2014

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December 17, 2013

TRB Paper 14-0301

Word Count: 3981 words + 12 x 250 words/Figure-Table = 3969 + 3000 = 6969

ABSTRACT
Detector occupancy is commonly used to measure traffic signal performance. Despite improvements in controller computational power, there have been relatively few innovations in occupancy-based performance measures or integration with other data. This paper introduces and demonstrates the use of graphical performance measures based on detector occupancy ratios to verify potential split failures and other signal timing shortcomings reported to practitioners by the public. The proposed performance measures combine detector occupancy during the green phase, detector occupancy during the first five seconds of the red phase, and phase termination cause (gap out or force off). These are summarized by time of day to indicate whether the phase is undersaturated, nearly saturated, or oversaturated. These graphical performance measures and related quantitative summaries provide a first-level screening and triaging tool for practitioners to assess user concerns regarding whether sufficient green times are being provided to avoid split failures. They can also provide outcome-based feedback to staff after making split adjustments to determine whether operation improved or worsened. The paper concludes by demonstrating how the information was used to make an operational decision to re-allocate green time that reduced the number of oversaturated cycles on minor movements from 304 to 222 during a Thursday 0900-1500 timing plan and from 240 to 180 during a Friday 0900-1500 timing plan.

INTRODUCTION

Traffic engineers frequently engage in the important task of responding to trouble calls from the public about perceived traffic signal timing deficiencies. A rather common reported issue is that the signal did not provide enough green time to serve the vehicles waiting for a particular movement. This event is known as a split failure. It is particularly aggravating to motorists because they must wait for an entire cycle length before the next green indication. It is therefore highly desirable to prevent split failures from occurring by proactively adjusting signal timings to accommodate evolving traffic demands. At the same time, in order to operate the intersection efficiently, it is desirable to terminate actuated phases as soon as their demand has been served. Increasing the split time for a problem phase is not always an adequate response to a trouble call, especially during times of day when there is moderate to heavy demand on competing phases.

Currently, detector occupancy is the primary performance measure for determining the condition of operations of each phase of a signal. Occupancy is used for performance monitoring and adaptive control in several advanced control systems. For example, SCATS (1,2) measures a “degree of saturation” based upon detector occupancy, while ACS-Lite (3) uses the “green occupancy ratio,” or the percent of time the detector is occupied during green, to drive split adjustments.

Detector occupancy is somewhat limited in that the rate of occupancy quickly attains a high value under moderate demand, which is shown by Smaglik *et al*. in a paper that compares green occupancy rates and volume to capacity ratios (4). Efficient operation occurs when there is expeditious termination of actuated phases, and a high green occupancy rate during a given cycle does not always correspond to a split failure. One possible solution is to utilize a vehicle counting detector, which provides higher fidelity data and can be used to monitor phase performance and adjust splits (5,6,7,8). In prior research, an upper bound threshold on the volume-to-capacity ratio was used to estimate the occurrences of split failures. This approach requires the installation of counting detector amplifiers. In contrast, occupancy measurements are feasible at any intersection with existing detection.

Recently, Hallenbeck *et al*. proposed the measurement of occupancy during both green and yellow for measuring phase performance (9). Sunkari *et al*. (10) proposed the measurement of “queue service time,” which measures the interval between the onset of green and the termination of a continuous call for the respective phase. They also measured the number of phase max outs. Li *et al*. (11) proposed monitoring the number of times when phases maxed out during three or more consecutive cycles.

CONCEPT

The study extends previous cited above by combining the green occupancy with the occupancy during the start of red and phase termination information to provide a more accurate view of phase performance than green occupancy alone can provide. This information can be used to identify split failures on actuated phases. This methodology is intended for use at any intersection with existing stop bar detection. The performance measure visualizations in this paper identify split failures with higher fidelity than green occupancy alone by additionally analyzing occupancy during the first five seconds of red, and by supplementing occupancy data with information about the phase termination cause.

The green occupancy ratio (GOR) is defined by

$$GOR = \frac{O_g}{g}$$ **Equation 1**

where O_g is the total detector occupancy time during green, and g is the duration of the green interval.

Occupancy during the first five seconds of the red phase (ROR_5) is similarly defined by

$$ROR_5 = \frac{O_r}{5}$$ **Equation 2**

where O_r is the total detector occupancy time during the first five seconds of the red interval. The red interval is defined as the interval directly following the end of yellow. In the case of protected/permitted left turns, the ROR_5 corresponds to the first five seconds of the permitted phase.

The GOR for a given cycle of a movement is an indicator of how saturated the movement was during that cycle, but is quite sensitive to detector length (4). For through movements and protected left turns, the ROR_5 can be used as an indicator of whether vehicles were present after the end of green. If there is unserved demand at the end of yellow, the unserved vehicles would occupy the detector during the first 5 seconds of red, and the ROR_5 would be 100%. For protected-permitted left turns, the ROR_5 can be used as an indicator that vehicles were present at the end of the protected phase. When the GOR is also high, and the phase forced off, it is very likely that a split failure occurred.

The duration of the red phase over which the ROR_5 is calculated is a parameter that can be varied. The longer interval over which the ROR is calculated make, the more likely that occupancy is due to new arrivals rather than vehicles present at the end of green, while a shorter duration would make it more likely that occupancy was due to vehicles passing through the intersection during the red clearance interval. Based on empirical observations of occupancy during yellow and red times following a phase, the authors identified the first five seconds of red as an intermediate reasonable duration that can indicate split failures with a high fidelity. Studying the sensitivity of this duration is a potential future research opportunity.

STUDY LOCATION

The location selected to demonstrate these performance measures is the intersection of US-31 (Meridian St.) and 126th St. (W. Carmel Dr.) north of Indianapolis (see Figure 1). Figure 1 shows a layout of the intersection, including the ring diagram, the directions of each phase, and callouts denoting the detector channels at the eastbound (EB) approach. This intersection is coordinated from 0600-2200. Phases 2 and 6 are the coordinated phases. Floating force-offs are used, which causes any time that is yielded by early terminating or omitted non-coordinated phases to be transferred to phases 2 and 6.

The EB approach of the intersection was chosen for groundtruthing the performance measures because it demonstrated an oversaturated movement (i.e. Phase 4, the EB thru/right movement) and an undersaturated movement (i.e. Phase 7, the EB left turn movement) on Wednesday, June 26th, 2013.

High-resolution event data was collected at this location using event-logging software embedded in the signal controller (6). The data was transported to a relational database via a cellular modem (12), and the performance measures were generated using standard database queries and server-side scripting.

EXAMPLE CALCULATION OF GOR AND ROR_5

Figure 2 contains an example of a single cycle of Phase 7 that cleared the queue during the protected phase on Wednesday, June 26th, 2013. Figure 2a illustrates how the GOR and ROR_5 are calculated. The square wave shows when the detector channel for the left turn lane is occupied, and the Phase 7 bar represents the signal head indication for the left turn. Callout i denotes the bar representing the GOR, which was 67% for the cycle, and callout ii denotes the bar representing the ROR_5, which was 0% for the cycle. Callouts iii and iv denote the portion of the green time and that of the first five seconds of the red time, respectively, during which the detector was unoccupied. Note that no detector occupancy measurements were made during the yellow time.

The pictures in Figure 2b-e, which correspond to callouts b-e in Figure 2a, are provided to visually illustrate how the GOR and ROR_5 were calculated. The pictures were taken twice per second by a mobile pan/tilt/zoom (PTZ) camera mounted on a trailer that was parked on the side of the road. Figure 2b shows that two vehicles were present when the Phase 7 signal head turned green, and Figure 2c shows an empty left turn lane when the signal head turned yellow, signifying that a gap out occurred as represented by callout iii of Figure 2a. The pictures in Figure 2d-e show that a vehicle was never present in the left turn lane during the first five seconds of the red phase, which is represented in callout iv of Figure 2a.

The cycle illustrated in Figure 2 provides an example of queue dissipation during the protected phase of a protected/permitted left turn movement. This is indicative of an undersaturated split timing because all of the vehicle demand was served.

