


Spring 2014

# GRAPHICAL PERFORMANCE MEASURES FOR PRACTITIONERS TO IDENTIFY SPLIT FAILURES

Richard Scott Freije  
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Thesis/Dissertation Acceptance**

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By Richard Scott Freije

Entitled

Graphical Performance Measures for Practitioners to Identify Split Failures

For the degree of Master of Science in Civil Engineering

Is approved by the final examining committee:

Darcy M. Bullock

Andrew P. Tarko

Jon D. Fricker

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04/29/14

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Date

GRAPHICAL PERFORMANCE MEASURES FOR PRACTITIONERS TO IDENTIFY  
SPLIT FAILURES

A Thesis

Submitted to the Faculty

of

Purdue University

by

Richard Scott Freije

In Partial Fulfillment of the

Requirements for the Degree

of

Master of Science in Civil Engineering

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West Lafayette, Indiana

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## TABLE OF CONTENTS

	Page
LIST OF FIGURES .....	v
ABSTRACT.....	vii
CHAPTER 1. INTRODUCTION .....	1
CHAPTER 2. METHODOLOGY .....	6
CHAPTER 3. US-31 AND 126 <sup>TH</sup> ST. CASE STUDY.....	8
3.1 Study Location .....	8
3.2 Example Calculation of GOR and ROR <sub>5</sub> .....	10
3.3 Graphical Integration of GOR, ROR <sub>5</sub> , and Phase Termination Cause .....	13
3.4 Example of Phase with Several Oversaturated Splits .....	17
3.5 Comparison of Phase 4 and 7 Split Performance.....	21
3.6 Implementation Recommendations.....	23
3.7 Example Implementation for Operational Tuning.....	25
CHAPTER 4. ADDITIONAL PERFORMANCE MEASURES.....	34
4.1 Enhancing the ROR <sub>5</sub> vs. GOR Plots .....	34
4.2 Counting Oversaturated Splits in 30-minute Bins .....	38
CHAPTER 5. NEW US-231 CASE STUDY .....	44
5.1 Study Location .....	44
5.2 Mitigating Split Failures at US-231 and River Rd.....	47
CHAPTER 6. CONCLUSIONS.....	60
WORKS CITED .....	63

## LIST OF FIGURES

Figure	Page
1.1 Examples of a split failure and an undersaturated split .....	2
3.1 The location, geometry, and ring and barrier diagram for the intersection of US-31 (Meridian St.) and 126 <sup>th</sup> St. (W. Carmel Dr.) .....	9
3.2 GOR and ROR <sub>5</sub> for a single split of an undersaturated left turn movement.....	12
3.3 GOR vs. TOD, ROR <sub>5</sub> vs. TOD, and ROR <sub>5</sub> vs. GOR for Phase 7 (Wed. 6/26/2013).....	16
3.4 GOR and ROR <sub>5</sub> for a single split of an oversaturated thru movement.....	19
3.5 GOR vs. TOD, ROR <sub>5</sub> vs. TOD, and ROR <sub>5</sub> vs. GOR for Phase 4 (Wed. 6/26/2013).....	20
3.6 Comparison of undersaturated and oversaturated phase performance (0900-1500 on 6/26).....	22
3.7 ROR <sub>5</sub> vs. GOR for all phases and v/c ratios for phases 2 and 6 (0900-1500 on 6/26).....	24
3.8 Split percentages before and after adjustment (0900-1500) .....	27
3.9 Before (Thurs. 7/18/2013) and after (Thurs. 7/25/2013) comparison of oversaturated splits for the minor movements (0900-1500) .....	28
3.10 Before (Thurs. 7/18/2013) and after (Thurs. 7/25/2013) comparison of three consecutive oversaturated splits for the minor movements (0900-1500).....	29
3.11 Before (7/18) and after (7/25) comparison of Phase 8 performance (0900-1500).....	30
3.12 Before (Fri. 7/19/2013) and after (Fri. 7/26/2013) comparison of oversaturated splits for the minor movements (0900-1500) .....	31
3.13 Before (Fri. 7/19/2013) and after (Fri. 7/26/2013) comparison of three consecutive oversaturated splits for the minor movements (0900-1500).....	32

Figure	Page
3.14 Thru movement v/c ratios before and after split adjustment (0900-1500) .....	33
4.1 ROR <sub>5</sub> vs. GOR for a protected-permitted left turn (Phase 3 at the intersection of SR-37 and Southport Rd. on Thurs. 1/23/2014 from 1500-1900) .....	36
4.2 Oversaturated splits in 30-min. bins with the AM peak highlighted (SR-37 and Southport Rd. on Wed. 3/5/2014) .....	41
4.3 ROR <sub>5</sub> vs. GOR plots for the minor movements during the AM Peak (SR-37 and Southport Rd. on Wed. 3/5/2014) .....	42
4.4 Mainline v/c plots over 24 hours with the AM peak highlighted (SR-37 and Southport Rd. on Wed. 3/5/2014) .....	43
5.1 The location and ring and barrier diagram for the intersection of US-231 and River Rd. ....	45
5.2 Comparison of cycle lengths before and after coordination (US-231 and River Rd.) .....	46
5.3 Sequence change and split adjustment to mitigate Phase 3 split failures at US-231 and River Rd. ....	49
5.4 Oversaturated splits before and after coordination and after adjustments to mitigate phase 3 split failures at US-231 and River Rd. ....	50
5.5 ROR <sub>5</sub> vs. GOR and v/c plots (PM peak) before and after coordination and after adjustments to mitigate phase 3 split failures at US-231 and River Rd. ....	51
5.6 Longitudinal comparison of oversaturated splits in 30-min. bins (US-231 and River Rd.) .....	52
5.7 Longitudinal comparison of ROR <sub>5</sub> vs. GOR and v/c plots during the AM peak (US-231 and River Rd.) .....	54
5.8 Longitudinal comparison of ROR <sub>5</sub> vs. GOR and v/c plots during the PM peak (US-231 and River Rd.) .....	55
5.9 Additional split adjustments at US-231 and River Rd. (2/28/14) .....	56
5.10 Comparison of US-231 and River Rd. during the AM Peak before (Mon. 2/10/2014) and after (Mon. 3/3/2014) split adjustment .....	58
5.11 Comparison of US-231 and River Rd. during the PM Peak before (Mon. 2/10/2014) and after (Mon. 3/3/2014) split adjustment .....	59



## ABSTRACT

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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 thesis 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 interval, detector occupancy during the first five seconds of the red interval, 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. In addition, they can provide insight about whether a split adjustment would be an

appropriate course of action, and they can provide outcome-based feedback to staff after making split adjustments to determine whether operation improved or worsened.

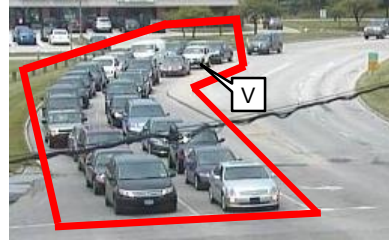
This thesis also includes two case studies that demonstrate how the performance measures can be used to identify phases experiencing several oversaturated splits and compare the number of oversaturated splits before and after reallocating green time to mitigate the oversaturation. Oversaturation was reduced at the intersection of US-31 and 126<sup>th</sup> St. north of Indianapolis and at the intersection of River Rd. and the US-231 bypass of West Lafayette.

## CHAPTER 1. 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.

- Figure 1.1a-c shows an example of a split failure because the vehicle denoted by callout v that is present near the back of the queue at the start of green is not able to progress through the intersection during the split.
- Figure 1.1d-f shows an example of an undersaturated split (not a split failure) because the two vehicles that are present at the stop bar at the start of green have progressed through the intersection by the time the light has turned yellow.

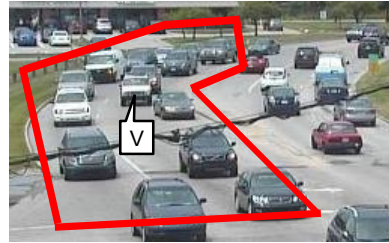
Split failures are particularly aggravating to motorists because they must wait for the next green indication before progressing through the intersection. It is therefore highly desirable to prevent split failures from occurring by proactively adjusting signal settings to accommodate evolving traffic 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.



**a) Start of green (12:52:21.1)**



**d) Start of green (9:30:24.1)**



**b) Start of yellow (12:52:40.1)**



**e) Start of yellow (9:30:33.1)**



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



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

Figure 1.1 Examples of a split failure and an undersaturated split

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. SCATS, ACS-Lite, and other adaptive control systems are designed to continually adjust cycle lengths, offsets, and splits to minimize delay and improve progression in real time (1,2,3). However, those systems are expensive, costing about \$55,000 per intersection on average according to 2009 survey data (4).

Detector occupancy during the green interval is somewhat limited in that the occupancy ratio quickly attains a high value under moderate demand, which is shown by Smaglik et al. in a paper that compares green occupancy ratios and volume to capacity ratios (5). Efficient operation occurs when there is expeditious termination of actuated phases, and a high green occupancy ratio during a given split 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 (6,7,8,9,10). In prior research, an upper bound threshold on the volume-to-capacity ratio was used to estimate the occurrences of split failures. This approach, however, requires the installation of counting detector amplifiers. An additional limitation of using the volume-to-capacity ratio to identify split failures is the inaccuracy of stop bar count

detectors in queueing situations (11). In contrast, occupancy measurements are feasible and accurate at any intersection with existing detection.

Recently, Hallenbeck et al. (12) proposed the measurement of occupancy during both green and yellow for measuring phase performance. Sunkari et al. (13) 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. (14) proposed monitoring the number of times when phases maxed out during three or more consecutive cycles. This thesis extends this work 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.

- Chapter 2 discusses the methodology used to calculate the occupancy ratios.
- Chapter 3 provides a case study of the implementation of the performance measures at US-31 and 126<sup>th</sup> St. It includes the following:
  - Example calculations of the occupancy ratios
  - The graphical integration of the occupancy ratios with the phase termination cause
  - The identification of oversaturated splits
  - The adjustment of split times to reduce oversaturation

- Chapter 4 explains enhancements to the performance measures. It includes the following:
  - Performance measures that address the permitted phase of protected-permitted left turns
  - Bar charts showing oversaturated splits over 24 hours grouped in 30-minute bins
- Chapter 5 provides a case study of the implementation of the performance measures at US-231 and River Rd. It includes the following:
  - The identification of Phase 3 split failures after the corridor was switched from free to coordinated operation
  - The mitigation of those split failures by changing the sequence and adjusting splits
- Chapter 6 concludes the thesis by summarizing the benefits of the performance measures.

## CHAPTER 2. METHODOLOGY

This thesis introduces a new methodology for analyzing detector occupancy 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 thesis 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

$$GOR = \frac{O_g}{g} \quad \text{Equation 1}$$

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

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

$$ROR_5 = \frac{O_r}{5} \quad \text{Equation 2}$$

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 split of a movement is an indicator of how saturated the movement was during that split, but is quite sensitive to detector length (5). 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 interval over which the ROR is calculated is a parameter that can be varied. A longer duration would make it more likely that occupancy was 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 first five seconds of red was identified 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.

