Congestion Ranking of Protected and Permitted Movements across Agency Inventory

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ABSTRACT

Signal systems are increasingly able to report the status of local operations using a variety of performance measures. As this data is compiled over time, the opportunity arises to assess agency-wide operations by aggregating individual intersection metrics. This paper focuses on capacity utilization performance measures. A decision tree methodology is presented for determining whether protected-permitted movements are saturated, based on whether each opportunity for service (a protected or permitted interval) meets saturation criteria. The data is compiled for an individual intersection for a 24-hour period and for a 7-month period to examine daily and seasonal trends in performance for the movements at an example 8-phase intersection. The analysis is then extended to a system of 61 intersections. The intersections are rank ordered according to the highest split failure rate of all movement. The analysis reveals that a relatively small portion of the total signal inventory experiences the most severe rates of oversaturation. The paper concludes by demonstrating the use of the performance measures in dashboard visualizations for corridor and intersection level views.
INTRODUCTION

One of the primary tasks of traffic signal operation pertinent to vehicular traffic is the allocation of capacity (green time) to competing movements at intersections. Under coordinated operation, the main parameters affecting capacity allocation are the cycle length and the splits. In actuated signals, the green intervals are truncated when a gap in the traffic flow is detected, or when the maximum green time is reached (while traffic is waiting for service on a competing phase). A panel of extension settings determine how sensitive the signal controller will be when deciding whether or not to continue serving a phase (1).

Many agencies are responsible for dozens, hundreds, and in some cases thousands of traffic signals. Therefore, it is important to prioritize locations for engineering resource investment according to need. In current practice, most agencies rely primarily on complaint calls or the anecdotal knowledge of engineering staff to identify problem areas (2). Complaint calls, however, are often very difficult to substantiate, as callers often do not provide detailed technical information about the problems they experienced, and conditions are often difficult to reproduce. In absence of performance monitoring, operational issues are not substantiated, and poor signal timing is often undetected, and retiming activity occurs on an arbitrary schedule, often years after the previous retiming.

Two enabling technologies facilitate signal system data monitoring on a wide scale. One is the development of internal controller data loggers. At the time of writing, at least five controller manufacturers currently offer (or are in the process of developing) controllers that can record individual controller events (e.g., output state changes and detector state changes) with timestamps to the nearest tenth of a second, or better (3). Previously, external data collectors were used to acquire event data (4, 5, 6, e.g.), which constrained deployments mostly to research studies and a limited number of high-priority locations. Now that the data can be obtained within the controller itself, the hardware requirements have been considerably moderated.

The other enabling technology is the growing ubiquity of inexpensive, high-bandwidth internet connections, which enables the data to be remotely gathered and aggregated. In Indiana, cellular access points have been used to achieve connectivity across a geographically distributed system (7), while in denser urban areas, Wi-Fi networks may be a feasible option (8). With these developments, it is becoming possible for a growing number of intersections to begin recording highly detailed information about their operations in ways that were previously only feasible within some advanced control systems (9), which are typically only used in the highest-priority corridors because of the greater amount of investment required.

As these capabilities continue to proliferate, there is an opportunity to make use of the incoming information to identify opportunities for system improvements, such as retiming, geometric improvements, or the acquisition of advanced control systems. A number of previous studies have developed performance measures from signal event data (3, 4, 5, 11, 6, 12, 13, 14, 17, 15, 16, 18). These studies have focused on a single intersection or corridor as a basis for demonstrating the
performance measures. There is a need to explore methods of aggregation from a single hour or day at the local intersection to a longer time period or wide area analysis.

The present paper extends the signal performance measure literature by proposing a scalable methodology for scanning an agency inventory of traffic signals to identify spatial and temporal locations of poor capacity allocation. In addition, the methodology is developed for movements that are served under both protected and permitted intervals and varying detector configurations. A decision-tree based methodology is proposed for this use case. A series of performance measures are demonstrated for evaluating individual intersection performance. These are then used to monitor intersection performance over a 6-month period, and across more than 60 intersections over a 24-hour period. The decision-tree and aggregation methodologies are compatible with local intersection performance measures other than those selected in this study.

**METHODOLOGY**

**Measuring Congestion on Protected and Permitted Movements**

Prior research has tended to focus on protected-only movements, or only on the protected portion of a protected-permitted movement. The operational difference is that protected movements are reserved by a specific signal indication, while permitted movements are controlled by, in addition to a particular signal state, gaps in a higher priority movement. Protected-permitted left turns have two opportunities for service during a typical cycle.

