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Scalable Dashboard for Identifying Split Failures and Heuristic for Reallocating Split Times

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ABSTRACT

The three fundamental parameters of a traffic signal system are split, cycle and offset. This paper describes the use of high-resolution data to identify time periods when split parameters may be insufficient and assist the practitioner with identifying opportunities to reallocate split time. A case study of 7 corridors with 47 intersections is presented. A drill-down approach is developed to find movements where there is opportunity to reallocate split times to improve performance. A heuristic that can reallocate up to 5 seconds of under-utilized green time on a competing phases is applied to these corridors. For the selected phase identified in this study, the adjustment was shown to reduce split failures by an average of 40% while also decreasing yellow occupancy by an average of 40% and red light violations by an average of 66%. The paper concludes by recommending central systems to implement drill-down split failure dashboards, similar to those shown in this paper to facilitate sustainable practices of monitoring split failures and easily identifying opportunities to reallocate green time when there is slack capacity in other phases.

INTRODUCTION

Traffic signal practitioners traditionally have relied on public complaint calls or anecdotal evidence for making split adjustment changes outside of regular maintenance schedules (1). With the development of high-resolution data logging capabilities in signal controllers (2) and latency-tolerant communications protocols (3), large traffic signal networks can now log phase change events and detector activations at 0.1-second resolution for subsequent split failure analysis (4, 5). This data can then be collected over many systems to evaluate capacity allocation and determine opportunities for split adjustments.

Split optimization has been well studied in microsimulation (6, 7) and implemented online using predefined traffic-responsive timing plans (8, 9). Kohls introduced the concept of finding “slack” time to distribute to a phase with the highest volume-to-capacity (V/C) ratio above 0.85 (10). It is well known that small increases to green time on critical phases can dramatically reduce split failures. The purpose of this study is to determine the feasibility of processing large quantities of signal controller data offline to systematically identify trouble locations, as there are no tools in the current generation of central systems that do this. Once a location is identified, recommendations for split adjustment can be made using occupancy data from the proposed heuristic.

Study Area

Seven corridors in central Indiana are included in the study to identify locations with split substantial split failures. These corridors are high-volume arterials maintained by the Indiana Department of Transportation, and have reliable long-term data connectivity for analysis. The corridors are situated mostly in suburban areas with low pedestrian phase utilization. Some mainly serve weekday commuter traffic, while others are in dense retail areas that experience high volumes on weekends. The location of the corridors are shown in Figure 1a.

Split Failure Definition

In this study, we define a split failure as the occurrence of a phase that operates near saturation during the green interval and has residual demand at the start of red (5). Split failures are also occasionally referred to as a cycle failure in the literature. Figure 2 shows how high resolution data can identify these conditions. The grey bars (callout *i*) illustrate stopbar detector occupancy. Two occupancy measures are computed, the Green Occupancy Ratio (GOR) between t_1 and t_2 , and the Red Occupancy Ratio (ROR) between t_3 and t_4 . The GOR indicates how saturated the green interval is, and the ROR indicates residual demand at the start of red (callout *v*). When GOR and ROR are both greater than 80%, as in this example, a split failure is considered to have occurred (5).

When split failures occur in sequential phases on the critical path, there is typically a lack of free capacity to redistribute (11). However, when split failures occur on phases that share time with under-saturated movements, there is a potential to redistribute splits.

a) Central Indiana corridor locations.

b) US-31 Greenwood intersections.

Figure 1. Map of study location.

Figure 2. Conceptual representation of a split failure for one phase occurrence.

SYSTEMWIDE SPLIT FAILURE EVALUATION

Split failure metrics can be aggregated to evaluate intersection and system performance over various time scales and at a high level. A practitioner can then drill down to find specific locations where split failures are occurring.

Statewide Patterns

Split failures for 47 signals over seven corridors (Figure 1a) were computed using data from May 2016 to identify candidate locations and time periods for split rebalancing. To compare split failures across different systems, the total number of split failures was averaged over the number of hours in each analysis period and normalized to the number of intersections in the system (Table 1). Periods where split failures per hour per intersection exceeded 10 are bolded. Figure 3 shows the average hourly split failures for each representative time-of-day (AM, 0600–0900; midday, 0900–1500; PM, 1500–1900). As shown by callouts *i–viii*, the US-31 Greenwood corridor (Figure 1b) consistently shows a high number of split failures per hour during the midday and PM periods on Saturdays, inconsistent with the generally good performance during the weekday period.