## CHAPTER 3. US-31 AND 126<sup>TH</sup> ST. CASE STUDY

### 3.1 Study Location

The location selected to demonstrate these performance measures is the intersection of US-31 (Meridian St.) and 126<sup>th</sup> St. (W. Carmel Dr.) north of Indianapolis (see Figure 3.1). Figure 3.1 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 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 26<sup>th</sup>, 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 (15), and the performance measures were generated using standard database queries and server-side scripting.

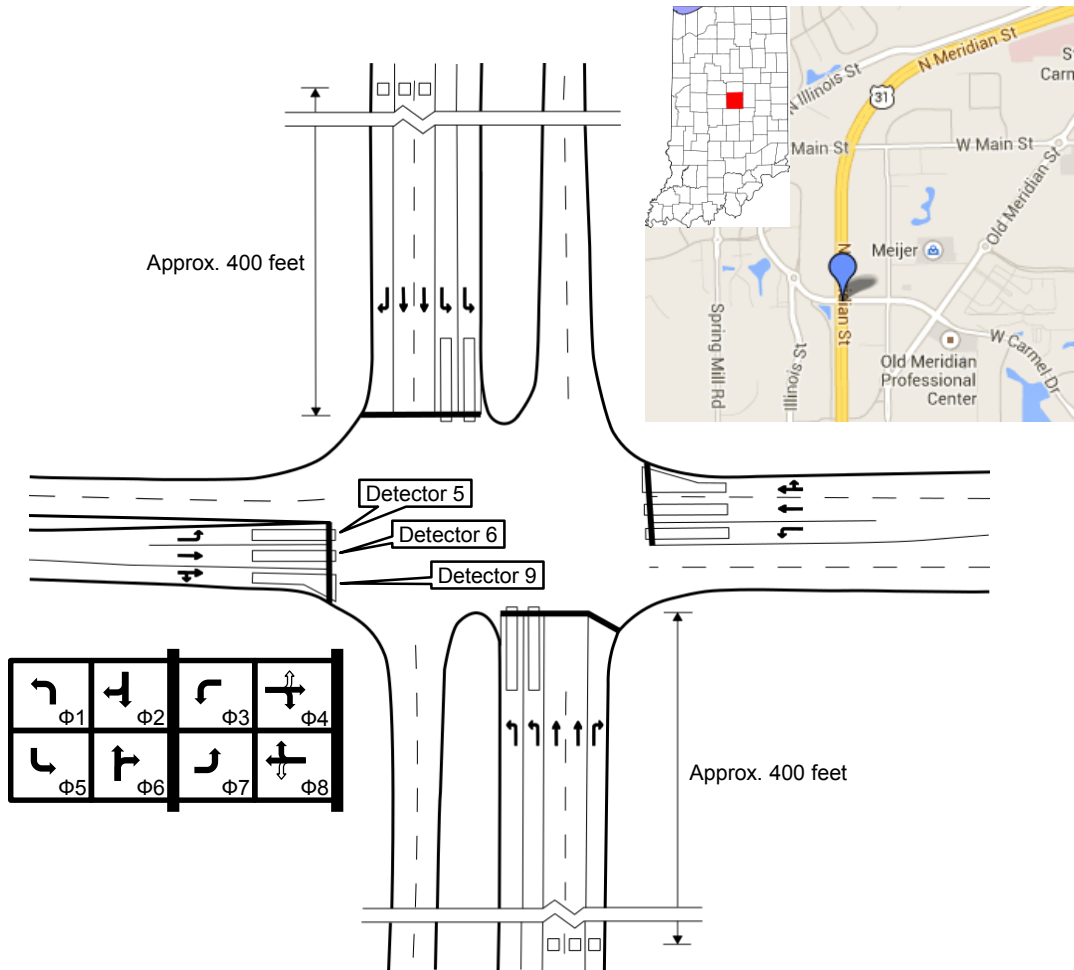


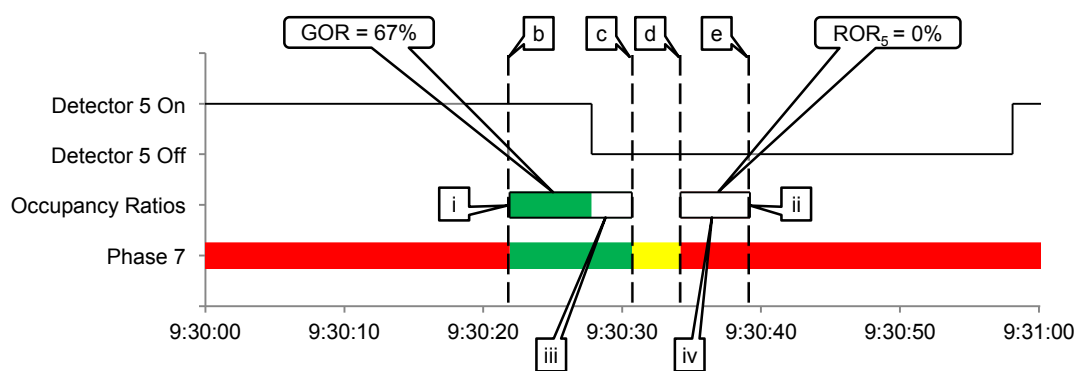
Figure 3.1 The location, geometry, and ring and barrier diagram for the intersection of US-31 (Meridian St.) and 126<sup>th</sup> St. (W. Carmel Dr.)

### 3.2 Example Calculation of GOR and ROR<sub>5</sub>

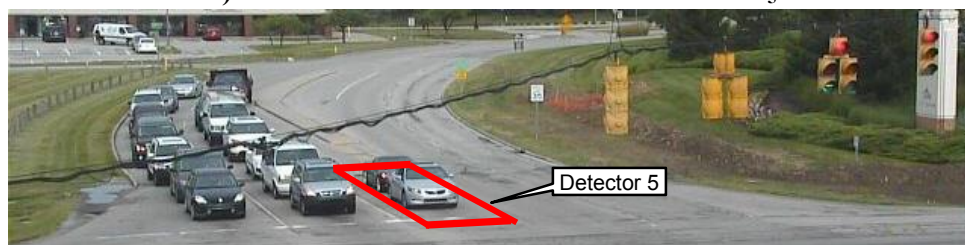
Figure 3.2 contains an example of a single split of Phase 7 that cleared the queue during the protected phase on Wednesday, June 26<sup>th</sup>, 2013. Figure 3.2a illustrates how the GOR and ROR<sub>5</sub> are calculated. The square wave shows when the detector channel for the left turn lane is occupied, 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 split, and callout ii denotes the bar representing the ROR<sub>5</sub>, which was 0% for the split. 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 3.2b-e, which correspond to callouts b-e in Figure 3.2a, are provided to visually illustrate how the GOR and ROR<sub>5</sub> 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 3.2b shows that two vehicles were present when the Phase 7 signal head turned green, and Figure 3.2c 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 3.2a. The pictures in Figure 3.2d-e show that a vehicle was never present in the left turn lane during the first five seconds of the red interval, which is represented in callout iv of Figure 3.2a.

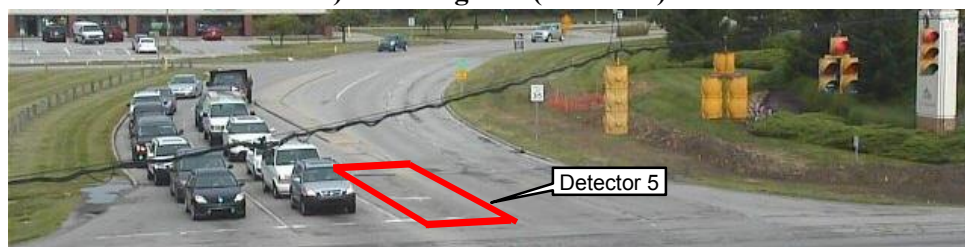
The split illustrated in Figure 3.2 provides an example of queue dissipation during the protected phase of a protected/permitted left turn movement. This is indicative of an undersaturated split timing because all of the vehicle demand was served.



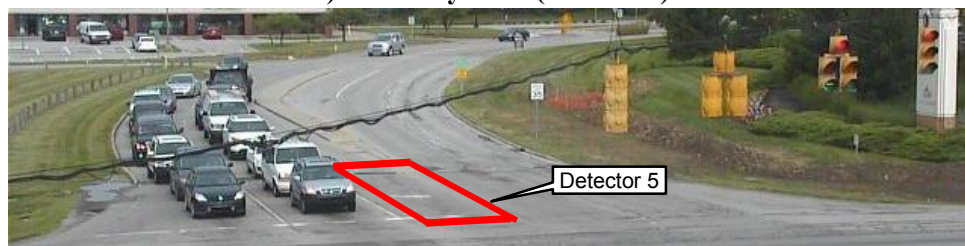
a) Calculation illustration of GOR and  $ROR_5$



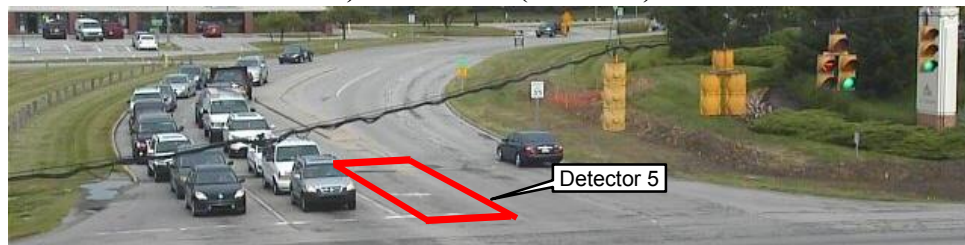
b) Start of green (9:30:24.1)



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 3.2 GOR and  $ROR_5$  for a single split of an undersaturated left turn movement

### 3.3 Graphical Integration of GOR, ROR<sub>5</sub>, and Phase Termination Cause

Figure 3.3 shows the integration of GOR, ROR<sub>5</sub>, and Force Off/Gap Out information for Phase 7, which experienced undersaturated operation throughout the day. In Figure 3.3a-j, callout i denotes the point corresponding to the split shown in Figure 3.2.

- Figure 3.3a, Figure 3.3d, and Figure 3.3g are plots of the GOR against the TOD for each split that occurred during the single hour 0900-1000, the period 0900-1500, and the entire 24 hours, respectively.
- Figure 3.3b, Figure 3.3e, and Figure 3.3h are plots of the ROR<sub>5</sub> against TOD during those three time periods.
- Figure 3.3c, Figure 3.3f, and Figure 3.3j are scatter plots of the ROR<sub>5</sub> vs. the corresponding GOR during those three time periods.
  - The black diamonds correspond to splits that forced off, and the gray circles correspond to splits 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<sub>5</sub> are usually representative of systematic oversaturated phases. They are representative of consistent unserved demand at the end of the protected phase for permitted-protected left turns. Long intervals containing bars with an ROR<sub>5</sub> < 50% are representative of undersaturated splits.