Figure 1 illustrates a timeline of protected-permitted left turn operation under a common signal configuration that includes a five-section signal head. The protected left turn occurs while the green arrow is present in the five-section head and is the first opportunity for service of the left turn movement. After the yellow arrow disappears, the left turn has no indication and is effectively controlled by the adjacent through movement indication. When the adjacent through is green, the left turns are allowed to proceed, but must yield to opposing through vehicles. This is the second opportunity for service.

![Signal Indications and Service Opportunities](image)

**Figure 1:** Opportunities for service on a protected-permitted movement.  
(“Y” = yellow; “rc” = red clearance.)
Congestion can be associated with the occurrence of a *split failure*, which is any occurrence when the signal does not serve all of the demand present on a movement during the splits designated for it in a given cycle.

- For a protected-only movement, a split failure is associated with high utilization of the protected green interval.
- For a protected-permitted movement, a split failure is associated with high utilization of the protected green and the permitted interval.

At an actuated signal, not every cycle is guaranteed to have both a protected and permitted interval. For example, if none of the compatible through movements are actuated, no permitted interval will occur. If vehicles arrive after the permissive periods close, they will not actuate the protected phase until the next cycle. A delayed left turn detector configuration can also be used to reduce the likelihood of serving the protected phase (19). Some agencies use a detector configuration that only actuates the protected phase when the queue reaches to a certain length. Movements that operate under overlaps rather than phases may exhibit even greater variation. Therefore, a methodology for general use cannot rely on assumptions about the predictability of when opportunities for service will occur, or the sequence in which they occur.

The possibilities of whether the protected and/or permitted phases are served in a cycle and whether the opportunities for service are saturated are combined in a decision tree illustrated in Figure 2. The four questions considered within this tree are:

- **PROT_G**. Is any permitted interval served?
- **PERM_G**. Is any protected interval served?
- **PROT_SAT**. Do the protected interval(s) have a high degree of utilization?
- **PERM_SAT**. Do the permitted interval(s) have a high degree of utilization?

From the answers to these questions, a possible outcome is selected:

- **Phase Omitted**. Neither a protected nor a permitted interval occurred for the phase. Most likely, no demand was present for the movement.
- **Undersaturated**. All of the opportunities for service had a low degree of utilization, indicating that the demand was likely fully served.
- **Only Permitted Saturated**. The protected interval was served and had a low degree of utilization, while the permitted interval was also served and had a high degree of utilization. The initial queued demand for the phase was likely served during the protected interval.
- **Only Protected Saturated**. The protected interval was served and had a high degree of utilization, while the permitted interval was also served and had a low degree of utilization. In this case, it is likely that the initial queued demand was unable to be cleared during the protected interval, but the remaining demand was served during the permitted interval.
• *All Opportunities Saturated.* Under this condition, all of the provided opportunities for vehicles on this movement to be served were associated with a high degree of utilization. It is therefore unlikely that all of the demand was served during this cycle.

In summary, if there is any undersaturated opportunity for service within the cycle, it is considered that the demand has been effectively cleared on the movement. While this is a simple concept, the decision tree formulation is particularly easy to translate into code, since each node corresponds to a branch in the logic. The same logic can be also applied to protected-only phases, with the only difference being that the `PERM_G` branches are set to a negative response.

![Decision tree](image)

Figure 2: Decision tree for determining whether a protected-permitted phase experiences a split failure during a cycle.
Table 1. Phase utilization performance measures.

<table>
<thead>
<tr>
<th>Performance Measure</th>
<th>Compatible Detection Types</th>
<th>Oversaturation Criteria</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume-to-Capacity Ratio</td>
<td>Any (with count detection)</td>
<td>Indicated by high values, particularly those greater than saturation (&gt; 1.0).</td>
<td>Requires assumptions about saturation flow rate and effective green time.</td>
</tr>
<tr>
<td>Rate of Force-Off / Max-Out</td>
<td>Any</td>
<td>Indicated by high recurrence of force-off / max out.</td>
<td>Sensitive to actuation settings. Not valid for phases in recall.</td>
</tr>
<tr>
<td>Green Occupancy Ratio</td>
<td>Stop Bar</td>
<td>Indicated by high values.</td>
<td>Sensitive to stop bar detection zone length. Tends to reach a high value relatively early. Utility may be limited by actuation behavior.</td>
</tr>
<tr>
<td>Green Occupancy Ratio and Red Occupancy Ratio</td>
<td>Stop Bar</td>
<td>Indicated by high green occupancy combined with high red occupancy.</td>
<td>Sensitive to stop bar detection zone length. Sensitive to choice of red duration interval length.</td>
</tr>
<tr>
<td>Queue Service Time</td>
<td>Stop Bar</td>
<td>Indicated by high values.</td>
<td>Sensitive to stop bar detection zone length.</td>
</tr>
<tr>
<td>Spatial and Temporal Oversaturation Severity Index</td>
<td>Advance</td>
<td>Indicated by high values.</td>
<td>Requires assumptions for determining unusable green time. Well suited for analysis where queuing and downstream blockage are factors.</td>
</tr>
</tbody>
</table>