Corridor Drill-down

The hourly split failures on the US-31 Greenwood corridor are examined at the intersection level in Figure 4 for Saturdays in May between 0900–1900. The intersections with the most split failures occurring can be prioritized for further evaluation. Fry Road (callout *b* in Figure 1) has the most split failures on the corridor, but is not a viable candidate for split rebalancing because split failures occurred on every phase. The intersection with the next highest number of split failures is the mall entrance (callout *a* in Figure 1) and is described in the next section.

Intersection Evaluation

Figure 5a illustrates the layout of intersection at the mall entrance. The mainline movements are the northbound and southbound approaches of US-31. The southbound left-turn is protected only. Figure 5b shows the volumes for each of the four Saturdays in the evaluation period of May 2016, with volumes in the adjustment period shown later in Figure 10a. Figure 5c shows the split failures per hour for each of the Saturdays in the evaluation period, colored by phase. The trend suggests that as volumes decrease, so do split failures.

Figure 5c shows split failures consistently occurring for the southbound left-turn movement (phase 1) throughout the period, even as split failures were decreasing through the month. The opposing movement that shares time with phase 1 is the northbound through (phase 2). This phase lacks stop bar detection, so its ROR and GOR cannot be computed. Instead, the northbound V/C ratio is calculated using vehicle counts from setback detectors, and is found to average approximately 0.70 for the month between 9AM and 7PM during the Saturday timing plan. This indicates an opportunity for split rebalancing, *i.e.* increasing green time for the southbound left-turn phase and decreasing green time for the northbound thru phase.

Table 1. Split failure summary, May 2016.

Day of week \ Corridor		SR-37 Martinsville	US-31 Greenwood	US-31 Columbus	US-421 Zionsville	Pendleton Pike	SR-37 Indianapolis South	SR-37 Noblesville
		Split failures per hour						
Monday - Thursday	AM	3.9	5.7	14.8	30.6	42.6	87.8	41.6
	Mid-day	3.8	20.4	42.7	35.4	18.2	50.8	38.8
	PM	5.9	58.8	73.4	50.4	65.2	124.0	98.9
Friday	AM	3.6	4.5	13.3	31.4	38.5	78.8	47.1
	Mid-day	5.7	44.3	73.0	51.2	27.1	67.0	54.2
	PM	10.8	92.3	111.9	58.3	77.3	154.1	108.2
Saturday	AM	2.6	0.4	0.6	1.8	12.3	27.8	6.3
	Mid-day	7.2	72.4	56.1	24.5	36.8	86.1	46.4
	PM	5.1	81.9	44.3	21.9	36.1	87.5	34.4
Sunday	AM	1.8	2.1	0.1	0.8	10.5	14.1	3.6
	Mid-day	5.6	32.9	20.3	12.7	22.0	51.9	17.5
	PM	4.5	29.1	14.7	16.6	22.1	55.6	20.5
Split failures per hour per intersection								
Monday - Thursday	AM	1.3	0.8	1.6	5.1	5.3	9.8	8.3
	Mid-day	1.3	2.9	4.7	5.9	2.3	5.6	7.8
	PM	2.0	8.4	8.2	8.4	8.3	13.8	19.8
Friday	AM	1.2	0.6	1.5	5.2	4.8	8.8	9.4
	Mid-day	1.9	6.3	8.1	8.5	3.5	7.4	11.0
	PM	3.6	13.2	12.4	9.7	9.9	17.1	22.2
Saturday	AM	0.9	0.1	0.1	0.3	1.5	3.1	1.3
	Mid-day	2.4	10.3	6.2	4.1	4.6	9.6	9.4
	PM	1.7	11.7	4.9	3.7	4.6	9.7	6.9
Sunday	AM	0.6	0.3	0.0	0.1	1.3	1.6	0.7
	Mid-day	1.9	4.7	2.3	2.1	2.8	5.8	3.5
	PM	1.5	4.2	1.6	2.8	2.8	6.2	4.1

Figure 3. Daily split failure rates by corridor, May 2016.