- *Nearly Saturated Phases:* Points within the lower right quadrant of the ROR<sub>5</sub> vs. GOR scatter plots are representative of a nearly saturated movement. The high GOR represents mostly saturated flow throughout the green interval, which means that the green time is being efficiently utilized, and the low ROR<sub>5</sub> signifies a lack of a split failure except in rare cases. An ROR<sub>5</sub> of zero represents no remaining vehicles at the stop bar. If the ROR<sub>5</sub> 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<sub>5</sub> ≥ 80% and GOR ≥ 80%. These force offs with high GOR and ROR<sub>5</sub> 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<sub>5</sub> interval. A gap out could also be caused by an inattentive driver or a truck with a long start-up time, in which case the point would represent a split failure. However, because the cause of the gap out is unknown for individual splits, only the force offs with high GOR and ROR<sub>5</sub> values will be considered split failures.
- *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 3.3d-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 3.3f (correspondingly, there are zero black bars representing an  $ROR_5 > 50\%$  in Figure 3.3e).

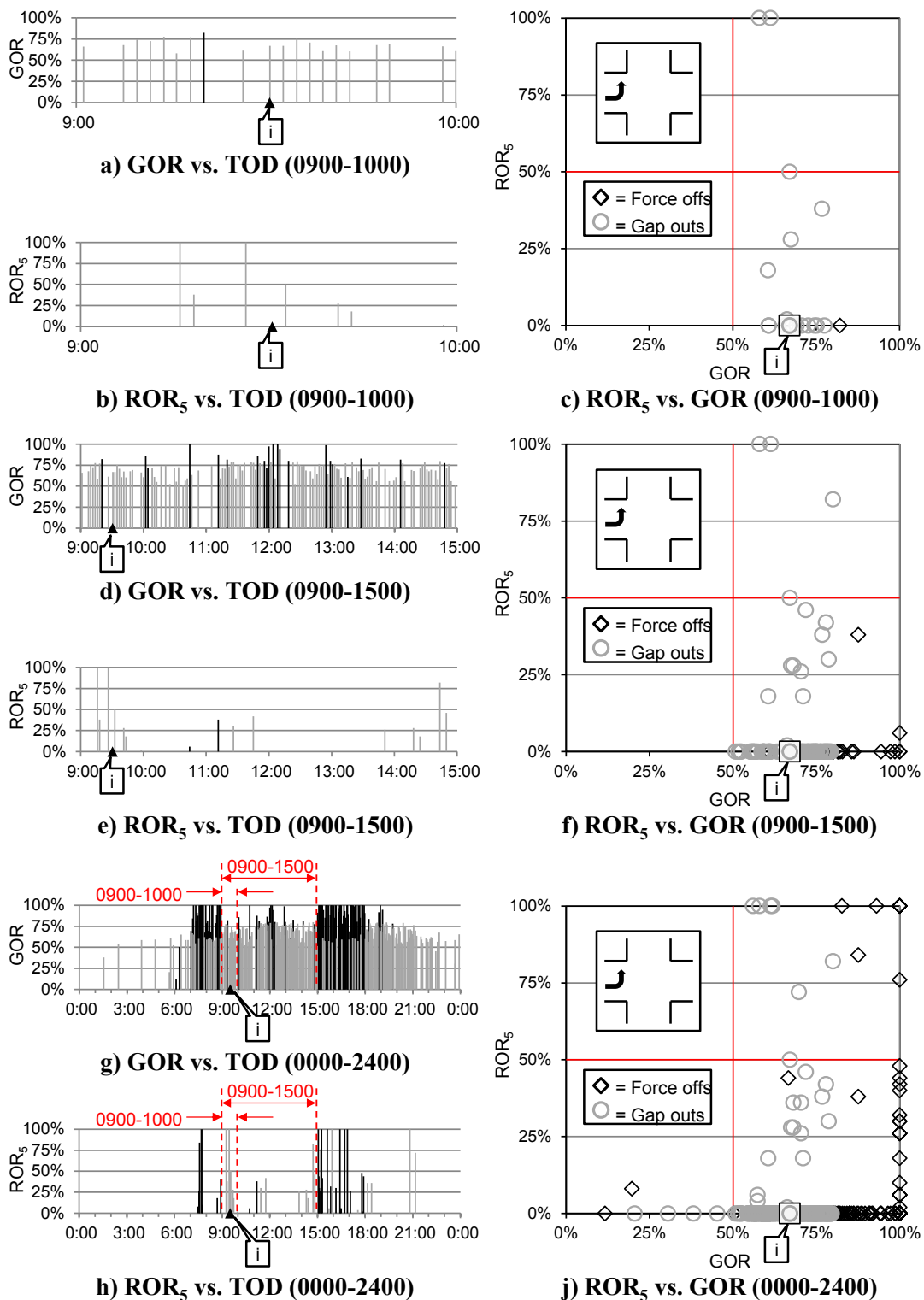


Figure 3.3 GOR vs. TOD, ROR<sub>5</sub> vs. TOD, and ROR<sub>5</sub> vs. GOR for Phase 7 (Wed. 6/26/2013)

### 3.4 Example of Phase with Several Oversaturated Splits

Figure 3.4 shows a single split of Phase 4 that experienced oversaturated conditions on Wednesday, June 26<sup>th</sup>, 2013. Figure 3.4a 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 were 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 split, and callout ii denotes the bar representing the  $ROR_5$ , which was 90% for the split.

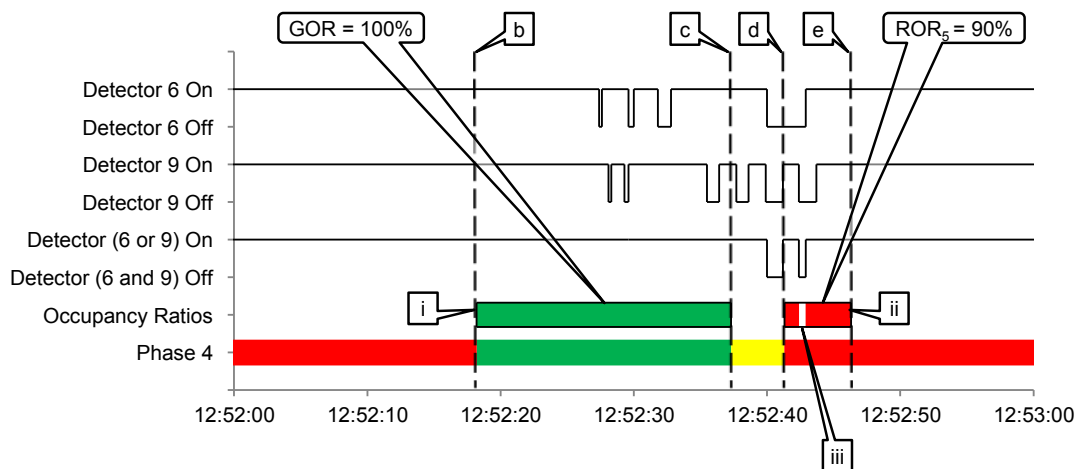
The pictures in Figure 3.4b-e, which correspond to callouts b-e in Figure 3.4a, display field conditions during this split. Callouts marked “v” in Figure 3.4b-e track a single vehicle, which was near the end of the queue at the start of green (Figure 3.4b), but remains waiting at the intersection five seconds after the start of green (Figure 3.4e). This confirms that a split failure took place, corresponding to the high GOR and  $ROR_5$  values associated with this split.

Callout iii denotes a miniscule portion of the first five seconds of red when neither detector was occupied (Figure 3.4a), corresponding to the small gap between vehicles in Figure 3.4d.

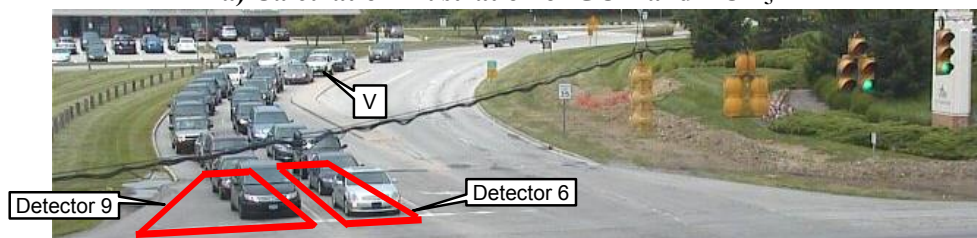
Figure 3.5 shows the assembly of GOR, ROR<sub>5</sub>, and Force Off/Gap Out information for Phase 4, which was oversaturated throughout most of the day. In Figure 3.5a-j, callout i denotes the point corresponding to the split shown in Figure 3.4.

- Figure 3.5a, Figure 3.5d, and Figure 3.5g are plots of the GOR against the TOD for each split that occurred during the single hour 1200-1300, the period 0900-1500, and the entire 24 hours, respectively.
- Figure 3.5b, Figure 3.5e, and Figure 3.5h are plots of the ROR<sub>5</sub> against TOD during those three time periods.
- Figure 3.5c, Figure 3.5f, and Figure 3.5j are scatter plots of the ROR<sub>5</sub> vs. the corresponding GOR during those three time periods.
  - The black diamonds correspond to splits that forced off, and the gray circles correspond to splits 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 splits, indicated by the numerous black diamonds in the upper right quadrant of Figure 3.5f (correspondingly, there are multiple closely-spaced bars with an ROR<sub>5</sub> > 80% in Figure 3.5e).



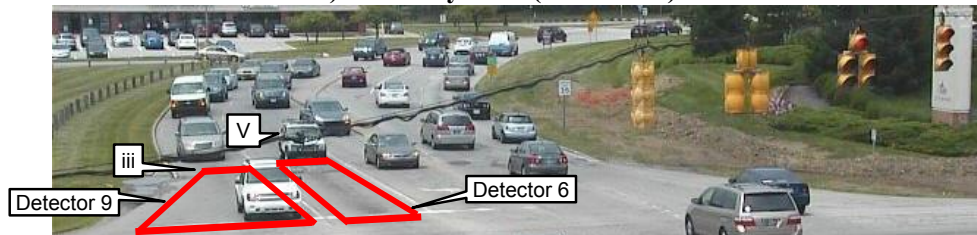
a) Calculation illustration of GOR and ROR<sub>5</sub>



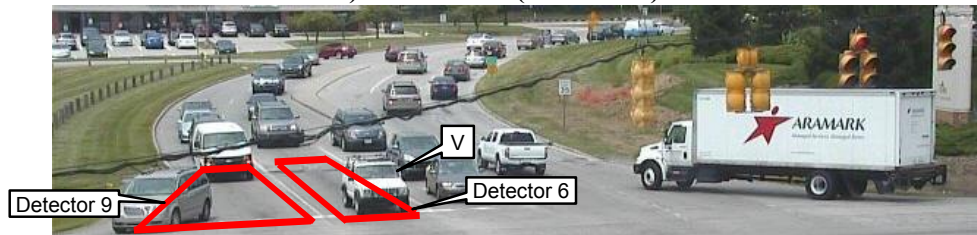
b) Start of green (12:52:21.1)



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 3.4 GOR and ROR<sub>5</sub> for a single split of an oversaturated thru movement