GRAPHICAL INTEGRATION OF GOR, ROR_5, AND PHASE TERMINATION CAUSE

Figure 3 shows the integration of GOR, ROR_5 and Force Off/Gap Out information for Phase 7, which experienced undersaturated operation throughout the day. It also includes graphs that zoom in to the timing plan (0900-1500) and to the hour during which the cycle shown in Figure 2 occurred (in Figure 3a-j, callout i denotes the point corresponding to the cycle shown in Figure 2).

- Figure 3a, Figure 3d, and Figure 3g are plots of the ROR_5 against the TOD for each cycle that occurred during the entire 24 hours, the period 0900-1500, and the single hour 0900-1000, respectively.
- Figure 3b, Figure 3e, and Figure 3h are plots of the GOR against TOD during those three time periods.
- Figure 3c, Figure 3f, and Figure 3j are scatter plots of the ROR_5 vs. the corresponding GOR during those three time periods.
    - The black diamonds correspond to cycles that forced off, and the gray circles correspond to cycles that gapped out (the same color scheme is used in the TOD plots as well).

The TOD plots enable the practitioner to determine at a glance whether a phase is oversaturated or undersaturated during each timing plan. Multiple closely-spaced bars with a high ROR_5 are usually representative of systematic oversaturated phases. They are representative of consistently unserved demand at the end of the protected phase for permitted-protected left turns. Long intervals containing bars with an $ROR_5 < 50\%$ are representative of undersaturated splits.

- **Nearly Saturated Phases**: Points within the lower right quadrant of the ROR_5 vs. GOR scatter plots are representative of a nearly saturated movement. The high GOR represents mostly saturated flow throughout the green phase, which means that the green time is being efficiently utilized, and the low ROR_5 signifies a lack of a split failure except in rare cases. An ROR_5 of zero represents no remaining vehicles at the stop bar. If the ROR_5 has a small non-zero value, it represents late-arriving vehicles or vehicles that traveled through the intersection during part of the red clearance interval.
- **Oversaturated Phases**: Points within the upper right quadrant are usually indicative of a split failure, especially black diamonds (denoting force offs) with $ROR_5 \geq 80\%$ and $GOR \geq 80\%$. These force offs with high GOR and ROR_5 values represent oversaturated conditions that likely led to a split failure. On the other hand, gray circles in the upper right quadrant are typically associated with a phase that gapped out due to insufficient demand, but had a late arriving vehicle occupy the detector near the start of the ROR_5 interval.
- **Undersaturated Phases**: Points in the lower left or upper left quadrants correspond to undersaturated conditions, usually occur in the middle of the night while the signal is running free, and are typically not noteworthy.

Figure 3d-f shows what the scatter plots and TOD plots look like for the timing plan running from 0900-1500, which was undersaturated as indicated by the lack of black diamonds in the upper right quadrant of Figure 3f (correspondingly, there are zero black bars representing an $ROR_5 > 50\%$ in Figure 3d).

EXAMPLE OF PHASE WITH SEVERAL OVERSATURATED CYCLES

Figure 4 shows a single cycle of Phase 4 that experienced oversaturated conditions on Wednesday, June 26th, 2013. Figure 4a is a conceptual illustration of how the GOR and ROR_5 are calculated. There are square waves for detector channel 6 (the thru lane) and detector channel 9 (the thru/right lane), as well as a square wave showing when either or both of the detector channels was occupied. The Phase 4 bar represents the signal head indication for the thru/right movement. Callout i denotes the bar representing the GOR, which was 100% for the cycle, and callout ii denotes the bar representing the ROR_5, which was 90% for the cycle.

The pictures in Figure 4b-e, which correspond to callouts b-e in Figure 4a, display field conditions during this cycle. Callouts marked “v” in Figure 4b-e track a single vehicle, which was near the end of the queue at the start of green (Figure 4b), but remains waiting at the intersection five seconds after the start of green (Figure 4e). This confirms that a split failure took place, corresponding to the high GOR and ROR_5 values associated with this cycle.

Callout iii denotes a miniscule portion of the first five seconds of red when neither detector was occupied (Figure 4a), corresponding to the small gap between vehicles in Figure 4d.

Figure 5 shows the assembly of GOR, ROR_5 and Force Off/Gap Out information for Phase 4, which was oversaturated throughout most of the day. This data is shown for the entire 24 hour period (Figure 5a-c), the 0900-1500 timing plan (Figure 5d-f), and the hour during which the cycle shown in Figure 4 occurred (Figure 5g-j). Callout i corresponds to this cycle.

- Figure 5a, Figure 5d, and Figure 5g are plots of the ROR_5 against the TOD for each cycle that occurred during the entire 24 hours, the period 0900-1500, and the single hour 0900-1000, respectively.

- Figure 5b, Figure 5e, and Figure 5h are plots of the GOR against TOD during those three time periods.
- Figure 5c, Figure 5f, and Figure 5j are scatter plots of the ROR_5 vs. the corresponding GOR during those three time periods.
    - The black diamonds correspond to cycles that forced off, and the gray circles correspond to cycles that gapped out (the same color scheme is used in the TOD plots as well).

The timing plan running from 0900-1500 has several oversaturated cycles, indicated by the numerous black diamonds in the upper right quadrant of Figure 5f (correspondingly, there are multiple closely-spaced bars with an $ROR_5 > 80\%$ in Figure 5d).

COMPARISON OF PHASE 4 AND 7 SPLIT PERFORMANCE

Figure 6 compares an undersaturated movement (i.e. Phase 7, the EB left turn movement) and an oversaturated movement (i.e. Phase 4, the EB thru/right movement) during the 0900-1500 timing plan. In addition to the scatter plots of ROR_5 vs. GOR, Figure 6 includes frequency tables with "heat map" color-coding. The numbers in the boxes correspond to the frequency of occurrence of each range of values. The bold numerals define the lower-bound values of each bin (e.g. in Figure 6c, from 0900-1500 there were 9 cycles of Phase 7 in which the ROR_5 was between 0% and 10% and the corresponding GOR was between 80% and 90%). The numbers in the upper right corner of the tables are indicative of the highest probability of a split failure. The heat maps in Figure 6c and Figure 6d represent only cycles that forced off during the 0900-1500 timing plan, whereas the heat maps in Figure 6e and Figure 6f represent only cycles that gapped out during the 0900-1500 timing plan.

IMPLEMENTATION RECOMMENDATIONS

The graphical performance measures discussed in this paper could be implemented by a practitioner to quickly verify or disprove the claim of a trouble call. Furthermore, Figure 7a-h illustrates how the ROR_5 vs. GOR scatter plots can be compared for all phases during a timing plan to determine whether a redistribution of the split times could lower the total number of split failures at an intersection. It can be ascertained from Figure 7 that phases 1,3,4, and 8 are frequently oversaturated during the 0900-1500 timing plan, whereas phases 5 and 7 are frequently undersaturated during the 0900-1500 timing plan.

The ROR_5 vs. GOR plots for phases 2 and 6 (Figure 7b and Figure 7f) appear substantially different from the others because these phases have only setback detectors (located 405 ft upstream of the intersection), and not stop bar detectors. To characterize the degree of saturation on these movements, it is more appropriate to use the volume-to-capacity (v/c) ratio. Figure 7i-j shows the v/c ratio plotted against TOD for phases 2 and 6 during the 0900-1500 timing plan. The overall degree of saturation is quite low; this is not unexpected, since this is an off-peak time of day. The low v/c ratios suggest that split time could probably be taken from phases 2 and 6 and given to minor phases during the 0900-1500 timing plan without adversely affecting the mainline.

EXAMPLE IMPLEMENTATION FOR OPERATIONAL TUNING

Using the information shown in Figure 7, a decision was made to re-allocate 4% of the split time from Phase 2 to Phase 3 and 4% of the split time from Phase 6 to Phase 8 on the morning of Thursday, July 25th, 2013. Figure 8 shows the split times of each phase before and after the adjustment was made. Data from Thursday, July 18th, 2013 (before the splits were changed) and

Thursday, July 25th, 2013 (after the splits were changed) was then collected and analyzed for the 0900-1500 timing plan.