Figure 4. Split failure performance of US-31 Greenwood intersections, Saturdays in May.

a) Intersection layout.

b) Mainline volumes, 0900-1900, Saturdays in May

c) Split failure performance, Saturdays in May.

Figure 5. US-31 at Mall entrance.

SPLITS ADJUSTMENT HEURISTIC

Identifying Protected and Permissive Time Intervals

To identify split adjustment opportunities, the interaction between different phases must be considered. Whereas split tradeoffs between competing protected phases are simple, protected-permissive phases are more complex. A left turn may be served by a protected phase (a left-turn arrow), and/or a permissive phase (a “green ball” on the adjacent through), during which the left turn vehicles may wait for gaps in a conflicting phase (the oncoming through). Figure 6 contains six scenarios illustrating how protected and permissive portions of a single cycle are considered.

Figure 6a shows a scenario where only the protected phase is timed without a conflicting phase in the same cycle. The permissive phase may also appear, but is irrelevant while the protected phase is active. At capacity, the protected movement would use all of the split time in the ring and no conflicting phase timings need consideration. Figure 6b shows a scenario where only the protected and conflicting phases are timed. This applies to protected-only lefts, or a protected-permitted setup where the permissive phase never appears (*e.g.*, when dual entry is not used).

For protected and permissive phases serving *with* a conflicting phase in the same cycle, Figure 6c, d, and e illustrate how the protected and permissive green intervals of the opportunity movement is determined. Figure 6c shows a leading protected phase timing separate from the permissive and conflicting phases. The protected portion of the movement’s green time is considered for the entire duration of the protected phase, while the latter two phases are concurrent with each other and are considered separately. The permissive portion overlaps the entire conflicting phase. Figure 6d shows a protected phase timing before both the permissive and conflicting phases, while the conflicting phase begins prior to the permissive phase. In this case, only the permissive green interval is considered, and the leading conflicting portion is excluded. Figure 6e illustrates a scenario where the permissive phase begins prior to the end of the protected portion of the cycle. In this case, only the permissive interval outside of the protected green and yellow is considered as the permissive portion of the cycle. This is the expectation for drivers where protected-permissive phasing is implemented using a five-section head. However, for a flashing yellow arrow (FYA) configuration, there may be a red clearance interval that would be excluded from the permissive interval (12). For scenarios illustrated in Figure 6c and 6d, a FYA would behave similar to a five-section signal head with its protected red clearance interval.

Figure 6f shows a scenario where no protected phase is timed. In this case, the permissive portion of the cycle is simply the duration of the permissive phase.

Figure 6. Protected and permissive time intervals for vehicle departure approximation.

Vehicle Estimation using Occupancy

The next step in the heuristic is to estimate the number of vehicles served by each phase. Figure 7 illustrates how volumes are estimated for protected and permissive phases using data recorded by setback and stopbar detection zones.

Figure 7a shows the estimation for a single protected movement, with the stopbar detection zone occupied for almost the entire duration of the phase. In this case, the duration of the two occupied time intervals during green determine the estimated number of vehicles. At the beginning of green, the detection zone is occupied, but the first served vehicle is not estimated until two seconds later (callout i). A startup lost time of 2 seconds is used if the detector is occupied at the start of green (*i.e.*, the first vehicle departs from a stationary position). The number of estimated vehicles is indicated by the solid black line. As time progresses, the number of served vehicles accumulates through the end of yellow clearance.

Table 2. Parameters for vehicle estimation using occupancy.