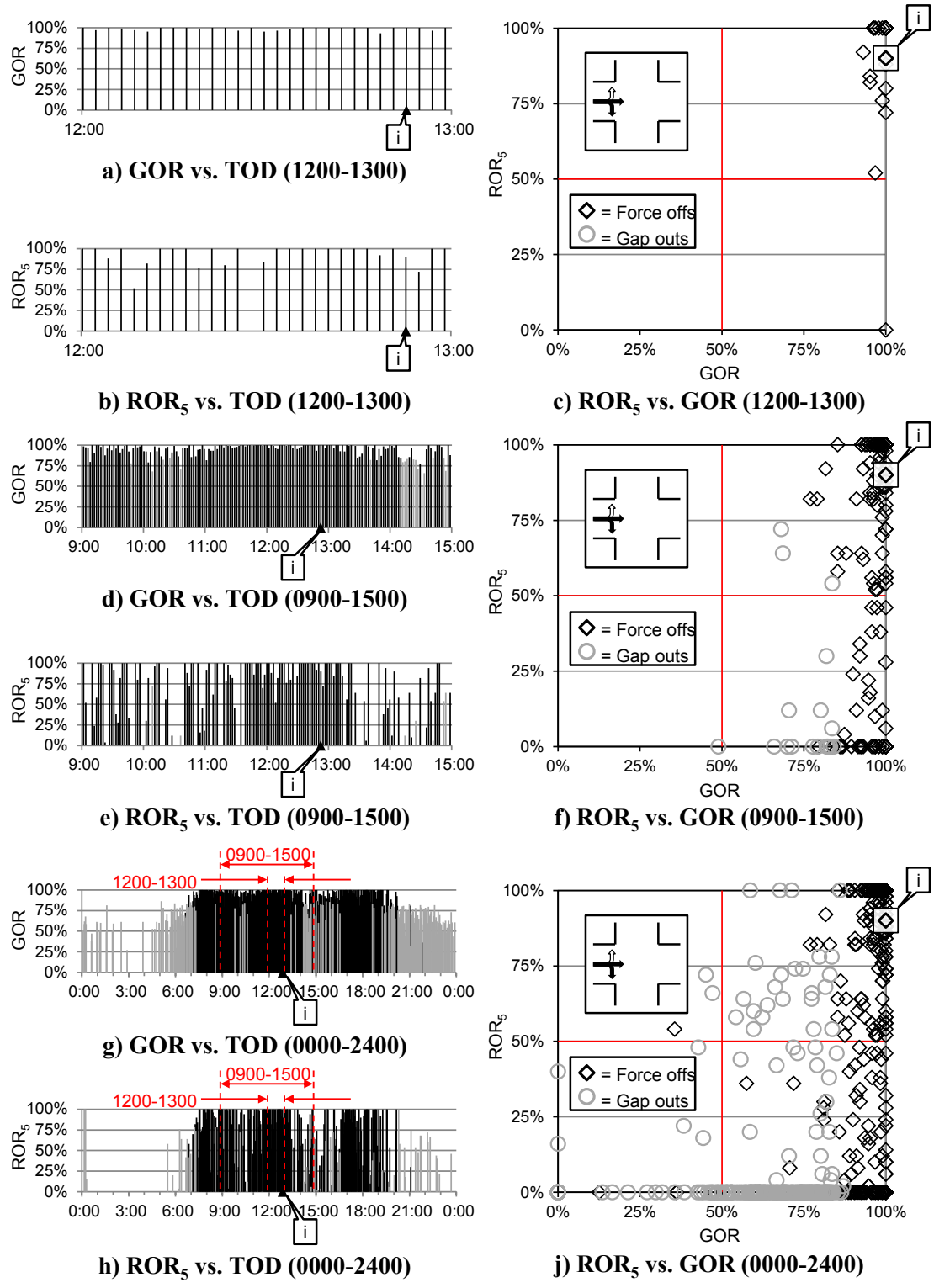
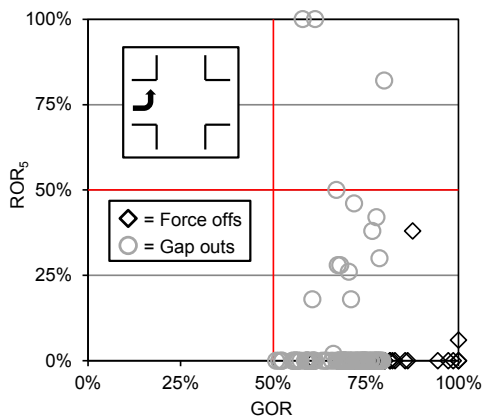


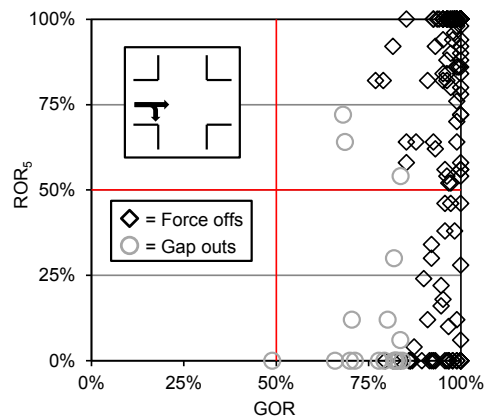
Figure 3.5 GOR vs. TOD, ROR<sub>5</sub> vs. TOD, and ROR<sub>5</sub> vs. GOR for Phase 4 (Wed. 6/26/2013)

### 3.5 Comparison of Phase 4 and 7 Split Performance

Figure 3.6 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 3.6 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 3.6c, from 0900-1500 there were 9 splits 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 3.6c and Figure 3.6d represent only splits that forced off during the 0900-1500 timing plan, whereas the heat maps in Figure 3.6e and Figure 3.6f represent only splits that gapped out during the 0900-1500 timing plan.



a) Phase 7 ROR<sub>5</sub> vs. GOR



b) Phase 4 ROR<sub>5</sub> vs. GOR

ROR <sub>5</sub> (%)	90										
	80										
	70										
	60										
	50										
	40										
	30										
	20								1		
	10										
	0						1	4	9	6	
		0	10	20	30	40	50	60	70	80	90
		GOR (%)									

c) Phase 7 heat map of force offs

ROR <sub>5</sub> (%)	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
		0	10	20	30	40	50	60	70	80	90
		GOR (%)									

d) Phase 4 heat map of force offs

ROR <sub>5</sub> (%)	90					1	1				
	80										1
	70										
	60										
	50						1				
	40								2		
	30								2		
	20							2	1		
	10							1	1		
	0						20	28	43		
		0	10	20	30	40	50	60	70	80	90
		GOR (%)									

e) Phase 7 heat map of gap outs

ROR <sub>5</sub> (%)	90										
	80										
	70						1				
	60						1				
	50									1	
	40										
	30									1	
	20										
	10										
	0					1	1	3	6		
		0	10	20	30	40	50	60	70	80	90
		GOR (%)									

f) Phase 4 heat map of gap outs

Figure 3.6 Comparison of undersaturated and oversaturated phase performance (0900-1500 on 6/26)



### 3.6 Implementation Recommendations

The graphical performance measures discussed in this thesis could be implemented by a practitioner (most likely using a central system) to quickly verify or disprove the claim of a trouble call. Furthermore, Figure 3.7a-h illustrates how the ROR<sub>5</sub> 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 3.7 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<sub>5</sub> vs. GOR plots for phases 2 and 6 (Figure 3.7b and Figure 3.7f) 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 3.7i-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.

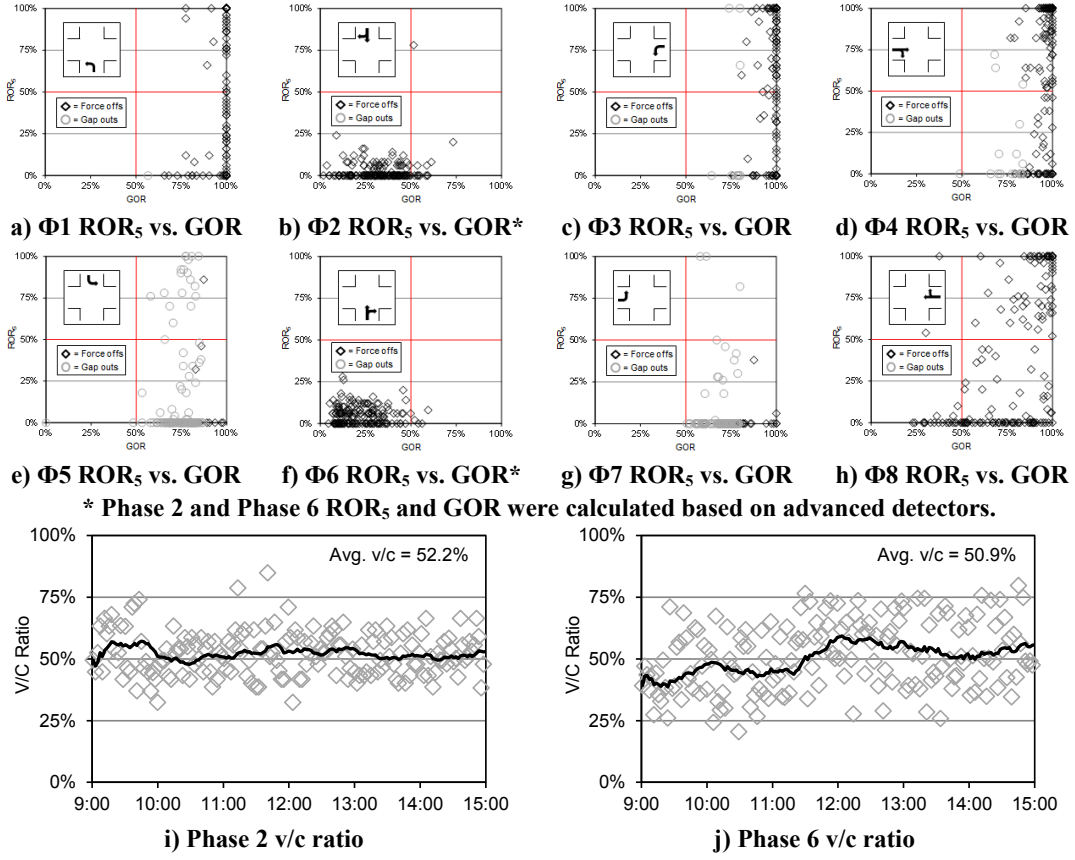


Figure 3.7 ROR<sub>5</sub> vs. GOR for all phases and v/c ratios for phases 2 and 6 (0900-1500 on 6/26)

### 3.7 Example Implementation for Operational Tuning





Using the information shown in Figure 3.7, 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 25<sup>th</sup>, 2013. Figure 3.8 shows the split times of each phase before and after the adjustment was made. Data from Thursday, July 18<sup>th</sup>, 2013 (before the splits were changed) and Thursday, July 25<sup>th</sup>, 2013 (after the splits were changed) was then collected and analyzed for the 0900-1500 timing plan.