Figure 9 provides a summary of each minor movement's performance before and after the split adjustment based on the total number of oversaturated cycles (GOR ≥ 80% and ROR_5 ≥ 80%) during the 0900-1500 timing plan. Figure 9 illustrates that phases 3 and 8 (the phases to which split time was added) dramatically improved. Figure 10 shows a more detailed comparison of Phase 8 before and after the split adjustment. A comparison between Figure 10a and Figure 10b visually illustrates the substantial improvement, and the heat maps in Figure 10c-f numerically confirm this improvement.

Note that there was very little change in the performance of phases 4, 5, and 7, and an increase in the number of oversaturated cycles on Phase 1. The change in Phase 1's performance was most likely unrelated to signal timing because its split time was not changed.

Figure 11 shows a comparison for a second pair of days, Friday, July 19th, 2013 (before the split adjustment) and Friday, July 26th, 2013 (after the adjustment). There was again a substantial reduction in oversaturated conditions on phases 3 and 8. The vehicle flow rates during the 0900-1500 timing plan did not change substantially from the Thursday and Friday before the splits were changed to the Thursday and Friday after the splits changed; therefore, the improvement was not due to a decrease in demand.

To gauge the split adjustment's effect on the mainline thru movements, Figure 12 shows v/c ratios for each cycle of phases 2 and 6 during the 0900-1500 timing plan on the Thursdays and Fridays before and after the change. Although the average v/c ratios for each phase increased, neither phase approached oversaturation. The percent of arrivals on green (POG) was calculated for phases 2 and 6 before and after the split adjustment to determine whether the progression was adversely affected. No negative impacts were observed; the POG of both phases actually increased by a few percentage points.

CONCLUSIONS

The performance measures presented in this paper provide a means for practitioners to efficiently validate complaint calls from the public reporting that a signal is not providing adequate green time for a particular movement. By combining the GOR, ROR_5, and the phase termination cause, one can better determine whether a split failure occurred than by using any of those individual performance measures alone. A variety of graphics (Figure 5, Figure 6, Figure 7, Figure 10) were presented based on these three elements that facilitate qualitative, visual analysis of the performance of individual phases at an intersection. The same data also provides a summary of overall performance by comparing the number of likely split failures for each phase (Figure 9, Figure 11).

By examining the plots of companion phases during the same timing plan, the practitioner can not only determine whether split failures are occurring but can also make an informed decision about whether adjustments of split times would be an appropriate course of action to remedy those split failures. Furthermore, after making those changes, the practitioner can assess the results by using the same performance measures in a before-and-after study. This paper illustrates the power of this analysis technique by showing the reduction in oversaturated minor movements on two different days after a 4% reallocation of split times.

ACKNOWLEDGEMENT

This work was supported by the Indiana Department of Transportation. The contents of this paper reflect the views of the authors, who are responsible for the facts and the accuracy of the

data presented herein, and do not necessarily reflect the official views or policies of the sponsoring organizations. These contents do not constitute a standard, specification, or regulation.

WORKS CITED

1. Sims AG, Dobinson KW. The Sydney Coordinated Adaptive Traffic (SCAT) System: Philosophy and Benefits. IEEE Transactions on Vehicular Technology. 1980; 29: p. 130-137.
2. Stevanovic A, Kergaye C, Martin PT. SCOOT and SCATS: A Closer Look Into Their Operations. In Transportation Research Board Annual Meeting; 2009.
3. Luyanda F, Gettman D, Head L, Shelby S, Bullock DM, Mirchandani P. ACS-Lite Algorithmic Architecture: Applying Adaptive Control System Technology to Closed-Loop Traffic Signal Control Systems. Transportation Research Record. 2003; 1856: p. 175-184.
4. Smaglik EJ, Sharma A, Bullock DM, Sturdevant JR, Duncan G. Event-Based Data Collection for Generating Actuated Controller Performance Measures. Transportation Research Record. 2007; 2035.
5. Smaglik EJ, Bullock DM, Gettman D, Day CM, Premachandra H. Comparison of Alternative Real-Time Performance Measures for Measuring Signal Phase Utilization and Identifying Oversatutration. Transportation Research Record. 2011 December; 2259: p. 123-131.
6. Smaglik EJ, Bullock DM, Urbanik T. Adaptive Split Control Using Enhanced Detector Data. In 2005 ITE International Annual Meeting and Exhibit; 2005; Melbourne, Austrailia.
7. Day CM, Sturdevant JR, Bullock DM. Outcome-Oriented Performance Measures for Management of Signalized Arterial Capacity. Transportation Research Record. 2010 December; 2192: p. 24-36.
8. Day CM. Performance Based Management of Arterial Traffic Signal Systems. PhD Thesis. Purdue University; 2010.
9. Hallenbeck ME, Ishimaru JM, Davis KD, Kang JM. Arterial Performance Monitoring Using Stop Bar Sensor Data. In Transportation Research Board Annual Meeting; 2008.
10. Sunkari S, Charara HA, Songchitruska P. Portable Toolbook for Monitoring and Evaluating Signal Operations. Transportation Research Record. 2012; 2311: p. 142-151.
11. Li H, Hainen AM, Day CM, Grimmer G, Sturdevant JR, Bullock DM. Longitudinal Performance Measures for Assessing Agency-Wide Signal management Objectives. In Transportation Research Board Annual Meeting; 2013.
12. Bullock DM, Day CM, Brennan TM, Sturdevant JR, Wasson JS. Architecture for Active Management of Geographically Distributed Signal Systems. ITE Journal. 2011 May; 81(5): p. 20-24.

LIST OF FIGURES

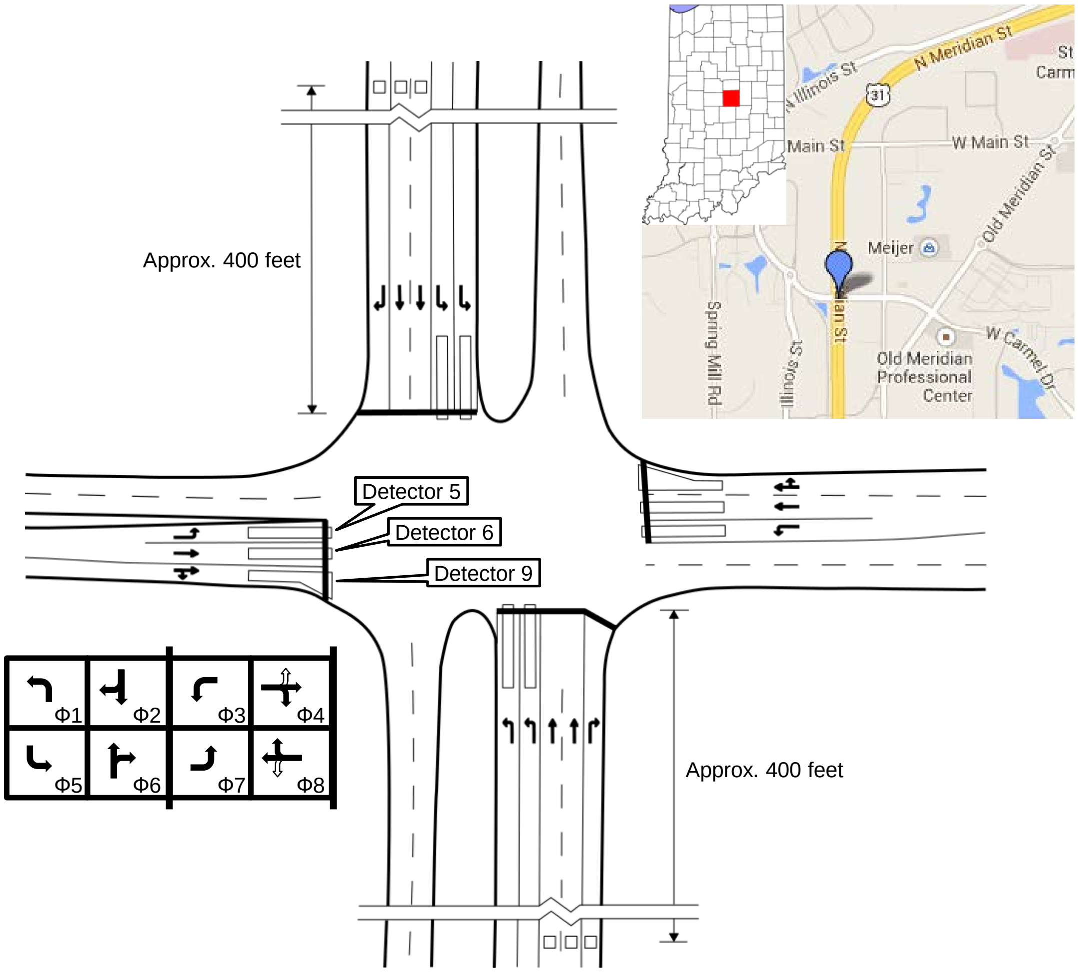
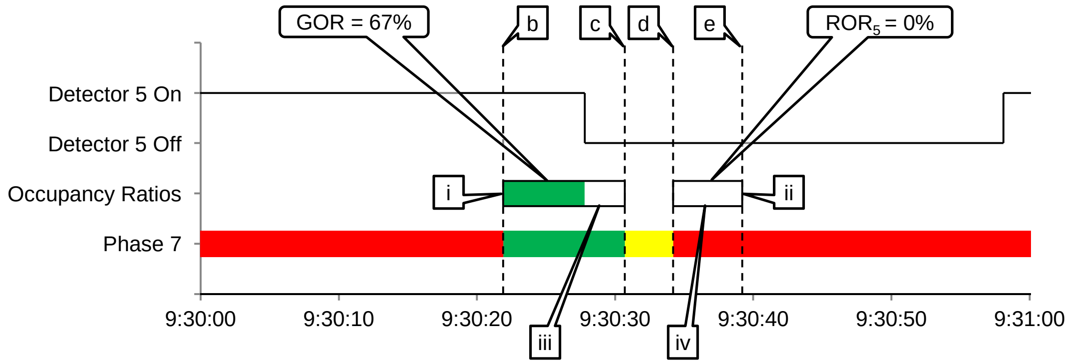