Parameter	Value used
Startup loss time (T_L)	2 seconds
Saturation flow rate (Q)	1900 vehicles per hour
Average vehicle length (L_v)	20 feet
Average vehicle spacing while moving (L_s)	20 feet
Detection zone length (L_d)	50 feet
Vehicle departure frequency, seconds per vehicle (F)	$\frac{3600}{Q}$ (1.89 seconds)
Vehicle departure speed, feet per second (V)	$\frac{(L_v + L_s)}{F}$ (21.1 feet per second)

The heuristic considers four parameters in addition to startup lost time: saturation flow rate, average vehicle length, average vehicle spacing, and detection zone length. Vehicle departure frequency and speed are also calculated as second-order variables. The assumed values are detailed in Table 2. Each departure is estimated as the time where the rear end of a vehicle exits the stopbar detection zone. The number of vehicles increases over the duration of occupied time during green, and is described by the function in Equation 1.

$$T_i' - T_L - \frac{n_i^0 L_v}{V} \geq 0 \quad \text{Equation 1}$$

Here, T_i' is the occupied duration in the current occupancy interval i that can serve vehicles. The number of vehicles estimated n_i^0 cannot be greater than what the occupied time allows, given the assumed parameters. For the first vehicle, $L_s = 0$ and $L_d = 0$ as only the length of the first vehicle needs to be cleared, and no vehicle spacing is assumed. Rearranging Equation 1, n_i^0 can be represented in terms of T_i' , T_L , V , L_v , and L_s (Equation 2).

$$n_i^0 \leq \frac{(T_i' - T_L)V}{L_v + L_s} = \frac{T_i' - T_L}{F} \quad \text{Equation 2}$$

If T_i' has a longer duration and is able to accommodate more than one vehicle, the spacing between vehicles is considered and $L_s > 0$.

a) Stopbar detection zone, protected phase.

b) Advance (setback) detection zone, protected phase.

c) Stopbar detection zone, permissive left-turn phase.

Figure 7. Estimation of volumes from occupancy and phase data.

For fractional results, an additional vehicle is added to the number of vehicles estimated n_i^0 and the final vehicle $n_i^0 + 1$ arrival time is interpolated using F (callout *ii*). At about 8.2 seconds into the phase in Figure 7a, a gap occurs in the occupancy, and the detector turns back on at about 8.5 seconds. The heuristic assumes the new occupancy interval beginning after the start of green represents a vehicle in motion, and therefore no startup lost time is needed. However, the incoming vehicle must now clear the length of the detection zone (Equation 3).

$$n_i \leq \frac{T_i' V}{L_v + L_s + L_d} \quad \text{Equation 3}$$

Here, n_i is the number of vehicles estimated for an occupancy interval that starts after the beginning of green. For the first vehicle estimated, $L_s = 0$, and for subsequent vehicles in the same interval, $L_s > 0$ and $L_d = 0$. Callout *iii* indicates the first estimated vehicle in the second occupancy interval, where the departure time is delayed to accommodate the time of travelling the length of the detection zone. Subsequent vehicles in the interval are estimated to arrive more frequently, and because of the parameter values used in this study, $L_d > L_s$ where two vehicles can simultaneously occupy the detection zone.

At the beginning of the yellow interval, the heuristic restarts the estimation process using a different function to estimate the number of vehicles departing during the yellow interval Y_i . Vehicles are estimated when the detection zone is occupied during Y_i' where vehicles can be served. In the case of Figure 7a, Y_i' persists as long as the yellow interval itself, and its occupancy starts before the beginning of yellow and extending past the end of yellow. In this scenario, it is uncertain whether any vehicles have used the yellow time or stayed behind until the next cycle. To account for the uncertainty, a random number variable ε_i is used as a multiplier for the estimation (Equation 4).

$$y_i \leq \varepsilon_i \left(\frac{Y_i' V}{L_v + L_s + L_d} \right) \quad \text{Equation 4}$$

$$\varepsilon_i = \begin{cases} 0 < \varepsilon \leq 1 & , \text{ if } Y_i' = Y_i \\ 1 & , \text{ otherwise} \end{cases}$$

Here, y_i is the number of vehicles estimated during the effected occupied yellow interval, and is indicated by the solid yellow line in the figure. Callout *iv* in Figure 7a indicates the duration until the first vehicle is estimated in the yellow interval where ε is close to 1. If the detector is occupied at the beginning of yellow, $L_d = 0$ and $L_s = 0$ for the first vehicle and $L_s > 0$ for subsequent vehicles in the same occupied interval. If the occupancy interval starts after the beginning of yellow, $L_d > 0$. For occupancy intervals less than Y_i , no random variable is used.

