highest proportion of split failures (12%) and the lowest proportion of vehicles arriving on green (49%). The following section discusses the impact of split failures on coordination in more detail and subsequent sections discuss comprehensive analysis of all movements along the corridor during shorter time intervals.

**Comparison of PCD and PPD**

The PCD has been the graphic traditionally utilized to visualize the quality of progression. In a PCD, the analysis pivots detector events on a cycle reference point. In PPD, the analysis pivots the arrival trajectory based on the time to arrival at the far side of an intersection.

A PCD for vehicles traveling SB at SR-37 and Southport Rd on July 22, 2019 is shown in Figure 8a. The vertical axis is the time-in-cycle of the traffic signal and the horizontal axis is TOD. The traffic signal cycle is divided into two sections: effective red and effective green. The red line marks the beginning of red, and the green line marks the beginning of green. Vehicle arrivals at the advance detector are depicted by black dots (2). Therefore, black dots that lie within the horizontal axis and the green line are vehicles that arrived to the intersection during the effective red; in contrast, black dots that lie between the green line and the red line are vehicles that arrived during the effective green. The PCD shown in Figure 8a also has vertical blue lines that separate the different TOD timing plans.

During the PM period in Figure 8a, there are moments where there are no AOGs (callout i) while the time-in-cycle advances, but then arrivals suddenly appear. This is an indication that vehicles had to wait in a long queue until they could cross over the advance detector. This suggests that the approach is operating at overcapacity and vehicles may have experienced split failures. However, with the traditional PCD graphic, it is impossible to be completely sure if vehicles are waiting for longer than one cycle length, since it is also possible that the queue is being completely discharged at every iteration.

Figure 8b shows a PPD for vehicle trajectories traveling SB at SR-37 and Southport Rd on July 22 2019 during the PM timing plan. In contrast to the PCD that pivots on a cycle reference time, the PPD pivots on the time a vehicle crosses the far side of the intersection. The PPD clearly shows trajectories that have experienced split failures (red), since they have stopped twice when approaching the intersection. This additional probe data verifies the assumptions made with the PCD with regard to the approach operating at overcapacity, but is not available using traditional event-based traffic signal performance measures.

An advantage of performance measures obtained from crowdsourced trajectories (e.g., PPDs) rather than high-resolution controller data (e.g., PCDs) is that the distance from the stop bar of virtual advance detectors can be modified. This allows for a more accurate representation of the state of the signal’s operation (27).
In Figure 8b, callout ii is the location where advance detectors are usually placed, 400 ft upstream from the stop bar. Arrival flow profiles (AFPs) can be derived by counting when vehicles are crossing the advance detection line. AFPs are especially useful to visualize the number of vehicles that arrive at an intersection and the delay that was experienced (28).

Two AFPs are created based on two different virtual advance detectors: one 400 ft before the stop bar (callout ii), and the other 1,000 ft before the stop bar (callout iii). In the first case, with the 400 ft virtual advance detector (Figure 8c), it would appear that a majority of vehicles, with diverse number of stops, arrive at the intersections without any significant delay (callout iv). This result is deceptive because, from the proximity of the virtual advance detector to the stop bar, relevant information on the vehicles’ trajectories from before crossing the detection line is lost. Conversely, an AFP based on the 1,000 ft virtual advance detector (Figure 8d) produces a more accurate characterization of when vehicles are arriving at the intersection.

Additionally, from the PCD, an AOG of 66% is obtained for the PM timing plan; nevertheless, as mentioned before, this result might be deceptive because the approach is operating at overcapacity. On the other hand, from the PPD we can calculate a more accurate AOG of 36%.
Proposed Summary Graphics for Corridors

Until now, only performance measures that describe the efficiency at the intersection level have been discussed. However, an agency needs corridor level reports and graphics for quick assessment of system level operation. To address this need for a system overview, six different graphs are proposed to broaden the scope of the signalized intersection analysis. Figures 9 and 10 characterize the SB through and protected left movements, respectively, for vehicle trajectories traveling on July 2019 weekdays during the different TOD timing plans. Figure 11 provides a comprehensive hourly overview of split failures for the SR 37 through movements and left turns for all the weekdays in July 2019. For the sake of space, the cross streets are omitted. Additional details on how to interpret these graphics are provided below:

1. Bar graphs indicating the number of unique trajectories that followed the analyzed movement by intersection and by TOD timing plan: Figures 9a and 10a. These graphics provide practitioners with a sense of the volume differences between intersections, which can facilitate comparisons.
2. Stacked bar graphs portraying LOS by intersection and by TOD timing plan: Figures 9b and 10b. Although this graphic is not particularly useful for operational decisions, agency planning departments use LOS quite frequently and this information can be easily included in the portfolio of summary graphics.

3. Stacked bar graphs indicating number of stops by intersection and by TOD timing plan: Figures 9c and 10c. These graphics are very useful for assessing quality of progression (smooth flow).

4. Bar graphs portraying percentage of trajectories that experienced split failures by intersection and by TOD timing plan: Figures 9d and 10d. These graphics are useful for identifying intersections where there may be opportunities to rebalance green times and what TOD plan to examine.

5. Bar graphs portraying percentage of trajectories that experienced downstream blockage by intersection and by TOD timing plan: Figures 9e and 10e. These graphics are useful for agencies to identify intersections impacted by adjacent intersections.