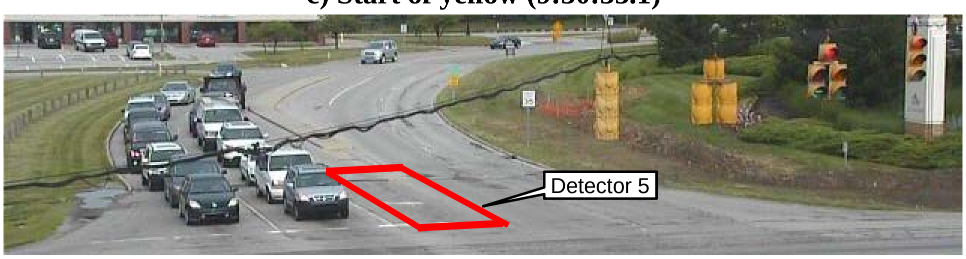
Figure 1 The location, geometry, and ring and barrier diagram for the intersection of US-31 (Meridian St.) and 126th St. (W. Carmel Dr.).



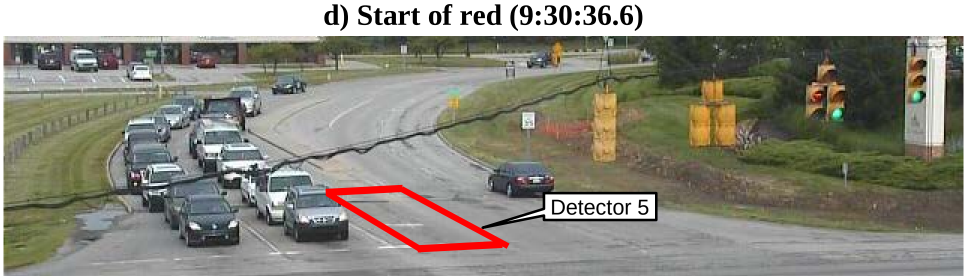
a) Calculation illustration of GOR and ROR_5

b) Start of green (9:30:24.1)

c) Start of yellow (9:30:33.1)



d) Start of red (9:30:36.6)



e) 5 seconds after start of red (9:30:41.6)

Figure 2 GOR and ROR_5 for a single cycle of an undersaturated left turn movement.

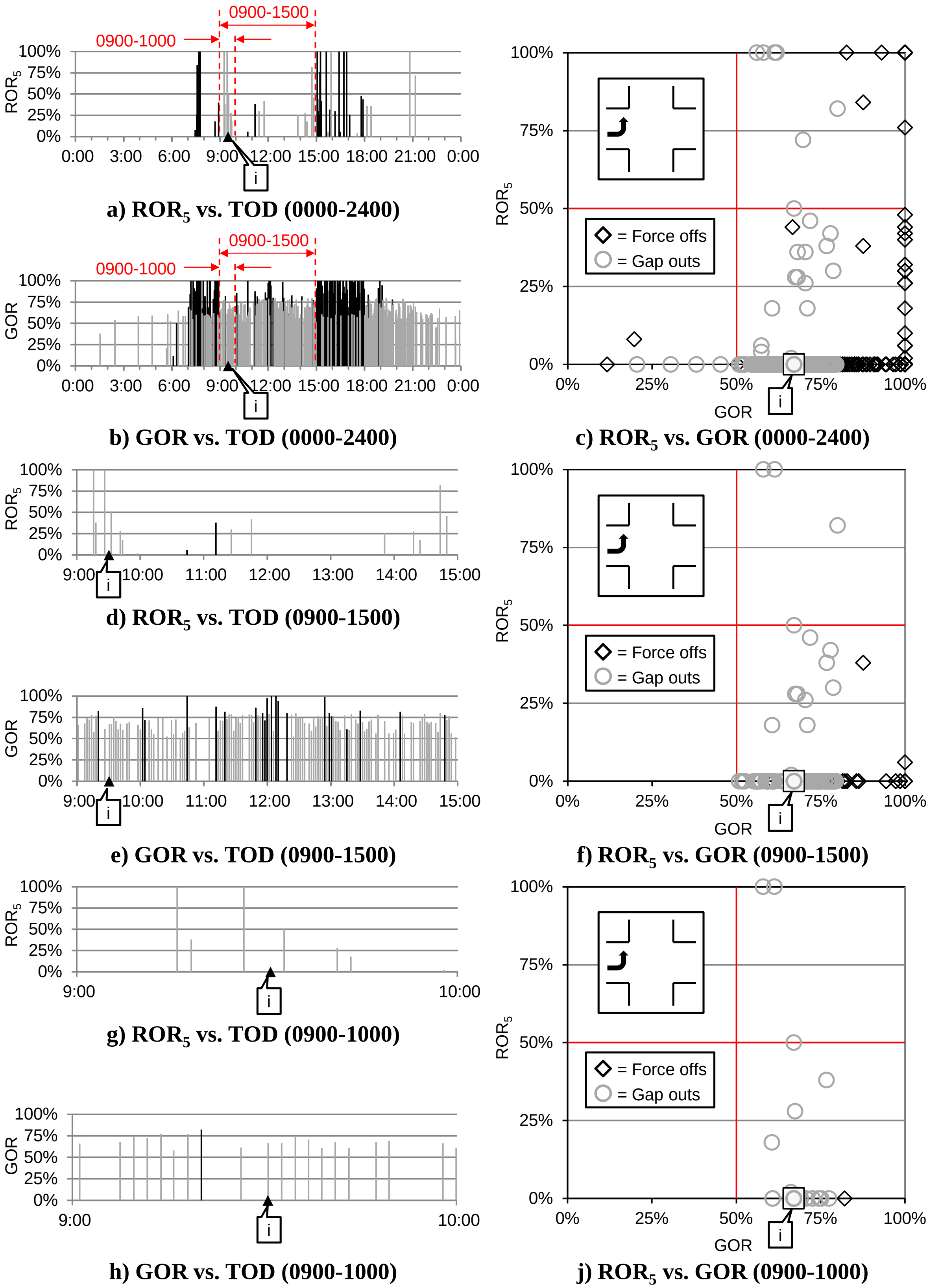
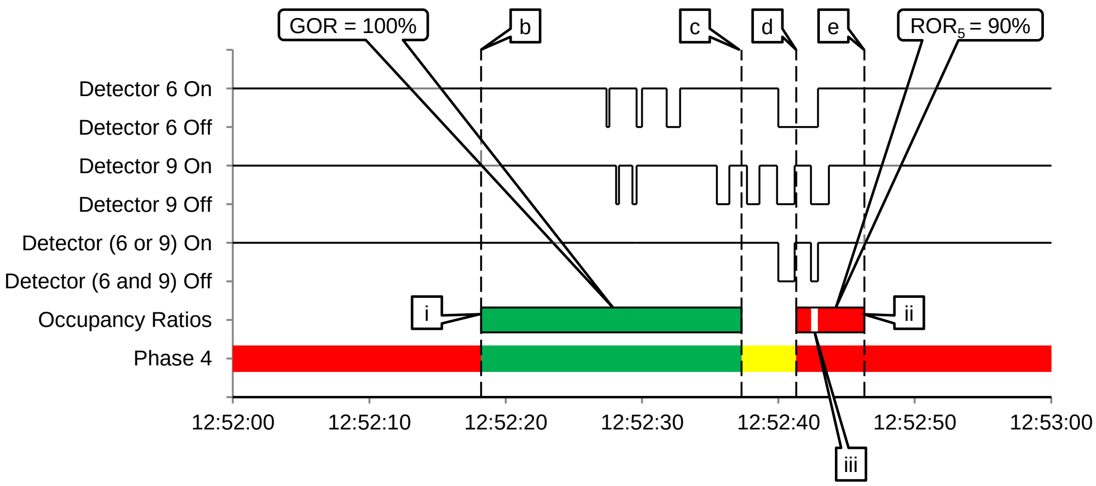
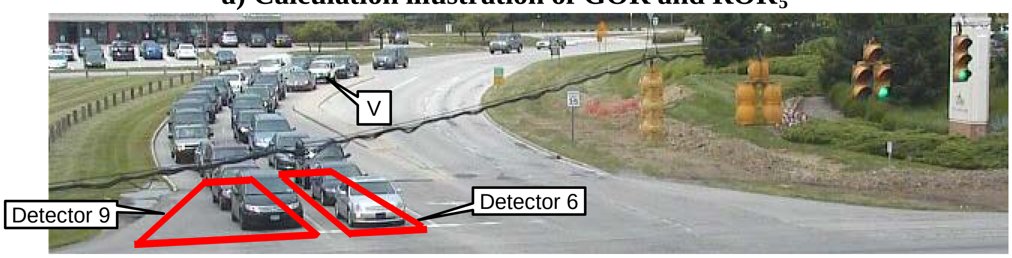