Figure 3.9 provides a summary of each minor movement's performance before and after the split adjustment based on the total number of oversaturated splits ( $GOR \geq 80\%$  and  $ROR_5 \geq 80\%$ ) during the 0900-1500 timing plan. Figure 3.9 illustrates that phases 3 and 8 (the phases to which split time was added) dramatically improved. Figure 3.10 shows a summary of the number of times that there were three consecutive oversaturated splits during the 0900-1500 timing plan before and after the split adjustment. Figure 3.10 further illustrates the dramatic improvement of phases 3 and 8 by emphasizing the reduction of repetitive oversaturation. Figure 3.11 shows a more detailed comparison of Phase 8 before and after the split adjustment. A comparison between Figure 3.11a and Figure 3.11b visually illustrates the substantial improvement, and the heat maps in Figure 3.11c-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 splits 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 3.12 shows a comparison of the number of oversaturated splits for a second pair of days, Friday, July 19<sup>th</sup>, 2013 (before the split adjustment) and Friday, July 26<sup>th</sup>, 2013 (after the adjustment). Figure 3.13 shows a comparison of the number of three consecutive oversaturated splits between the two Fridays. Figure 3.12 and Figure 3.13 show that 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 3.14 shows  $v/c$  ratios for each split 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.

 $\Phi_1$ 11%	 $\Phi_2$ 53%	 $\Phi_3$ 16%	 $\Phi_4$ 20%
 $\Phi_5$ 22%	 $\Phi_6$ 42%	 $\Phi_7$ 16%	 $\Phi_8$ 20%

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

 $\Phi_1$ 11%	 $\Phi_2$ 49%	 $\Phi_3$ 20%	 $\Phi_4$ 20%
 $\Phi_5$ 22%	 $\Phi_6$ 38%	 $\Phi_7$ 16%	 $\Phi_8$ 24%

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

Figure 3.8 Split percentages before and after adjustment (0900-1500)

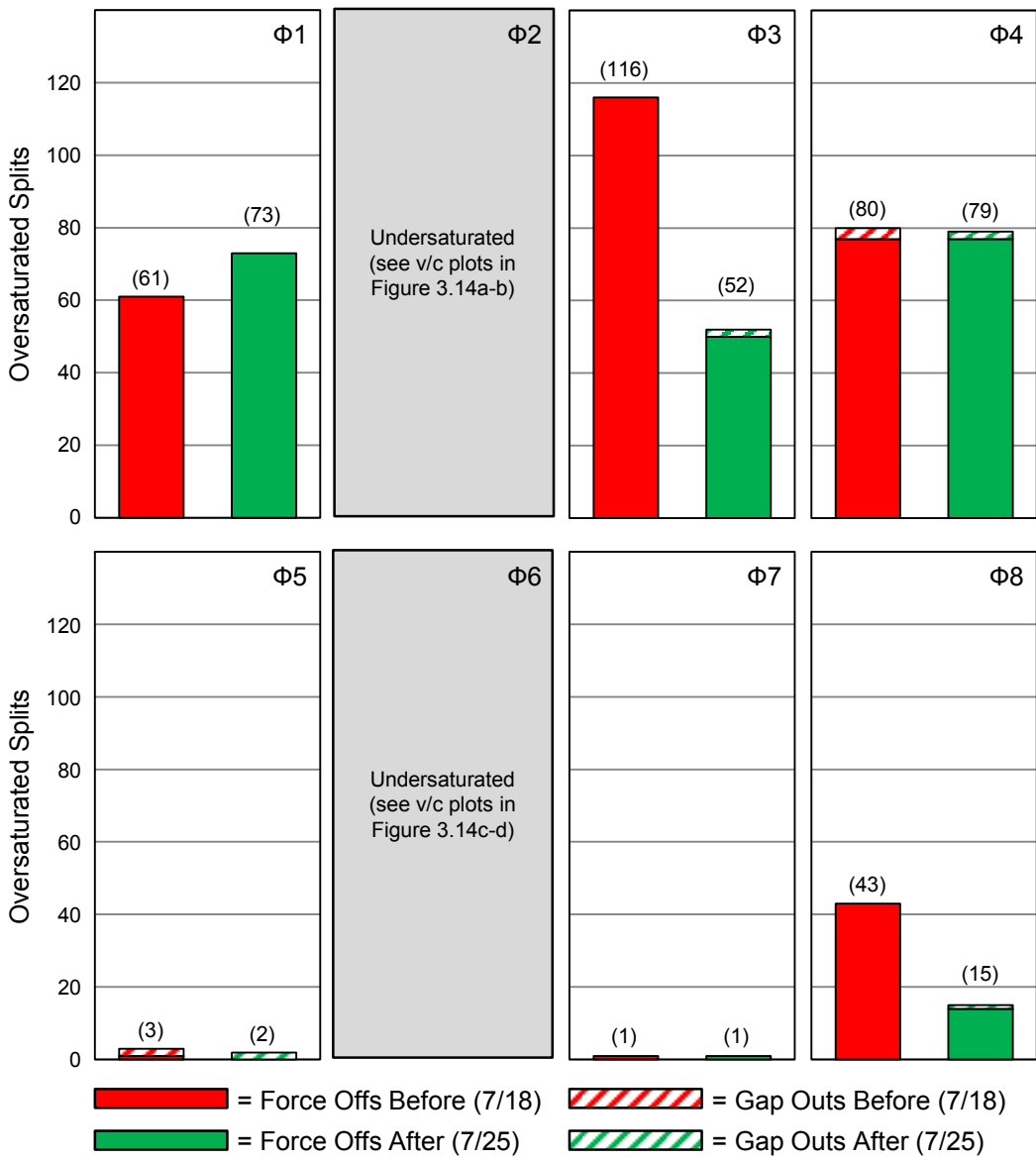


Figure 3.9 Before (Thurs. 7/18/2013) and after (Thurs. 7/25/2013) comparison of oversaturated splits for the minor movements (0900-1500)

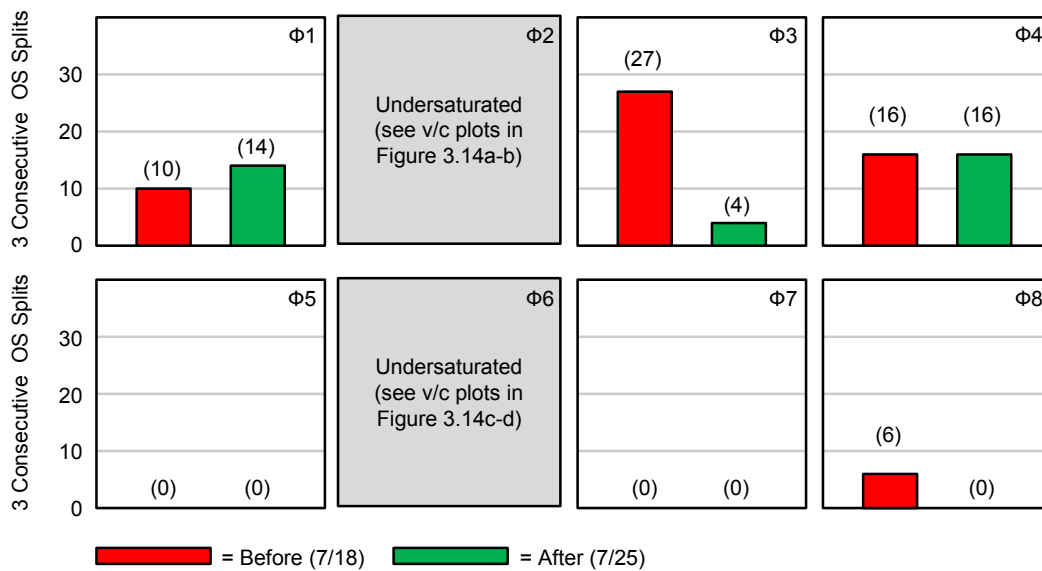
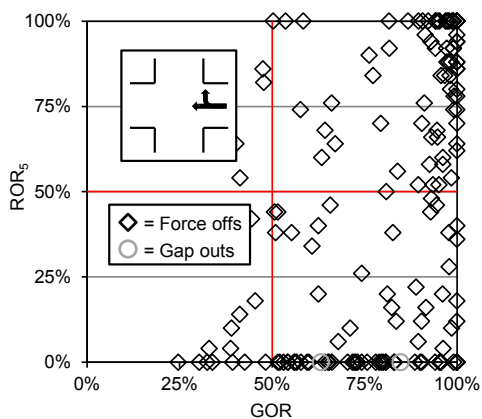


Figure 3.10 Before (Thurs. 7/18/2013) and after (Thurs. 7/25/2013) comparison of three consecutive oversaturated splits for the minor movements (0900-1500)



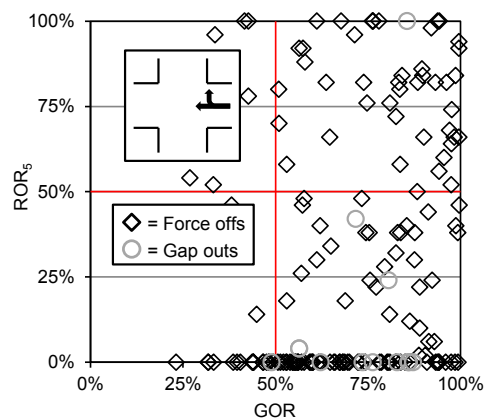
a) ROR<sub>5</sub> vs. GOR before split adjustment

ROR <sub>5</sub> (%)	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	2
	20							1	1	2	2
	10				1	2			1	2	5
	0		1	6	2	10	6	10	7	15	
		0	10	20	30	40	50	60	70	80	90
GOR (%)											

c) Heat map of force offs before adjustment

ROR <sub>5</sub> (%)	90										
	80										
	70										
	60										
	50										
	40										
	30										
	20										
	10										
	0						1		1		
		0	10	20	30	40	50	60	70	80	90
GOR (%)											

e) Heat map of gap outs before adjustment



b) ROR<sub>5</sub> vs. GOR after split adjustment

ROR <sub>5</sub> (%)	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	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			
		0	10	20	30	40	50	60	70	80	90		
GOR (%)													

d) Heat map of force offs after adjustment

ROR <sub>5</sub> (%)	90												1
	80												
	70												
	60												
	50												
	40									1			
	30												
	20											1	
	10												
	0						1	1	1	2	4		
		0	10	20	30	40	50	60	70	80	90		
GOR (%)													

f) Heat map of gap outs after adjustment

Figure 3.11 Before (7/18) and after (7/25) comparison of Phase 8 performance (0900-1500)