Selection of Performance Measures

The final component in the analysis methodology is a selection of the appropriate performance measure, which depends on the type of detection that is available and, to some degree, the characteristics of the site. These performance measures are summarized in Table 1, along with the detection requirements needed to implement them and notes on their applicability. This paper does not evaluate the relative performance of these metrics, but rather investigates what can be done to analyze system performance after they have been compiled at the local intersection level.

The volume-to-capacity ratio (v/c) is a traditional concept that relies on an estimate of the capacity provided by the green time, and compares it to the amount of demand volume during a given time period:

\[
v / c = \frac{v}{s \cdot g}
\]

Equation 1

Here, \( v \) is the volume (vehicles), \( s \) is the saturation flow rate (veh/s), and \( g \) is the effective green time (s). The volume-to-capacity ratio relies on an assumption of \( s \), which converts the green time into capacity, and in the identification of effective green time. The effective green time takes into account the start-up lost time and the portion of yellow used for vehicle movement. It is necessary to have accurate count detection when computing \( v/c \) on a cycle-by-cycle basis.
Other performance measures can be derived from the process of actuation, using detector occupancy and phase termination status. A phase that consistently maxes out or is forced off is more likely to be oversaturated than one that consistently gaps out (20). While this is a simple binary performance measure, it is sensitive to the detection settings at the controller, since long extension times, combined detection across multiple lanes, and use of simultaneous gap increase the likelihood of maxing out or forcing off. The measure also provides no information about phases that are in recall or that have failed detection.

The amount of time that a stop bar detector is occupied during green provides a method of evaluating the degree of utilization on a phase (21). The green occupancy ratio (GOR) is given by

\[
\text{GOR} = 100\% \cdot \frac{O_g}{g},
\]

Equation 2

where \(O_g\) is the total amount of occupancy time during green (s), and \(g\) is the duration of green (s). The performance measure ranges from 0–100%, with the maximum value indicating that the detection zone experienced vehicle presence during the entire duration of green. GOR has a tendency to saturate at high values relative to other performance measures such as the v/c ratio (14). Actuated phases are terminated by a gap, which places an upper bound on the difference between \(O_g\) and \(g\) during gap out. Also, vehicles sometimes continue moving during yellow, meaning that it is possible that all of the demand may have been served in a cycle, yet GOR could still be 100% because the detector was occupied during the entirety of green.

Examining occupancy at the beginning of red can help to confirm the existence of leftover demand (17). The red occupancy ratio (\(ROR_T\)) is given by

\[
\text{ROR}_T = 100\% \cdot \frac{O_T}{T},
\]

Equation 3

where \(O_T\) is the total amount of occupancy time during an interval of length \(T\) that starts at the beginning of red. A value of \(T = 5\) (i.e., \(ROR_5\)) was used in a previous study (17). The purpose of this metric is to determine whether or not vehicles are present after the most recent opportunity for service has ended. The GOR and \(ROR_5\) metrics require stop bar detection.