6. Heat maps indicating the percentage of trajectories that experienced split failures by intersection and by TOD: Figure 11. These provide a one-page graphic that broadly characterizes green time allocation for both through and left turn movements. They are particularly useful for sharing before/after studies with non-technical groups. They summarize the split failures in shorter time periods than the other graphics, in this case 15 min.

**Scalability and Implementation Recommendations**

Data storage for generating the performance measures proposed in this paper can be a challenge. With the emergence and increasing adoption of cloud storage and computing services, queries and processing of the data can reside in the cloud, as opposed to procuring and upgrading traditional on-premises systems to meet capacity requirements. For instance, using a popular cloud database platform for data queries and stores, automated dashboards can be developed to generate figures such as those shown in Figures 6, 7, 9, 10, and 11 in under 1 min for computation costs of $0.01, $0.01, $0.09, $0.09, and $0.38 respectively. Additionally, data ingestion and yearly storage for the state of Indiana July 2019 trajectory data can be acquired for a cost of $2.11 and $55.86, respectively.

Based on the 2% penetration observed in this data set, the authors believe the methodologies presented in this paper can be scaled to most urban areas without deploying any intersection-based hardware. For any agency wanting to prioritize infrastructure investments over 100 intersections, one could produce a report similar to that in Figure 11 for less than $5.00 in cloud computing costs without the need of any fixed sensors or site visits. Additional costs for the data are needed and vary by state and locale. If the side streets were included, the cloud computation cost would be approximately $10.00.

The analyzed signalized intersections experience an average annual daily traffic (AADT) of ~15,000 vehicles per day for each mainline through movement. These volumes yielded accurate results. As penetration rates
increase, the lower bound on the necessary AADT will decrease. Further, since the query cost represents a significant component of the total cost of producing reports and performance measures, creating subsets along targeted study corridors and partitioning the data could reduce costs.

Figure 9. SR-37 results for vehicles traveling southbound (SB) through during all the weekdays in July 2019 for the different time of day timing plans: (a) unique trajectory counts, (b) percentage of trajectories by level of service, (c) percentage of trajectories by number of stops, (d) percentage of trajectories with split failures, and (e) percentage of trajectories with downstream blockage. Note: AM = 05:00–09:15; MD = 09:15–14:30; PM = 14:30–19:00; EV = 19:00–22:00.

**Conclusion**

This paper proposed a methodology for analyzing vehicle trajectories to derive operational performance measures for traffic signals. This methodology was demonstrated using an eight-intersection corridor in Indianapolis.
utilizing 1.4 million GPS points associated with 160,000 trips with a 3 s ping interval, during all the weekdays in July 2019 between 5:00 a.m. and 10:00 p.m. A new visualization graphic, PPD, was introduced that provides a holistic look at a vehicle’s experience on a corridor. The graphic provides a tool for quickly assessing the proportion of vehicles arriving on green (Figure 4b), locations with insufficient allocation of green time (Figure 6d), and the impact of downstream intersection spillback (Figure 5). Intersection level summaries provide at-a-glance visualization (Figures 6 and 7). The relationship between this new PPD visualization and the traditional

Figure 10. SR-37 results for vehicles traveling southbound (SB) and turning left during all the weekdays in July 2019 for the different time of day timing plans: (a) unique trajectory counts, (b) percentage of trajectories by level of service, (c) percentage of trajectories by number of stops, (d) percentage of trajectories with split failures, and (e) percentage of trajectories with downstream blockage.

Note: AM = 05:00–09:15; MD = 09:15–14:30; PM = 14:30–19:00; EV = 19:00–22:00.
PCD is illustrated in Figure 8. Figures 9 to 11 show how these graphics can be used to quickly assess the operation of a corridor.

Acknowledgments
Trajectory data from weekdays between July 1 and July 31, 2019 used in this study, were provided by Wejo Data Services, Inc. Google’s Cloud Platform BigQuery was utilized to generate cost estimates.

Author Contributions
The authors confirm contribution to the paper as follows: study conception and design: Enrique Saldivar-Carranza, Howell Li, Jijo Mathew, Darcy Bullock; data collection: Enrique Saldivar-Carranza, Howell Li, Margaret Hunter; analysis and

Figure 11. Percentage of vehicle trajectories experiencing split failures at SR-37 intersections during all weekdays in July 2019: (a) northbound, through, (b) southbound, through, (c) northbound, left, and (d) southbound, left.
interpretation of results: Enrique Saldivar-Carranza, Howell Li, Jijo Mathew, James Sturdevant, Darcy Bullock; draft manuscript preparation: Enrique Saldivar-Carranza, Howell Li, Jijo Mathew, James Sturdevant, Darcy Bullock. All authors reviewed the results and approved the final version of the manuscript.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported in part by the Joint Transportation Research Program and Pooled Fund Study, TPF-5(377), led by the Indiana Department of Transportation (INDOT) and supported by the state transportation agencies of California, Connecticut, Georgia, Minnesota, North Carolina, Ohio, Pennsylvania, Texas, Utah, Wisconsin, plus the City of College Station, Texas, and FHWA Operations Technical Services Team.

Data Accessibility

The data that support the findings of this study are available from the corresponding author, Enrique Saldivar-Carranza, on reasonable request.

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