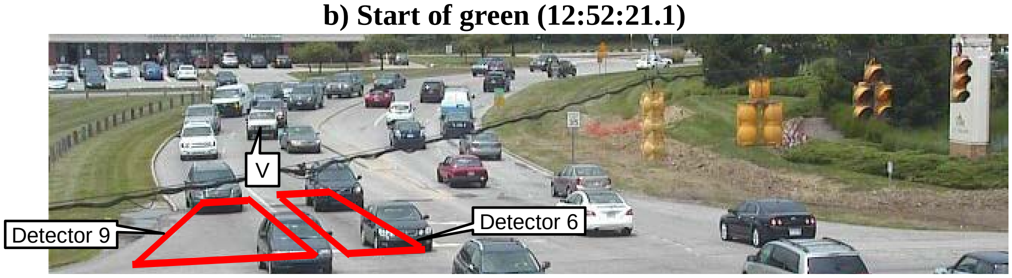
Figure 3 ROR_5 vs. GOR, ROR_5 vs. TOD, and GOR vs. TOD for Phase 7 (Wed. 6/26/2013).



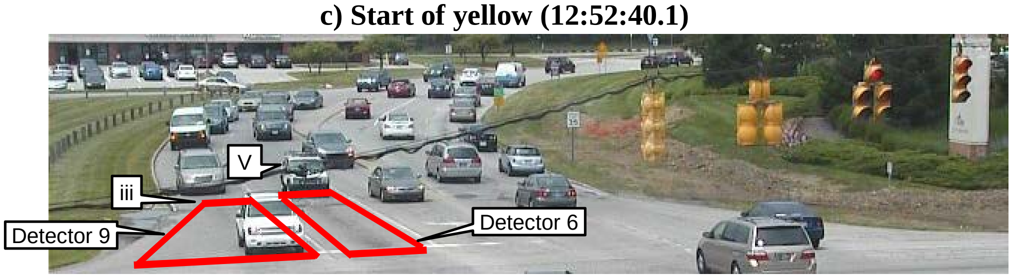
a) Calculation illustration of GOR and ROR_5



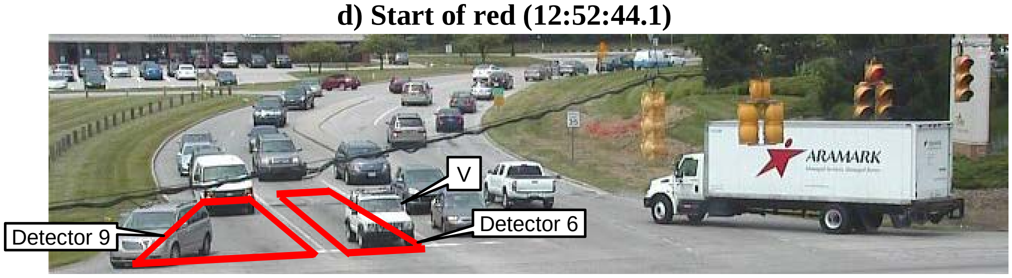
b) Start of green (12:52:21.1)



c) Start of yellow (12:52:40.1)



d) Start of red (12:52:44.1)



e) 5 seconds after start of red (12:52:49.1)

Figure 4 GOR and ROR5 for a single cycle of an oversaturated thru movement.