This paper uses the v/c ratio and \(ROR/GOR_5\) as indicators of oversaturation across the inventory of signals with high-resolution data in the state of Indiana. However, other indicators could also be used within this methodology. Examples include the queue service time (4) and oversaturation severity index (OSI) (13). The present study selected v/c ratio and \(ROR/GOR_5\) because they are relatively independent of the site detector configurations (other than classifying a phase’s detection as stop bar or advance). However, future research should compare alternative performance measures and identify how to aggregate across different phases and intersections using different performance measures.
LOCAL INTERSECTION PERFORMANCE

Test Intersection
To demonstrate the decision-tree methodology, an intersection was selected that had typical arterial volume characteristics and a detector profile similar to most state highway intersections in Indiana. The intersection of US 36 (Pendleton Pike) and Post Road in Indianapolis was chosen. Figure 3 provides a view of the intersection, showing the location of detectors and a diagram of the 8-phase scheme used to control the intersection. The six through lanes on the mainline (US 36) feature advance detectors located 330 feet from the stop bar, providing dilemma zone detection at the 45 mph speed limit. The other lanes feature stop bar detection only. These detection zones are 51 feet in length, comprised of four 6-foot loops separated by 9 feet. All four left turns are protected-permitted, with five-section heads.

The signal at this location is coordinated from 6:00 to 19:00. A 100-second cycle length is used during this entire time period, with different splits and offsets used to accommodate different traffic patterns during the AM peak, midday, and PM peak. From 19:00 to 6:00, the intersection operates in a fully-actuated, non-coordinated mode.

Based on the detection available at the intersection, the GOR/ROR<sub>S</sub> performance measure was selected to determine whether split failures occurred on any of the movements served by stop bar detectors (phases 1,3,4,5,7, and 8), while the v/c ratio was used to determine split failure on the advance detector movements (phases 2 and 6), following the conventions described in the previous section. GOR and ROR<sub>S</sub> threshold values of 75% and a v/c threshold value of 1.00 was used for determining whether a phase was congested. A phase was considered to have a failure if any of the individual lanes met these conditions.
24-Hour Analysis
Data from Tuesday, July 1, 2014 were analyzed to examine the performance of individual phases at the intersection on a typical day of operation. Figure 4 shows the proportion of cycles per hour that fell within each of the decision tree performance categories, for all eight phases arranged in a ring-diagram structure. At a glance, this view shows that most of the likely split failures, where all opportunities for service are oversaturated, occur on the left turn phases (1,3,5, and 7). The mainline through phases (2 and 6) report very few split failures, while the through phases on Post Road (4 and 8) have a substantial number only during the PM peak. Note that the peak is somewhat narrower for phase 8. The plot also reveals that during the coordinated portion of the day, there are very few phase omits. This indicates that all phases are served in almost every cycle throughout the entire day.

Interestingly, the mainline lefts (1 and 5) have a higher incidence of failures where the protected phases are not oversaturated, but the permitted phases are oversaturated, while the opposite is true for the side-street lefts (3 and 7). This likely reflects the timing of the arrivals at the
intersection during the cycle, because of coordination with adjacent signals. The mainline lefts appear to adequately serve the vehicles that are queued at the start of green. Later in the cycle, additional left turn vehicles with the stream of coordinated traffic scheduled to arrive during phases 2 and 6. Only a few of these left turners are served during the permitted interval, meaning that a queue forms, which is served during the protected green in the next cycle.

Figure 4: Number of split failures per hour: US 36 and Post Road, Indianapolis, Indiana, July 1, 2014. Dashed lines indicate coordination pattern changes.

7-Month Analysis
Figure 5 expands the analysis to the first seven months of 2014. Data from all the Wednesdays in that time period are shown. In each column, the proportions of all the cycles within the time-of-day plan periods are aggregated together. Part (a) shows data for the AM peak, while part (b) shows the PM peak. The rate of split failures appears smaller in these figures as compared to Figure 4, since the aggregation is over the entire peak period rather than individual hours. For example, in Figure 5b, phase 4 exhibits a higher rate of failure than phase 8. This reflects that phase 4’s split failure rate is sustained throughout the PM peak while phase 8’s split failures occur within only part of the peak, as illustrated in Figure 4.

Overall, the plots reveal consistent performance over the course of the year, with few seasonal features, except for a very slightly reduced level of utilization during the summer months. This is not surprising, given that the intersection controls two commuter corridors with demands that are unlikely to change from day to day. Anomalies, however, are easily detected from this view. For example, on January 16, 2014, there is an unusual spike in the number of split failures on phase 3 during the AM peak (Figure 5a). This reveals a temporary spike in demand that was not observed elsewhere in the analysis period.
Figure 5: Rate of split failure by phase on Wednesdays, US 36 and Post Road, Indianapolis, January 2014–July 2014.