Figure 7b illustrates vehicle estimation using occupancy data from an advance detection zone set back at approximately 5 seconds of travel time from the stopbar. In this case, each occupancy interval persists for less than one second in non-saturated conditions, and would likely estimate fractional vehicles. The estimation function in Equation 3 can be replaced with $n_i = 1$ for all i where $T_i' < F$ (Equation 5).

$$n_i \begin{cases} = 1 & , \text{ if } T_i' < F_i \\ \leq \frac{T_i' V}{L_v + L_s + L_d} & , \text{ otherwise} \end{cases} \quad \text{Equation 5}$$

The heuristic requires occupancy data from the permissive movement as well as the conflicting movement to estimate vehicles during the permissive phase. Figure 7c illustrates a permissive phase occurrence where both the permissive movement and conflicting movement are occupied at the start of green. Unlike the protected phase, the permissive occupied interval is only considered to serve vehicles when there is an adequate gap in the conflicting movement, as measured by its detector. Callout *i* indicates the first gap in the phase interval where this occurs. Here, a separate threshold d_{gap} accounts for gap acceptance and is set to 2 seconds for this study, but can be adjusted to accommodate the size of the conflicting movement detection zone. The first vehicle is estimated just after d_{gap} .

The number of vehicles m_i estimated during a permissive phase for an occupied interval *i* depends on gaps in the conflict occupancy (Equation 6).

$$m_i = \sum_{j=1}^{J_i} \left(1 + \left\lfloor \frac{(G_{ij}' - d_{gap})V}{L_v + L_s + L_d} \right\rfloor \right) , \quad \forall \quad G_{ij}' \geq d_{gap} \quad \text{Equation 6}$$

Here, G_{ij} is the occupied time during interval *i* and gap *j* that can serve vehicles, computed over all overlapping gaps J_i . Additionally, $L_d = 0$ and $L_s = 0$ when the first vehicle is estimated for an occupied permissive interval starting before a gap. Callout *ii* in Figure 7c indicates the end of the first occupied interval where there is some overlap with the second gap, and an additional vehicle is estimated at this point.

Callout *iii* indicates a third vehicle estimated at the beginning of the second occupancy interval. Since at this time a vehicle presumably arrives well within the second gap, and well outside of the threshold d_{gap} from the last conflicting vehicle's departure, the vehicle is accounted for immediately. Because L_d and L_s are now included to account for a vehicle travelling the length of a detector and spacing between vehicles, the occupied time in this case is not long enough to account for a second vehicle. Finally, callout *iv* shows the estimation of the fourth vehicle in this permissive interval after the last conflicting vehicle has departed, with consideration to the gap acceptance threshold. Occupied intervals during the yellow interval can also be considered as in Equation 4, but is not shown in this example.

Determining Slack Time between Movements

After the volumes are estimated for the protected, permissive and conflicting movements, the "slack time" or time that can be distributed to an opportunity movement can be computed for each cycle. For this study, slack time is only distributed to protected phases that have terminated with a max-out or force-off. The amount of time available to distribute from a conflict phase is δ (Equation 7).

$$\delta = \begin{cases} \text{MAX} \left[F \left(\frac{c_i - n_i + m_i + y_i}{2} \right), \right. & , \quad t_c > c_i F \\ 0 & , \quad \text{otherwise} \end{cases} \quad \text{Equation 7}$$

For each cycle, the duration of the conflicting phase (t_c) is compared with the amount of time required to discharge the number of estimated vehicles on the movement ($c_i \times F$). If there is time remaining, the discharge time is half of the difference between the number of vehicles estimated for the conflict phase and the protected and permissive phases, or all the unused time from the conflicting phase, whichever is greater.

Figure 8 illustrates the cumulative green time for a protected left-turn and a conflicting through phase at US-31 and the mall entrance over a 10 hour period. Callout *i* indicates the slack time accumulated as the day progresses. By 7PM, the total slack time is 1,682 seconds (callout *ii*), for 317 forced-off protected phase occurrences, or 5.3 seconds per occurrence. The amount of time that can be taken from the competing phase is also subject to its minimum time and pedestrian clearance limitations; at this location the time redistributed satisfies those limits.