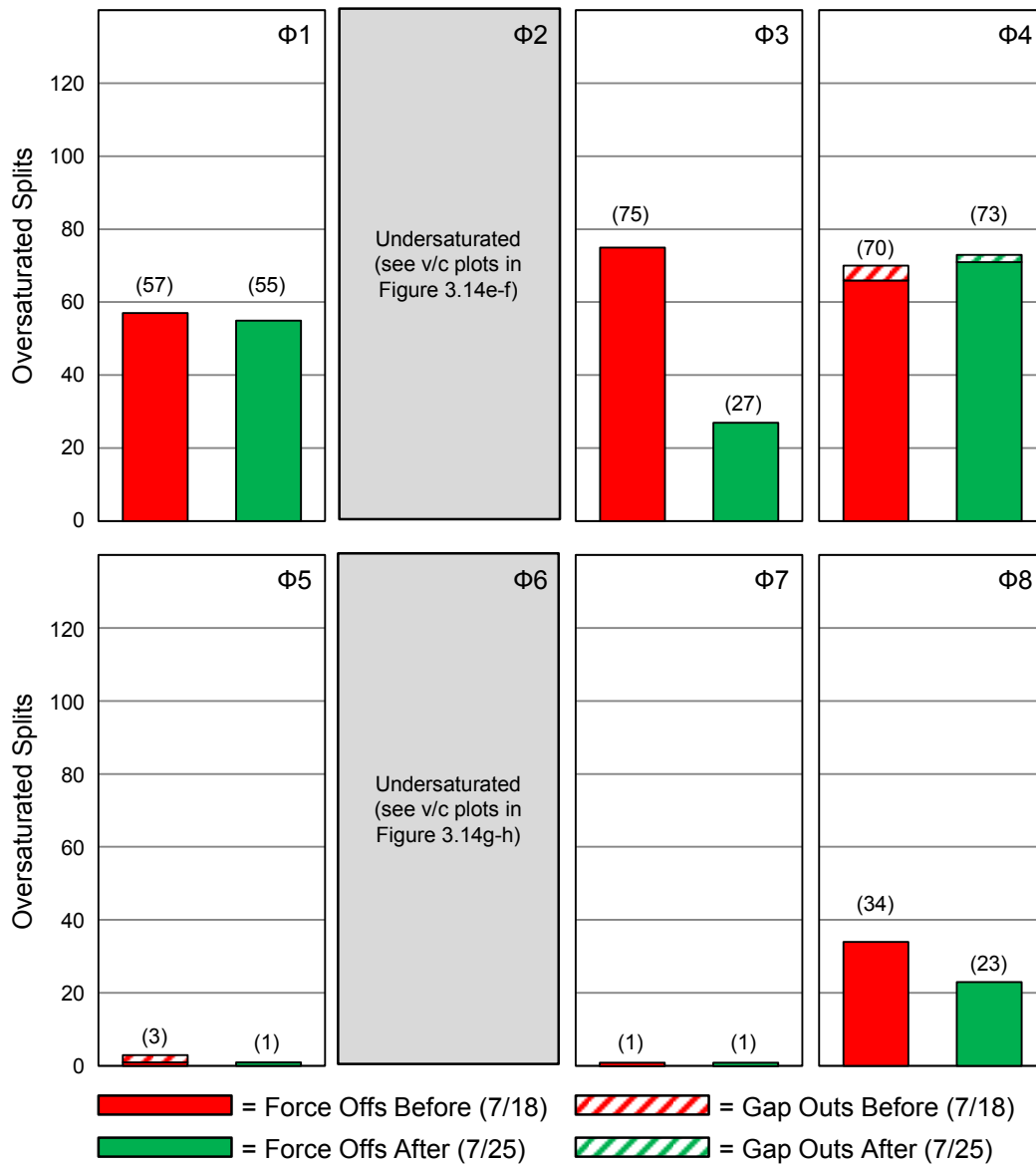


Figure 3.12 Before (Fri. 7/19/2013) and after (Fri. 7/26/2013) comparison of oversaturated splits for the minor movements (0900-1500)

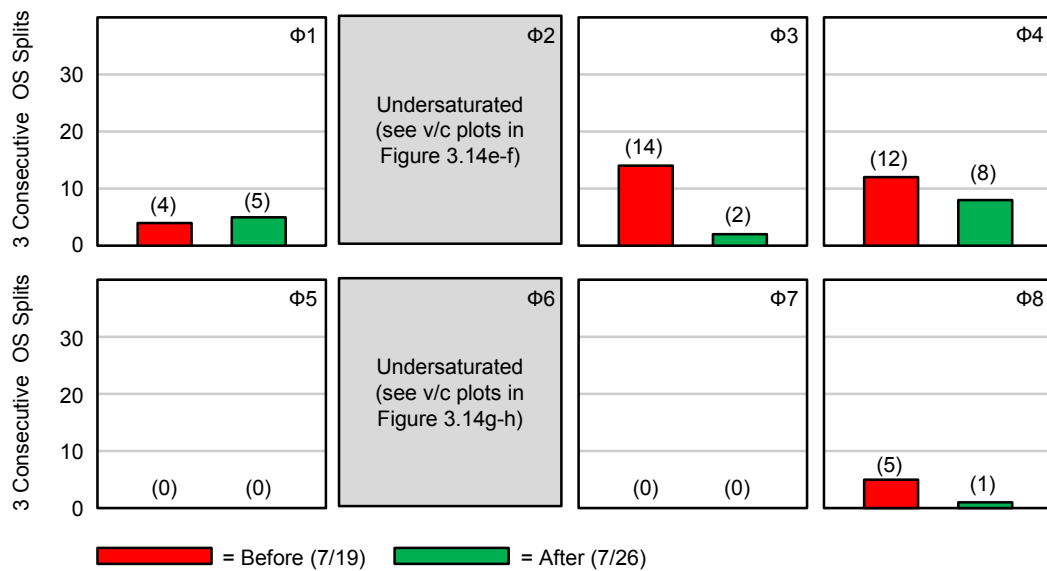


Figure 3.13 Before (Fri. 7/19/2013) and after (Fri. 7/26/2013) comparison of three consecutive oversaturated splits for the minor movements (0900-1500)

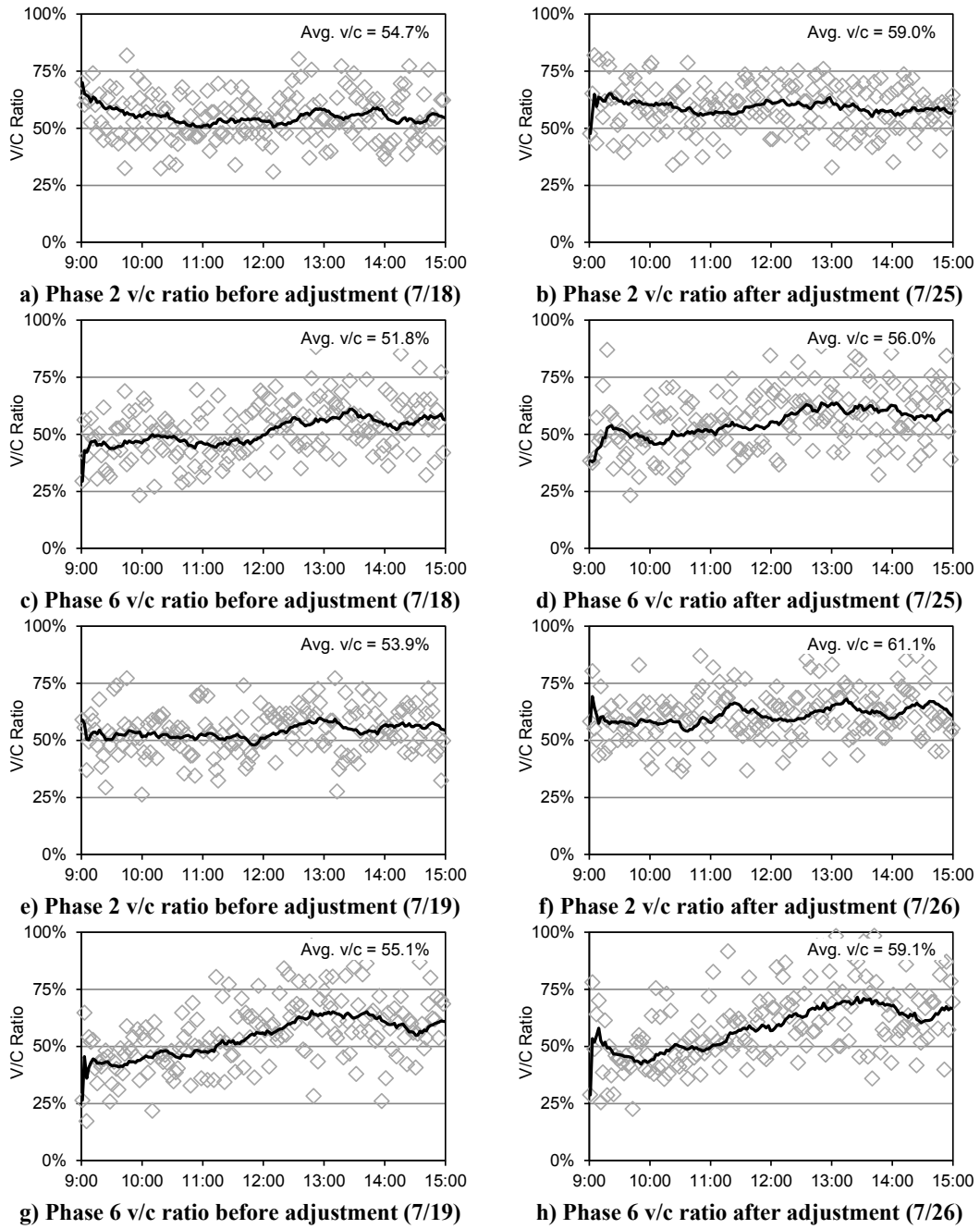


Figure 3.14 Thru movement v/c ratios before and after split adjustment (0900-1500)

## CHAPTER 4. ADDITIONAL PERFORMANCE MEASURES

### 4.1 Enhancing the ROR<sub>5</sub> vs. GOR Plots

Because the methodology for analyzing protected-permitted left turns used for the US-31 and 126<sup>th</sup> St. case study only takes into account oversaturation during the protected phase, a method that considers the permitted phase was desired. To accomplish this, the GOR is calculated during the permitted phase rather than the protected phase, and the ROR<sub>5</sub> is calculated during the first five seconds of red for the concurrent thru movement rather than the first five seconds of the permitted phase. The phase termination cause still corresponds to the protected phase.

On the ROR<sub>5</sub> vs. GOR plots for protected-permitted left turns, points are plotted for each permitted phase regardless of whether the protected phase was called. Each point can be represented by five different symbols, which correspond to different conditions during the protected and permitted phases:

- Gray circles correspond to gap outs, or splits in which the protected phase gapped out (regardless of the saturation of the permitted phase).
- Gray squares correspond to undersaturated omitted (US omitted) splits, or splits in which the protected phase was omitted and the permitted phase was undersaturated or nearly saturated ( $GOR < 80\%$  or  $ROR_5 < 80\%$ ).

- Gray diamonds correspond to undersaturated force offs (US force offs), or splits in which the protected phase forced off and the permitted phase was undersaturated or nearly saturated ( $GOR < 80\%$  or  $ROR_5 < 80\%$ ).
- Orange squares correspond to oversaturated omitted (OS omitted) splits, or splits in which the protected phase was omitted and the permitted phase was oversaturated ( $GOR \geq 80\%$  and  $ROR_5 \geq 80\%$ ).
- Red diamonds correspond to oversaturated force offs (OS force offs), or splits in which the protected phase forced off and the permitted phase was oversaturated ( $GOR \geq 80\%$  and  $ROR_5 \geq 80\%$ ).