(a) AM Peak (6:00-9:00)

(b) PM Peak (15:00-19:00)
SCALING TO AGENCY-WIDE ANALYSIS

The next step was to apply the methodology on an agency-wide scale in order to determine opportunities for improvement among the state inventory of traffic signals. Data from 61 intersections was harvested on May 31, 2014, and analyzed using the same process as used at the pilot intersection. The performance measure of interest was the percentage of phases during a given time period satisfying the “all opportunities saturated” criteria (Figure 2), the black portions of the stacked bar graphs in Figure 3 and Figure 4. Based on the objective of identifying the worst-performing movements throughout the system, the maximum failure rate of any individual phase was used as a value for comparing one intersection to another.

A sample of the results is given in Table 2, which shows the top 20 intersections in terms of the highest split failure rates during the PM peak. All of the intersections considered here operate an 8-phase scheme, which allows the results to be shown rather concisely. The first three intersections stand out, each having one or more phases that fail in over 85% of the cycles. There is a fairly sharp drop-off in the maximum failure rate, which suggests that a relatively small proportion of the overall number of intersections experience the most severe problems, a system performance characteristic known as the Pareto principle or the “80/20” rule. For example, it is sometimes anecdotally observed that 20% of customers generate 80% of sales, or that correcting 20% of bugs in computer code can ameliorate 80% of user issues. The implication is that taking action at a relatively small number of intersections might correct a disproportionately large amount of the total number of problems across the system as a whole.

Table 2. Example of agency-wide data: Top 20 intersections, sorted by maximum rate of failures during the PM peak (1500-1900), May 31, 2014.

<table>
<thead>
<tr>
<th>Signal ID</th>
<th>Intersection</th>
<th>Location</th>
<th>Max Rate (%)</th>
<th>Failure Rate, by phase (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4458</td>
<td>SR 37 &amp; SR 144</td>
<td>Morgan County</td>
<td>100</td>
<td>12 0 0 12 6 100 14 1</td>
</tr>
<tr>
<td>4417</td>
<td>US 36 &amp; Steeplechase</td>
<td>Avon</td>
<td>97</td>
<td>21 97 89 0 2 0 1 8</td>
</tr>
<tr>
<td>4414</td>
<td>SR 37 &amp; 141st St</td>
<td>Fishers</td>
<td>87</td>
<td>0 0 6 87 0 3 0</td>
</tr>
<tr>
<td>1293</td>
<td>US 31 &amp; Fry Rd</td>
<td>Greenwood</td>
<td>79</td>
<td>5 0 0 19 6 0 53 79</td>
</tr>
<tr>
<td>4428</td>
<td>SR 37 &amp; 146th St</td>
<td>Fishers</td>
<td>65</td>
<td>13 0 65 0 31 0 8 0</td>
</tr>
<tr>
<td>4441</td>
<td>US 36, SR 67 &amp; 42nd St</td>
<td>Indianapolis</td>
<td>63</td>
<td>0 0 63 0 0 0 0 0</td>
</tr>
<tr>
<td>4437</td>
<td>SR 37 &amp; Southport Rd</td>
<td>Indianapolis</td>
<td>59</td>
<td>26 0 25 54 3 0 4 59</td>
</tr>
<tr>
<td>990</td>
<td>US 421 &amp; 106th St</td>
<td>Zionsville</td>
<td>57</td>
<td>6 0 0 0 2 57 3 1</td>
</tr>
<tr>
<td>2062</td>
<td>US 36 &amp; Raceway Rd.</td>
<td>Avon</td>
<td>51</td>
<td>22 0 0 14 51 0 1 3</td>
</tr>
<tr>
<td>4469</td>
<td>SR 37 &amp; Smith Valley Rd</td>
<td>Morgan County</td>
<td>50</td>
<td>0 32 0 50 23 0 0 0</td>
</tr>
<tr>
<td>4419</td>
<td>US 36 &amp; Ronald Reagan Pkwy</td>
<td>Avon</td>
<td>49</td>
<td>30 0 18 28 32 0 49 6</td>
</tr>
<tr>
<td>4412</td>
<td>SR 32/38 &amp; SR 37</td>
<td>Noblesville</td>
<td>39</td>
<td>2 9 17 33 39 17 0 0</td>
</tr>
<tr>
<td>4399</td>
<td>US 36 &amp; Gable Dr</td>
<td>Avon</td>
<td>37</td>
<td>0 0 25 0 1 0 37 0</td>
</tr>
<tr>
<td>4408</td>
<td>SR 37 &amp; 126th St</td>
<td>Fishers</td>
<td>35</td>
<td>8 0 0 11 13 0 33 35</td>
</tr>
<tr>
<td>1289</td>
<td>US 31 &amp; Main St</td>
<td>Greenwood</td>
<td>34</td>
<td>0 0 0 8 5 34 9 24</td>
</tr>
<tr>
<td>2046</td>
<td>US 31 &amp; County Line Rd</td>
<td>Greenwood</td>
<td>31</td>
<td>31 0 27 8 14 0 4 9</td>
</tr>
<tr>
<td>985</td>
<td>US 421 &amp; 96th St</td>
<td>Indianapolis</td>
<td>31</td>
<td>3 0 31 1 6 0 4 0</td>
</tr>
<tr>
<td>1300</td>
<td>US 31 &amp; Stop 18</td>
<td>Greenwood</td>
<td>30</td>
<td>16 0 24 16 1 0 20 30</td>
</tr>
<tr>
<td>1011</td>
<td>US 421 &amp; Retail</td>
<td>Zionsville</td>
<td>28</td>
<td>1 0 28 15 1 0 0 0</td>
</tr>
<tr>
<td>4418</td>
<td>US 36 &amp; Meijer</td>
<td>Avon</td>
<td>28</td>
<td>3 0 0 7 0 0 28</td>
</tr>
</tbody>
</table>
Similar trends can be seen for other times of day (Figure 6). Here, the intersection values are sorted from greatest to least, for all 61 intersections sampled, with the data aggregated from different times of day. Not surprisingly, the overnight period had the lowest rates of failure, with the vast majority of intersections having less than 10% of failure for any phase. The midday and PM peak periods have similar performance, with the evening and AM peaks somewhere in between. There appears to be a change in the slope of the line falling approximately around the end of the first quintile, which suggests that the upper 20% of the signal inventory experiences the most severe problems. Although the intersections comprising the 1st quintile vary from one time period to another, the agency-level view nevertheless serves as a starting point for understanding the spatial and temporal distribution of oversaturated signalized movements.