Figure 8. Southbound left-turn at US-31 and mall entrance, June 18, 2016 from 0900 to 1900.

EVALUATION OF ADJUSTMENTS

The split adjustment recommended by the heuristic was implemented at the southbound protected-only left-turn and northbound through phases at US-31 and mall entrance for the Saturday plan. A field adjustment of +5 seconds was made for the southbound left-turn at the expense of the northbound through. Figure 9 shows the number of hourly and cumulative split failures at the

southbound left-turn for June 18 and June 25 before the adjustment and July 2, July 9, and July 16 after the adjustment.

Figure 9a shows an overall reduction in the number of split failures per hour for the after period. Figure 9b shows cumulative split failures every 15 minutes throughout the same time period for each day. The before period (callouts *i* and *ii*) recorded 60 split failures and 48 split failures for June 18 and June 25, respectively. In the after period, for July 2 there were 46 split failures recorded (callout *iii*), while July 9 and July 16 (callouts *iv* and *v*) experienced 17 and 35 split failures, respectively, or on average about 40% of the original amount.

The volumes for each Saturday for both directions was measured by the advance detection zone in the mainline travel lanes (Figure 10a). Overall, the volumes were between 12,700 and 15,700 vehicles in the southbound direction and 11,700 to 14,000 in the northbound direction. Individual turning movement counts for movements such as the southbound left-turn and other minor movements were not available.

While the split failures for July 2 did not substantially decrease, this movement serves a busy shopping center and experienced a large number of split failures during the Independence Day weekend. On July 2 just after the adjustment, the mainline volumes were the lowest of the five days, yet the southbound left-turn movement saw a high number of split failures, likely due to higher shopping activity during the holiday weekend.

Figure 9. Before (6/18-6/25) and after (7/2-7/16) split adjustment at southbound left turn, US-31 and Mall entrance.

Figure 10b shows the northbound V/C ratio converted from volumes in 15-minute bins for each of the five days over the 10-hour period. Even with lower volumes northbound on July 2, the V/C ratio did not drop compared to the two Saturdays before the splits adjustment, and peaked as high as 0.77 between 1315–1330. This suggests that the southbound left-turn movement was using most of its split time. July 9 saw the lowest number of split failures for the southbound left-turn movement (Figure 9b), but with higher volumes than July 2, suggesting the demand to the shopping center had eased. Finally, for July 16, the highest mainline volumes were experienced, and V/C ratios were up from 0.65-0.72 to 0.85 at the peak compared to the previous four days due to less capacity (Figure 10b, callout i). The number of split failures on the southbound left-turn movement was also high, but lower than the Saturdays before the adjustment, suggesting effectiveness of the added split.

The yellow and red clearance are analyzed in Figure 11. Figure 11a shows the cumulative seconds of yellow time for which the stopbar detection zone was occupied over the 10-hour period for each of the five days. Overall, the amount of yellow time with a vehicle at the stopbar decreased

after the adjustment. In the before period, at least 337 seconds of yellow time were occupied while in the after period at most 203 seconds of yellow time was occupied: a decrease of at least 40%.

Figure 10. US-31 and mall entrance volumes.

Figure 11b shows the number of red light infractions for each of the five days (13). The after period experienced considerably fewer red light infractions than the before period (5 per day compared to 1.6 per day; a 66% decrease), with July 16 having no recorded infractions at all (callout *i*). This suggests that the increased capacity also may have contributed to added safety for drivers.

Overall, the heuristic was successful in reducing the number of split failures at this intersection because there was sufficient unused green time available for redistribution. However, movements that experience severely oversaturated periods may not see significant impacts on split failures, such as during special events. Intersections with downstream blocked movements would also not be good candidates for this method since the heuristic makes assumptions about vehicle discharge during occupied intervals in the green phase.

Figure 11. Clearance time metrics for southbound left movement, US-31 and Mall Entrance.