Figure 4.1 shows an example of an  $ROR_5$  vs. GOR plot for a protected-permitted left turn at the intersection of SR-37 and Southport Rd. The points denoted by callouts i, ii, and iii are gray because they represent undersaturated or nearly saturated permitted phases. Callout i corresponds to a gap out because the protected phase gapped out and the permitted phase had a GOR of 65% and an  $ROR_5$  of 100%. Callout ii corresponds to a US force off because the protected phase forced off and the permitted phase had a GOR of 100% and an  $ROR_5$  of 12%. Callout iii corresponds to a US omitted split because the protected phase was omitted and the permitted phase had a GOR of 100% and an  $ROR_5$  of 42%. The point denoted by callout iv is red because it corresponds to an OS force off in which the protected phase forced off and the permitted phase had a GOR of 87% and an  $ROR_5$  of 100%. The point denoted by callout v is orange because it corresponds to an OS omitted split in which the protected phase was omitted and the permitted phase had a GOR of 97% and an  $ROR_5$  of 100%.

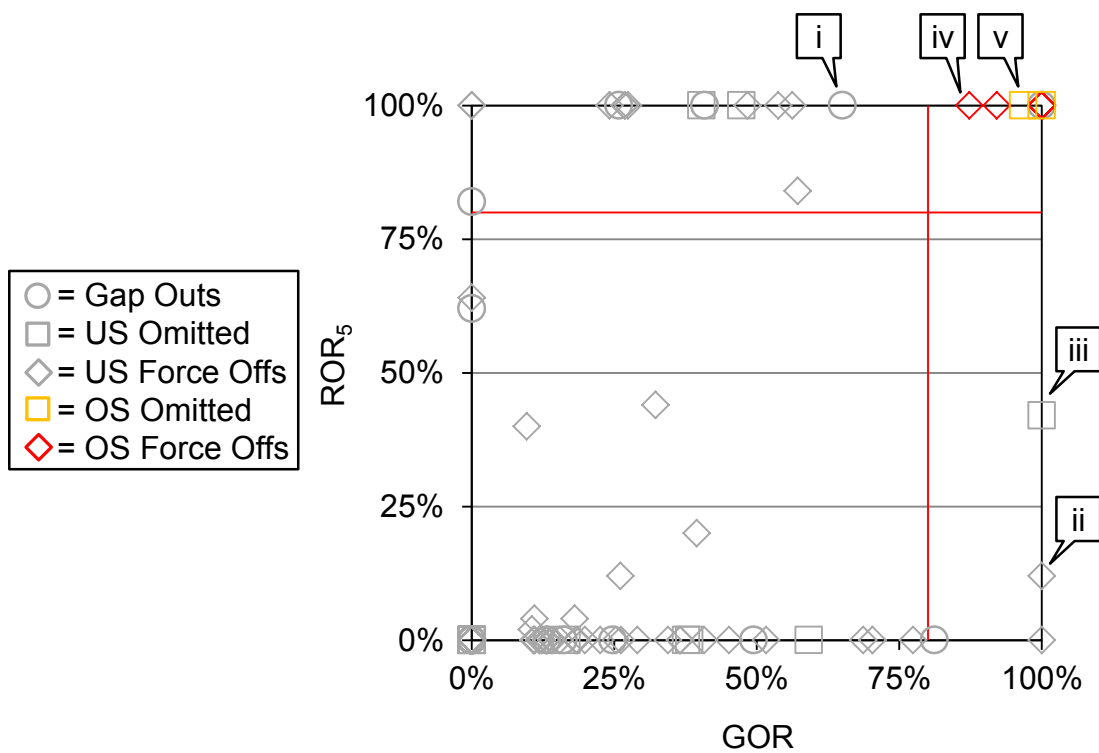


Figure 4.1 ROR<sub>5</sub> vs. GOR for a protected-permitted left turn (Phase 3 at the intersection of SR-37 and Southport Rd. on Thurs. 1/23/2014 from 1500-1900)

On the  $ROR_5$  vs. GOR plots for protected left turns and minor thru movements, the same methodology is used that was demonstrated in the US-31 and 126<sup>th</sup> St. case study, but now each point can be represented by three different symbols, which correspond to the following conditions:

- Gray circles correspond to gap outs (regardless of the saturation of the split).
- Gray diamonds correspond to undersaturated force offs (US force offs), or force offs in which the split was undersaturated or nearly saturated ( $GOR < 80\%$  or  $ROR_5 < 80\%$ ).
- Red diamonds correspond to oversaturated force offs (OS force offs), or force offs in which the split was oversaturated ( $GOR \geq 80\%$  and  $ROR_5 \geq 80\%$ ).

#### 4.2 Counting Oversaturated Splits in 30-minute Bins

An additional graphical performance measure is a ring diagram of bar charts that represent the number of oversaturated splits for each phase grouped into 30-minute bins over a 24-hour period. These bar charts prove very useful in the identification of phases that repeatedly experience split failures during a given timing plan. They also enable the practitioner to evaluate whether there are opportunities to re-allocate split time from the mainline to a phase that experiences multiple split failures within a timing plan.

Figure 4.2 shows an example of bar charts of oversaturated splits in 30-minute bins for each phase at the intersection of SR-37 and Southport Rd. The red dashed lines represent timing plan cutoffs. The timing plans for SR-37 and Southport Rd. are 0600-0900 (the AM peak), 0900-1400 (the mid-day plan), 1400-1900 (the PM peak), and 1900-2200 (the evening plan). Phases 1 and 5 are protected left turns, Phases 2 and 6 are mainline movements, Phases 3 and 7 are protected-permitted left turns, and Phases 4 and 8 are minor thru movements.

For protected left turns and minor thru movements:

- The red bars count the number of splits in which the phase forced off and had a  $GOR \geq 80\%$  and an  $ROR_5 \geq 80\%$ .

For protected-permitted left turns:

- The orange bars count the number of splits in which the protected phase was omitted and the permitted phase had a  $GOR \geq 80\%$  and an  $ROR_5 \geq 80\%$ .



- The red bars count the number of splits in which the protected phase forced off and the permitted phase had a  $GOR \geq 80\%$  and an  $ROR_5 \geq 80\%$ .

For mainline movements:

- The orange bars count the number of splits in which the  $v/c$  ratio is between 0.85 and 0.95.
- The red bars count the number of splits in which the  $v/c$  ratio is greater than 0.95.

To better understand the information provided in Figure 4.2, it is useful to examine Figure 4.3, which shows  $ROR_5$  vs.  $GOR$  plots for each of the minor movements during the AM peak, and Figure 4.4, which shows  $v/c$  plots for the mainline movements over 24 hours with the AM peak highlighted in light blue. The following conclusions about the operation of SR-37 and Southport Rd. during the AM peak can be made by looking at Figure 4.2, Figure 4.3, and Figure 4.4:

- Phases 1 and 7 are experiencing very little oversaturation.
  - Figure 4.2 shows that there are very few red bars within the AM timing plan for Phases 1 and 7.
  - This corresponds to the  $ROR_5$  vs.  $GOR$  plots for Phases 1 and 7 shown in Figure 4.3, which contain very few red diamonds.
- Phases 4, 5, and 8 are experiencing moderate oversaturation.
  - Figure 4.2 shows that there are some red bars within the AM timing plan for Phases 4, 5, and 8.
  - This corresponds to the  $ROR_5$  vs.  $GOR$  plots for Phases 4, 5, and 8 shown in Figure 4.3, which contain some red diamonds.

- Phase 3 is experiencing heavy oversaturation.
  - Figure 4.2 shows that there are many tall red bars within the AM timing plan for Phase 3.
  - This corresponds to the  $ROR_5$  vs. GOR plot for Phase 3 shown in Figure 4.3, which contains several red diamonds.
- Phase 2 is undersaturated.
  - Figure 4.2 shows that there are zero red or orange bars within the AM timing plan (highlighted in blue) for Phase 2.
  - This corresponds to the highlighted portion of the v/c plot for Phase 2 shown in Figure 4.4, which contains zero red or orange diamonds.
- Phase 6 is approaching oversaturation.
  - Figure 4.2 shows that there is a short red bar and some orange bars within the AM timing plan (highlighted in blue) for Phase 6.
  - This corresponds to the highlighted portion of the v/c plot for Phase 6 shown in Figure 4.4, which contains one red diamond and a cluster of orange diamonds.

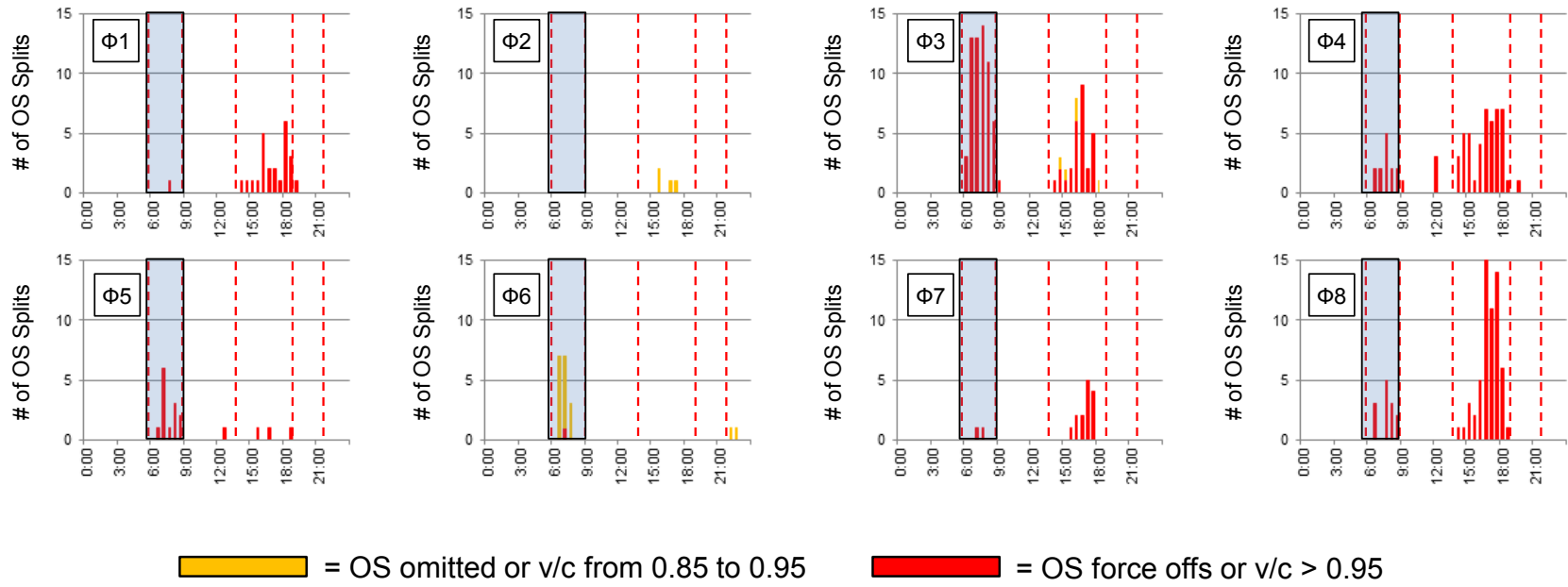


Figure 4.2 Oversaturated splits in 30-min. bins with the AM peak highlighted (SR-37 and Southport Rd. on Wed. 3/5/2014)