![Figure 6: Agency-wide analysis: Maximum phase failure rate by intersection. Data is shown for 61 intersections with data from May 31, 2014.](image)

Taking action on a report of an oversaturated phase requires that the analyst “drill down” to the corridor and intersection levels to evaluate the situation in more detail. Figure 7 illustrates how the data can be used for this purpose. Here, six intersections on US 421 on the northwest side of Indianapolis are shown. Each intersection is represented with a graphical representation of the maximum failure rate for any phase during a particular time period. Figure 7a, Figure 7b, and Figure 7c illustrate conditions under the AM peak, midday, and PM peak respectively across the
corridor, while Figure 7d, Figure 7e, and Figure 7f drill down further to the intersection level for US 421 and 106th St. for those three time periods.

It is possible to quickly compare conditions across the corridor using such a representation. Clearly, the intersection at 106th Street experiences the most severe split failure rates across all of the intersections in this corridor, exceeding 50% of cycles during all of the time periods shown (Figure 7a-c). The number represented here graphically appears numerically in the system level analysis seen earlier (Table 2). At the intersection level (Figure 7d-f), it is possible to identify which individual movement is contributing to the overall intersection failure rate. In this case, it is the northbound through movement in each case. The other movements have relatively few failures in comparison. It is at this point that the engineer would begin to triage split failures and determine possible means of correcting them.

Figure 7: Dashboard level views of failure rates at the corridor and intersection levels (background imagery from Google Maps).
CONCLUSIONS

This paper presents a methodology for aggregating phase utilization metrics across an intersection for analyzing the performance of traffic signals throughout an agency-wide inventory. This method includes a decision tree approach to determine whether protected-permitted movements are saturated, depending on whether protected or permitted intervals are served for the phase during a given cycle, and whether the individual opportunities for service are saturated according to the selected performance measure. After this data is computed for individual intersections, it can be compiled across the signal network to ascertain the worst performing locations in terms of capacity utilization. A system-wide rank ordering of 61 intersections by congestion severity reveals that a relatively small proportion of the signal inventory experiences severe rates of oversaturation, in this case. Finally, the utility of the performance measures is demonstrated for visualizing performance in corridor- and intersection-level dashboards.

Future research will continue to refine the methodology, and close the monitoring and operations loop by determining how the information can be used to suggest changes to signal timing, as well as how to identify when signal timing changes are unlikely to adequately address an oversaturation condition, to assist capital investment decision making.

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