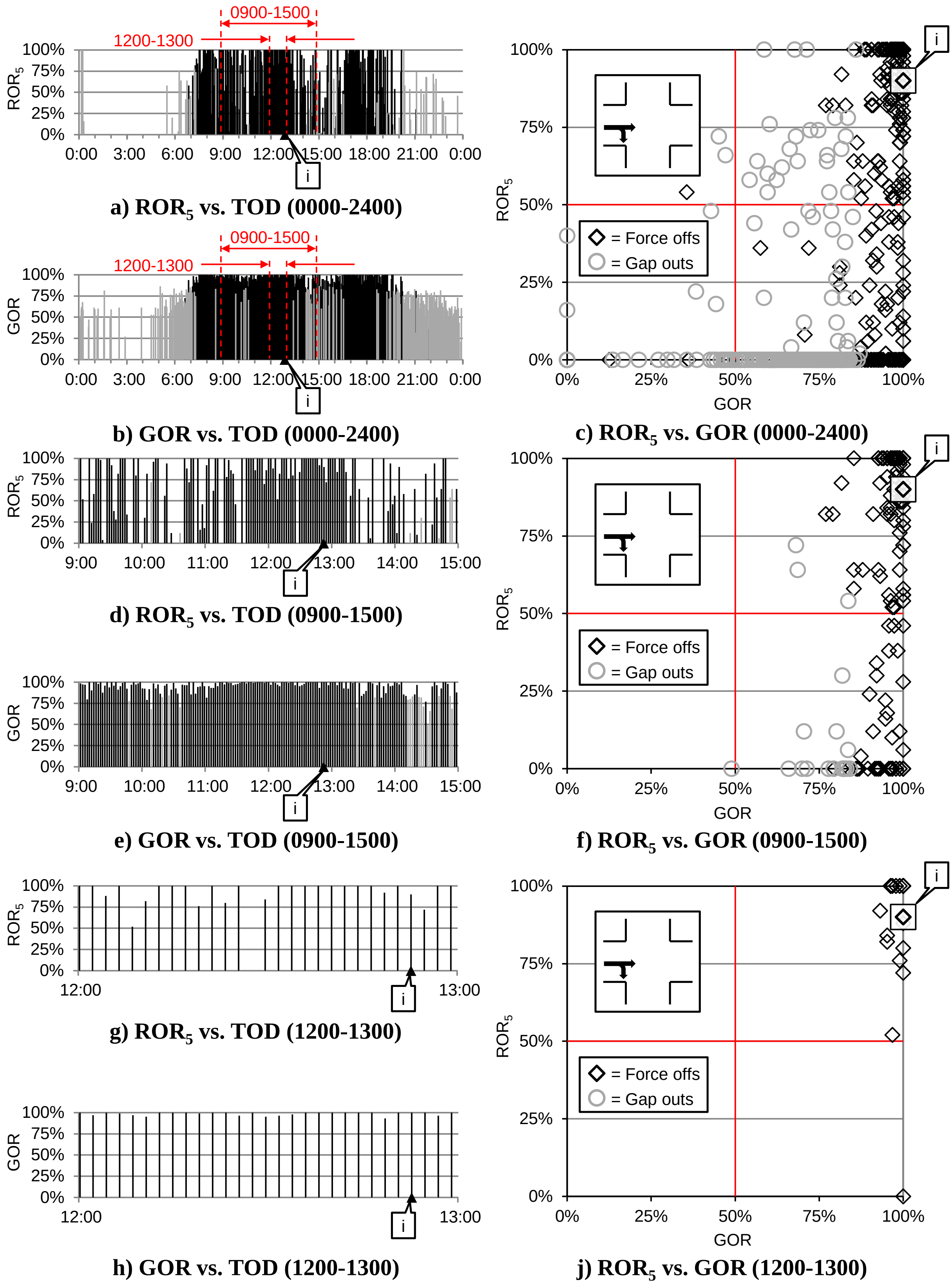
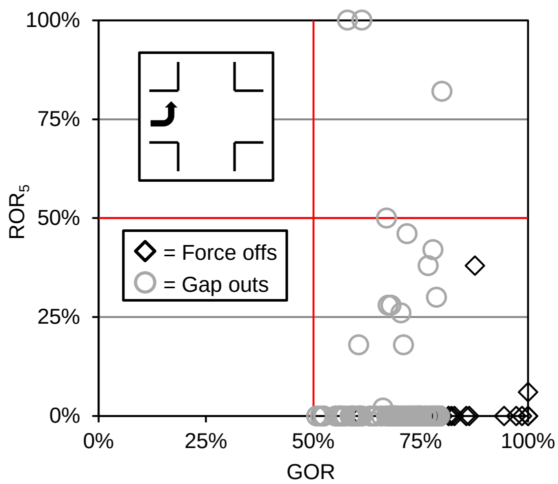
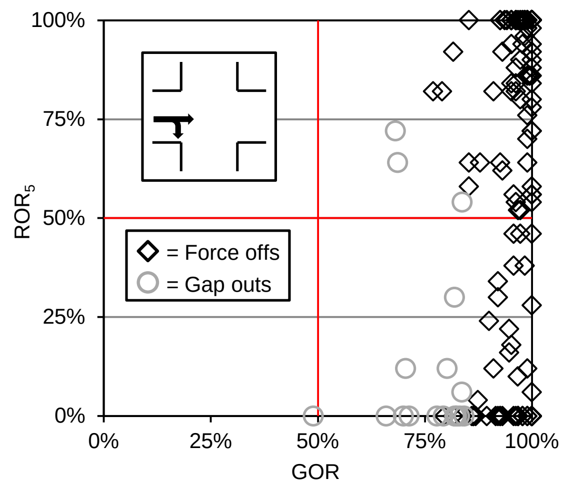


Figure 5 ROR_5 vs. GOR, ROR_5 vs. TOD, and GOR vs. TOD for Phase 4 (Wed. 6/26/2013).



a) Phase 7 ROR$_5$ vs. GOR



b) Phase 4 ROR$_5$ vs. GOR

ROR$_5$ (%) \ GOR (%)	0	10	20	30	40	50	60	70	80	90
90										
80										
70										
60										
50										
40										
30									1	
20										
10										
0							1	4	9	6

c) Phase 7 heat map of force offs

ROR$_5$ (%) \ GOR (%)	0	10	20	30	40	50	60	70	80	90
90									2	68
80								2		13
70										5
60									2	3
50									1	8
40										3
30										4
20										3
10										5
0								1	10	23

d) Phase 4 heat map of force offs

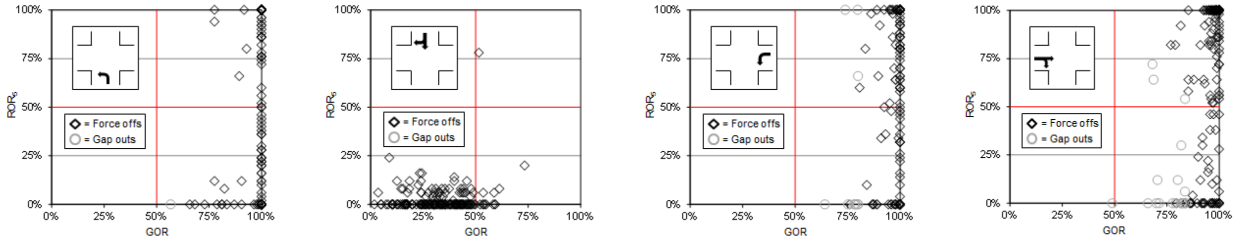
ROR$_5$ (%) \ GOR (%)	0	10	20	30	40	50	60	70	80	90
90						1	1			
80									1	
70										
60										
50							1			
40								2		
30								2		
20							2	1		
10							1	1		
0						20	28	43		

e) Phase 7 heat map of gap outs

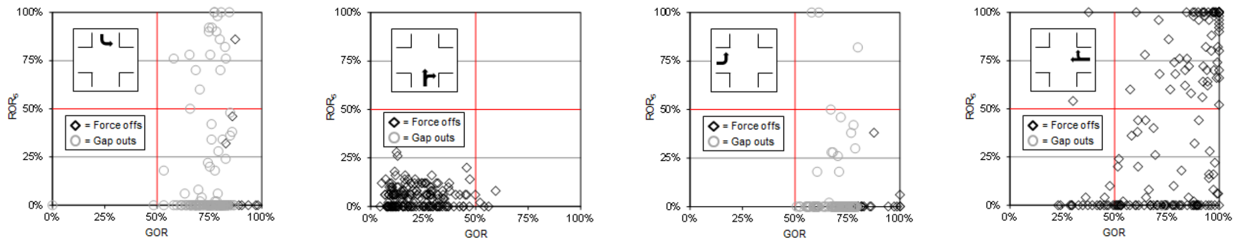
ROR$_5$ (%) \ GOR (%)	0	10	20	30	40	50	60	70	80	90
90										
80										
70							1			
60							1			
50									1	
40										
30									1	
20										
10								1	1	
0					1		1	3	6	

f) Phase 4 heat map of gap outs

Figure 6 Comparison of undersaturated and oversaturated phase performance (0900-1500 on 6/26).