CONCLUSIONS AND FUTURE WORK

A method for identifying split failures for a network consisting of 47 intersections was presented. A drill-down approach was developed to find a candidate movement where there was opportunity to adjust split timings to improve performance. A heuristic was developed to estimate the amount of time that can be reallocated. At the study intersection, 5 seconds of allocable split time was computed by the heuristic and changes were made in the field. The adjustment reduced split failures on the phase identified by an average of 40% while also decreasing yellow occupancy by an average of 40% and red light infractions by an average of 66%, while increasing the V/C ratio on the competing movement by 18-31%.

Future research includes applying the heuristic to other locations with different geometric and phase configurations and activity patterns to determine the sensitivity of response. Implementations of these methods include interactive dashboards and automated notification of opportunity phases. Ideally, these applications will be integrated into central system dashboards so that agencies have sustainable tools for efficiently triaging split failure improvement opportunities.

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REFERENCES

1. National Transportation Operations Coalition. *2012 National Traffic Signal Report Card*. Washington, D.C.: Institute of Transportation Engineers, 2012. Available online: <http://www.ite.org/reportcard/>.
2. Smaglik, E.J., A. Sharma, D.M. Bullock, J.R. Sturdevant, and G. Duncan. Event-Based Data Collection for Generating Actuated Controller Performance Measures. *Transportation Research Record No. 2035*, 97–106, 2007.
3. Bullock, D.M., C.M. Day, T.M. Brennan, J.R. Sturdevant, and J.S. Wasson. Architecture for Active Management of Geographically Distributed Signal Systems. *ITE Journal*, 81 (5), 20-24, 2011.
4. Sturdevant, J. R., et al. Indiana Traffic Signal Hi Resolution Data Logger Enumerations, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana, 2012. doi: <http://data.datacite.org/10.4231/K4RN35SH>.
5. Freije, R. S., A.M. Hainen, A.L. Stevens, H. Li, W.B. Smith, H. Summers, C.M. Day, J.R. Sturdevant, and D.M. Bullock, Graphical Performance Measures for Practitioners to Triage Split Failure Trouble Calls. *Transportation Research Record No. 2439*, 27-40, 2014.
6. Stevanovic, A., P.T. Martin. Split-cycle offset optimization technique and coordinated actuated traffic control evaluated through microsimulation. *Transportation Research Record*, no. 2080, p 48-56, 2008.
7. Stamatiadis, N., A. Hedges, A. Kirk. A simulation-based approach in determining permitted left-turn capacities. *Transportation Research Part C: Emerging Technologies*, v 55, p 486-495, June 2015.
8. Luk, J., A. Sims. Evaluating Four Methods of Area Traffic Control – The Parramatta Experiment. *Australian Journal of Instrumentation and Control*, v 39, n 4, p 75-77, Aug 1983.
9. Luyanda, F., D. Gettman, S. Shelby, L. Head, D. Bullock, P. Mirchandani, “ACS-Lite Algorithmic Architecture: Applying Adaptive Control System Technology to Closed-Loop Traffic Signal Control Systems,” *Transportation Research Record: Journal of the Transportation Research Board*, No. 1856, Transportation Research Board of the National Academies, Washington, D.C., pp. 175-184, 2003. DOI: 10.3141/1856-19.
10. Kohls, A.G. *Flow-based Adaptive Split Signal Control* (Doctoral dissertation). University of Tennessee, 2010. http://trace.tennessee.edu/utk_graddiss/716
11. Day, C.M., J.R. Sturdevant, and D.M. Bullock, D.M. Outcome Oriented Performance Measures for Management of Signalized Arterial Capacity. *Transportation Research Record No. 2192*, 24-36, 2010.
12. Urbanik, T. et al. *Traffic Signal Timing Manual – Second Edition*. NCHRP Report 812, section 4, pp. 19. 2015.
13. Lavrenz, S.M., C.M. Day, J. Grossman, R. Freije, and D.M. Bullock. Use of High-Resolution Signal Controller Data to Identify Red-Light-Running Vehicles. *Transportation Research Board Annual Meeting 2016*. Paper No. 16-0209.