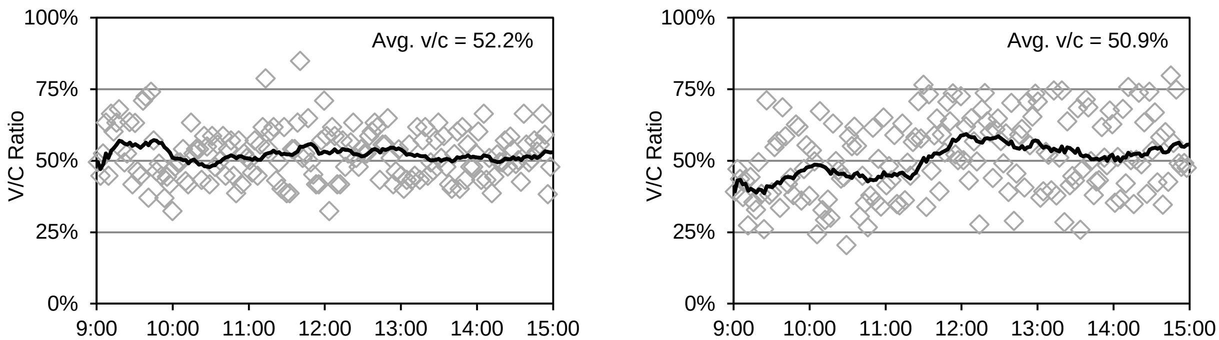


a) Φ1 ROR_5 vs. GOR b) Φ2 ROR_5 vs. GOR* c) Φ3 ROR_5 vs. GOR d) Φ4 ROR_5 vs. GOR



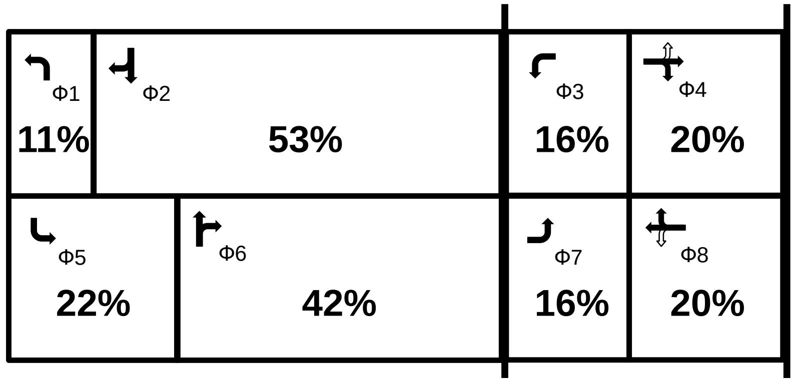
e) Φ5 ROR_5 vs. GOR f) Φ6 ROR_5 vs. GOR* g) Φ7 ROR_5 vs. GOR h) Φ8 ROR_5 vs. GOR

*** Phase 2 and Phase 6 ROR_5 and GOR were calculated based on advanced detectors.**

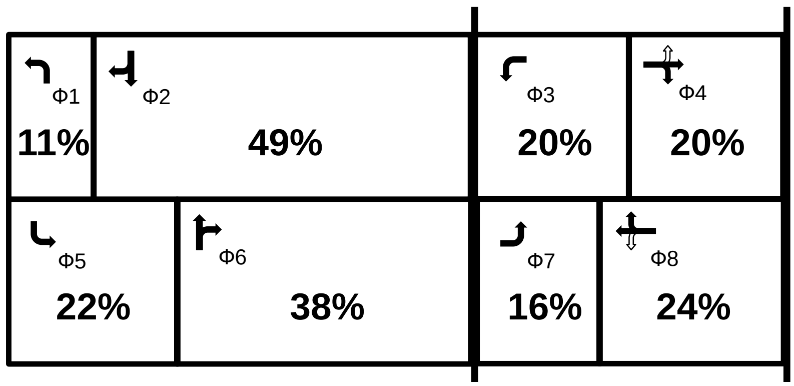


i) Phase 2 v/c ratio j) Phase 6 v/c ratio

Figure 7 ROR_5 vs. GOR for all phases and v/c ratios for phases 2 and 6 (0900-1500 on 6/26).



a) Split percentages before adjustment (7/18/2013)



b) Split percentages after adjustment (7/25/2013)

Figure 8 Split percentages before and after adjustment (0900-1500).

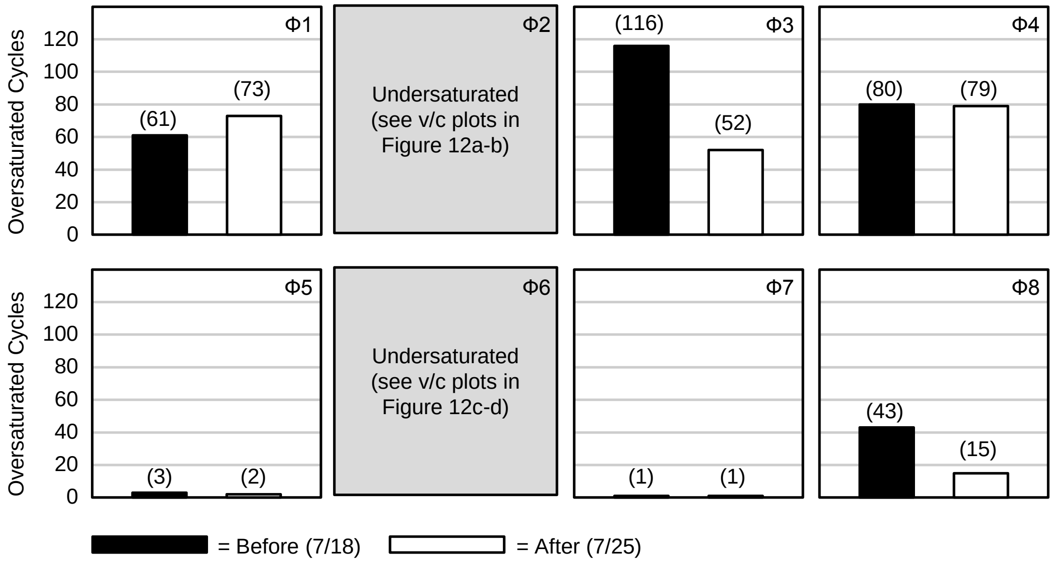
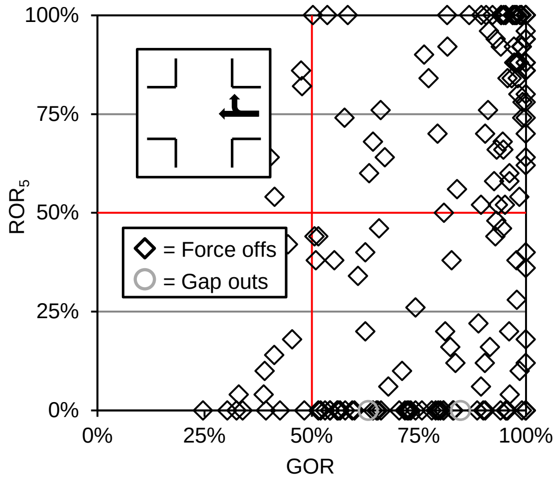
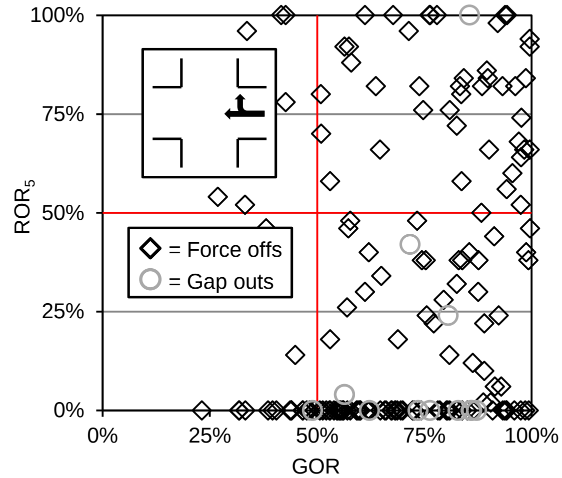


Figure 9 Before (Thurs. 7/18/2013) and after (Thurs. 7/25/2013) comparison of oversaturated cycles for the minor movements (0900-1500).



a) ROR$_5$ vs. GOR before split adjustment



b) ROR$_5$ vs. GOR after split adjustment

ROR$_5$ (%)	0	10	20	30	40	50	60	70	80	90
90						3		1	4	27
80					2			1		12
70						1	1	1		7
60					1		3			6
50					1				3	5
40					1	2	2			4
30				1		2	1		1	2
20							1	1	2	2
10				1	2			1	2	5
0			1	6	2	10	6	10	7	15
	GOR (%)									

c) Heat map of force offs before adjustment

ROR$_5$ (%)	0	10	20	30	40	50	60	70	80	90
90				1	2	2	2	5		5
80				1		2	1	1	6	3
70					1	1		1	2	1
60							1			6
50			1	1		1			2	2
40				1		2	1	1	1	3
30							2	2	5	1
20						1		3	1	1
10					1	1	1		3	
0			1	5	11	19	13	6	10	12
	GOR (%)									

d) Heat map of force offs after adjustment

ROR$_5$ (%)	0	10	20	30	40	50	60	70	80	90
90										
80										
70										
60										
50										
40										
30										
20										
10										
0							1		1	
	GOR (%)									

e) Heat map of gap outs before adjustment

ROR$_5$ (%)	0	10	20	30	40	50	60	70	80	90
90									1	
80										
70										
60										
50										
40								1		
30										
20									1	
10										
0					1	1	1	2	4	
	GOR (%)									

f) Heat map of gap outs after adjustment

Figure 10 Before (7/18) and after (7/25) comparison of Phase 8 performance (0900-1500).

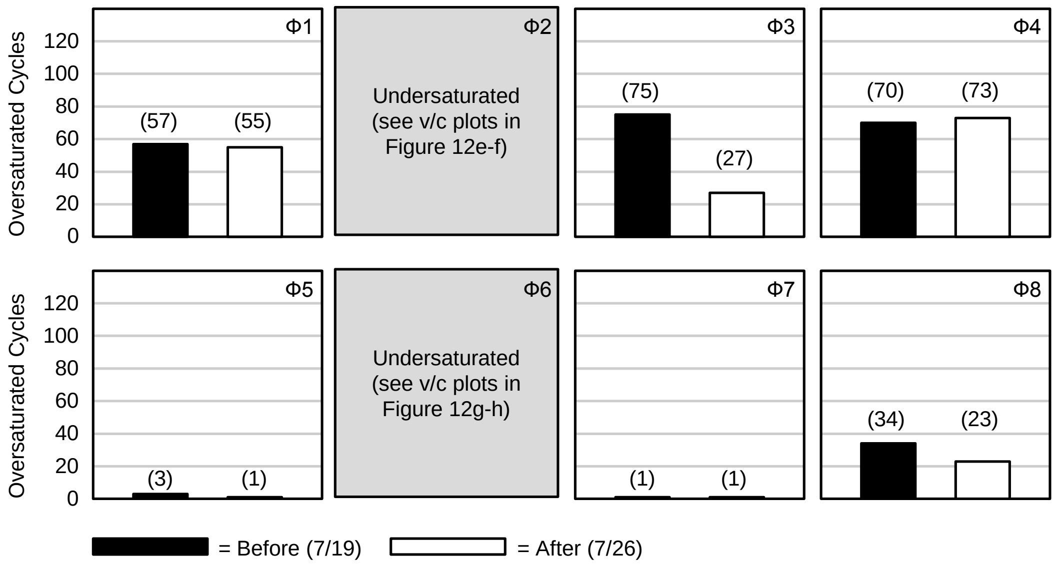
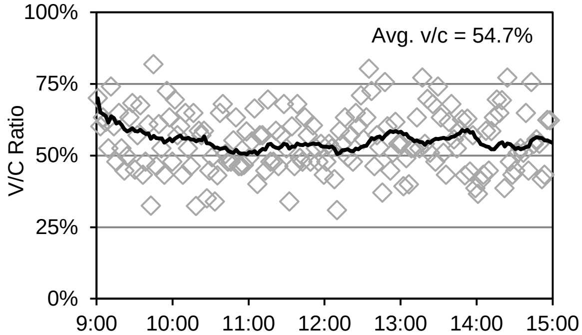
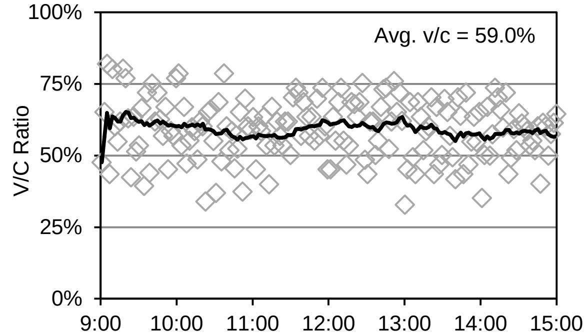


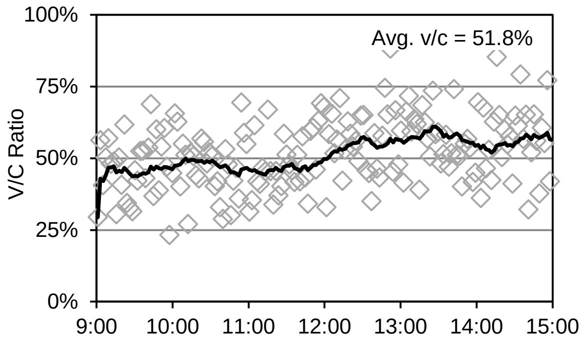
Figure 11 Before (Fri. 7/19/2013) and after (Fri. 7/26/2013) comparison of oversaturated cycles for the minor movements (0900-1500).



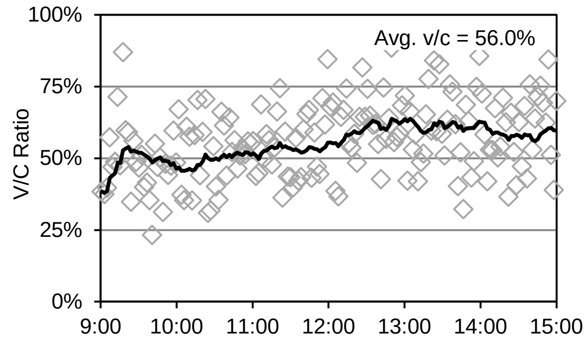
a) Phase 2 v/c ratio before adjustment (7/18)



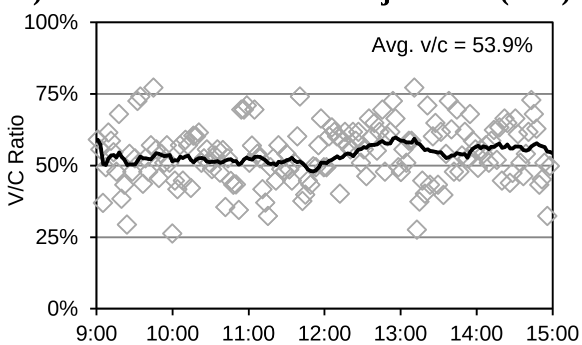
b) Phase 2 v/c ratio after adjustment (7/25)



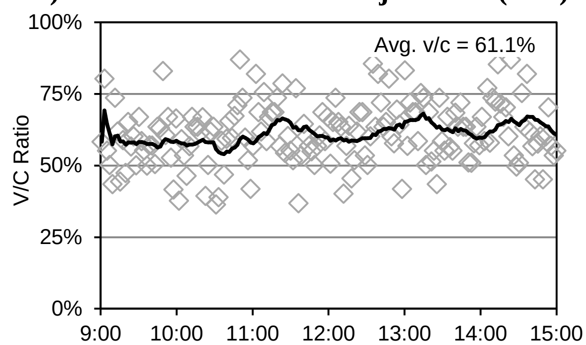
c) Phase 6 v/c ratio before adjustment (7/18)



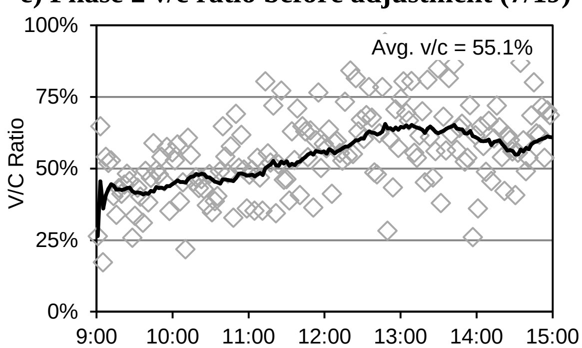
d) Phase 6 v/c ratio after adjustment (7/25)



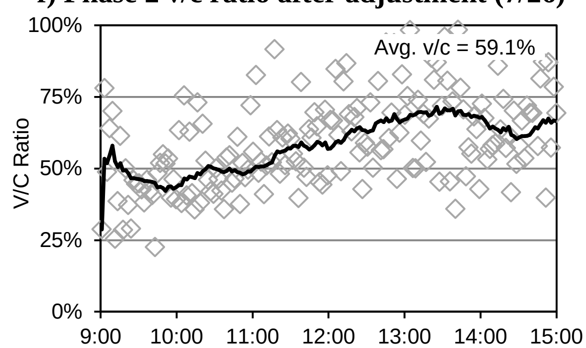
e) Phase 2 v/c ratio before adjustment (7/19)



f) Phase 2 v/c ratio after adjustment (7/26)



g) Phase 6 v/c ratio before adjustment (7/19)



h) Phase 6 v/c ratio after adjustment (7/26)

Figure 12 Thru movement v/c ratios before and after split adjustment (0900-1500).