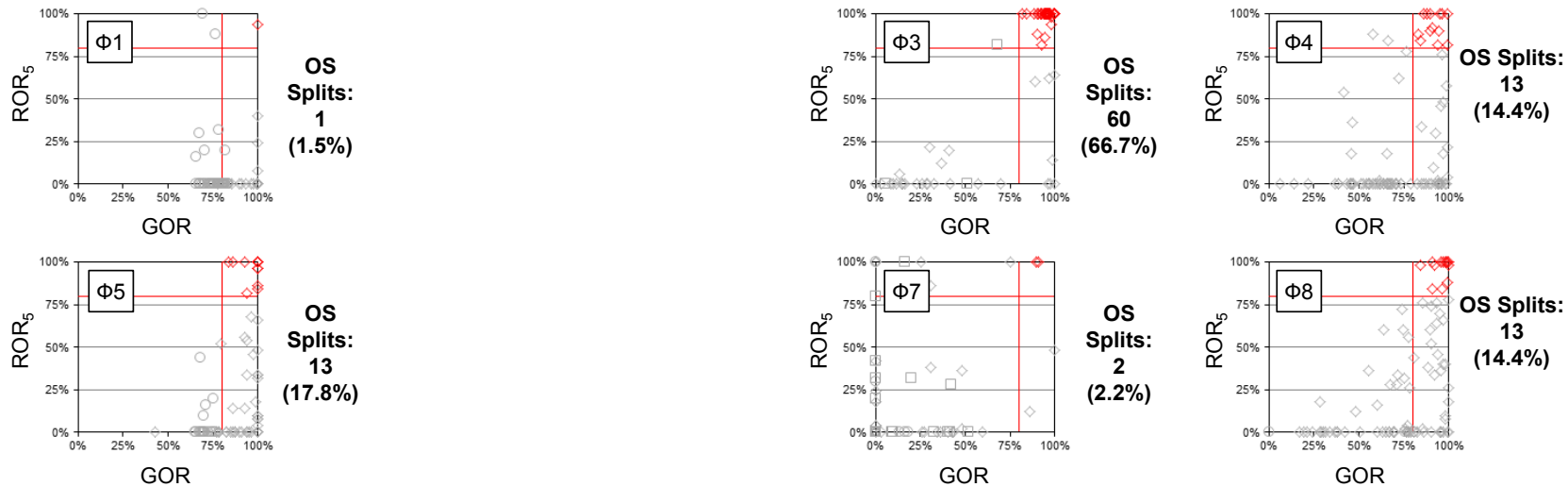


Figure 4.3 ROR<sub>5</sub> vs. GOR plots for the minor movements during the AM Peak (SR-37 and Southport Rd. on Wed. 3/5/2014)

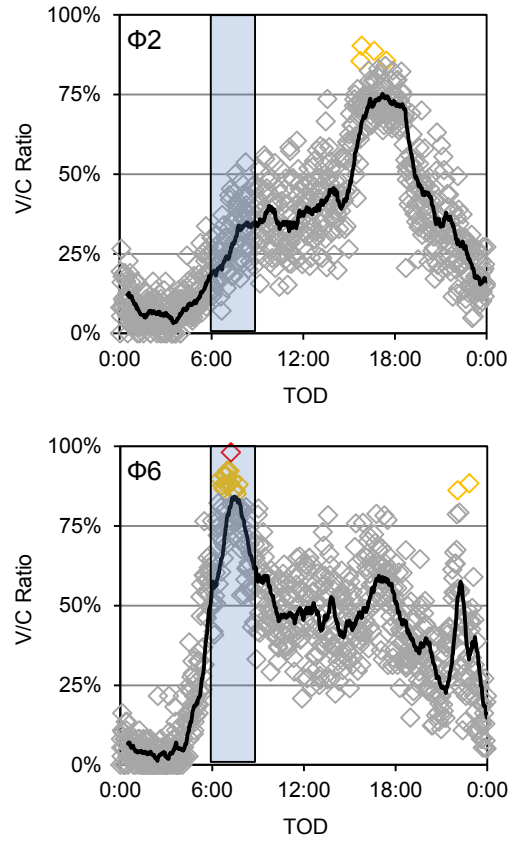


Figure 4.4 Mainline v/c plots over 24 hours with the AM peak highlighted (SR-37 and Southport Rd. on Wed. 3/5/2014)

## CHAPTER 5. NEW US-231 CASE STUDY

### 5.1 Study Location

The US-231 bypass around West Lafayette, which opened in September 2013, provided another opportunity to implement split adjustments to mitigate oversaturation identified by the graphical performance measures. Figure 5.1 shows the location, geometry, and ring diagram for the intersection of River Rd. and US-231.

The US-231 corridor was initially running free until it was coordinated on January 21<sup>st</sup>, 2014. The corridor experienced coordinated operation (on weekdays) from January 22<sup>nd</sup> to February 14<sup>th</sup>. It was briefly switched back to free operation from February 17<sup>th</sup> to February 19<sup>th</sup> for the purposes of data collection, and then it was returned to coordinated operation on February 20<sup>th</sup>, 2014. From River Rd. to Lindberg Rd, phases 2 and 6 are coordinated from 0600 to 2200 (on weekdays), and fixed force offs are used. Figure 5.2 shows a comparison of effective cycle lengths during free operation and during coordinated operation at the intersection of US-231 and River Rd.

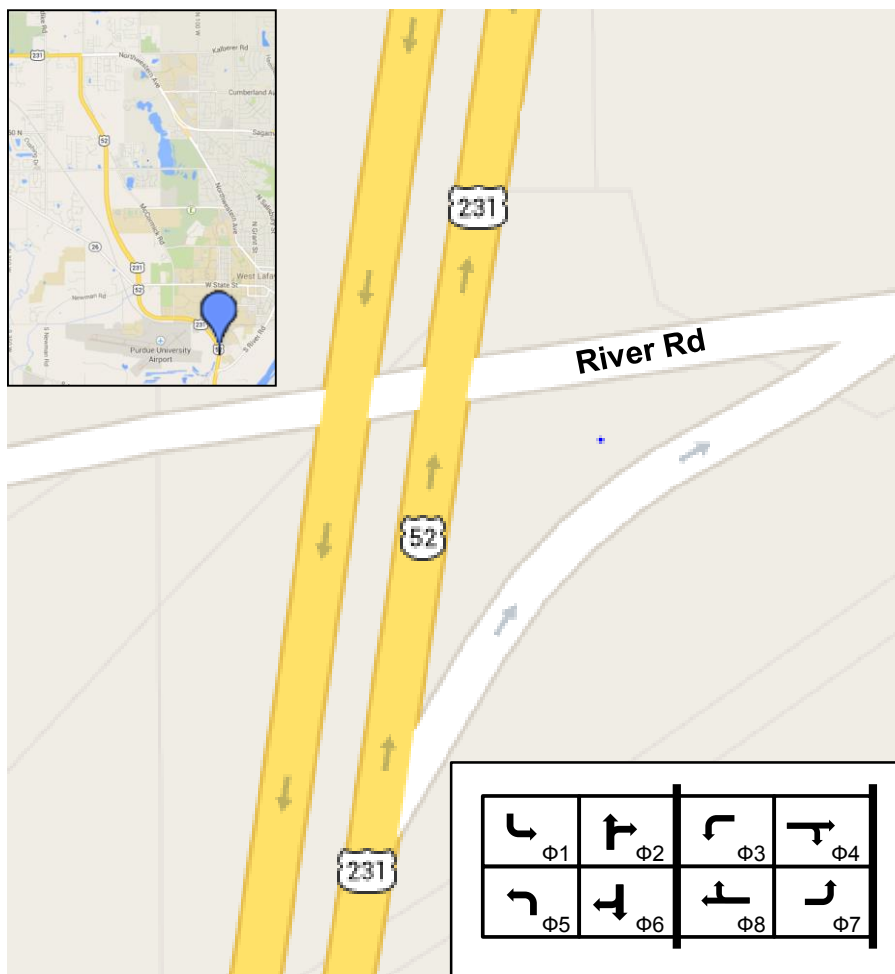
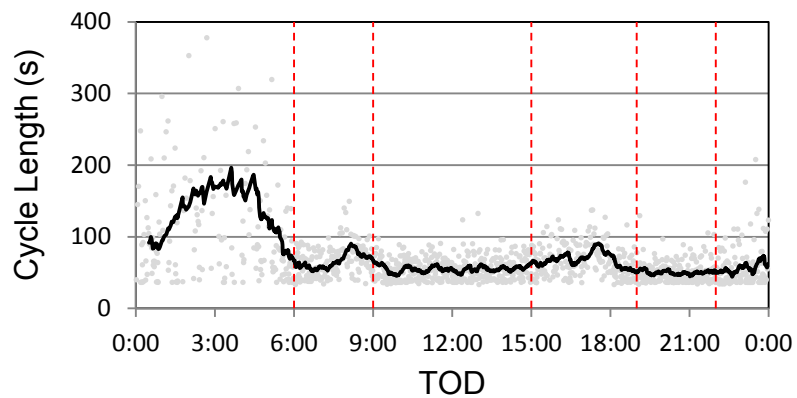
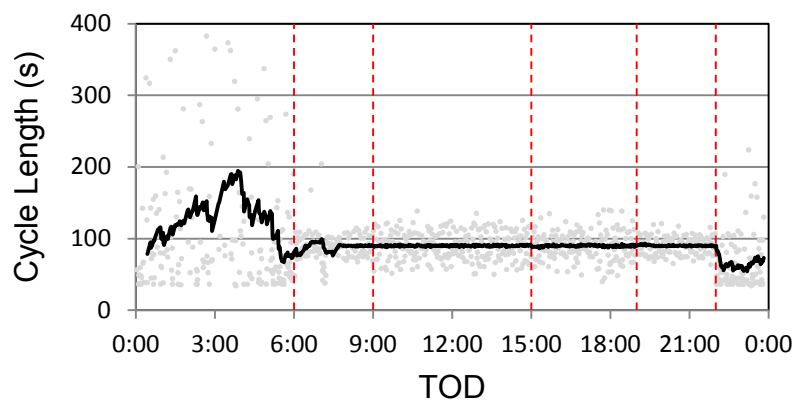


Figure 5.1 The location and ring and barrier diagram for the intersection of US-231 and River Rd.



**a) Free Operation (Tues. 2/18/2014)**



**b) Coordinated Operation (Tues. 2/11/2014)**

Figure 5.2 Comparison of cycle lengths before and after coordination (US-231 and River Rd.)

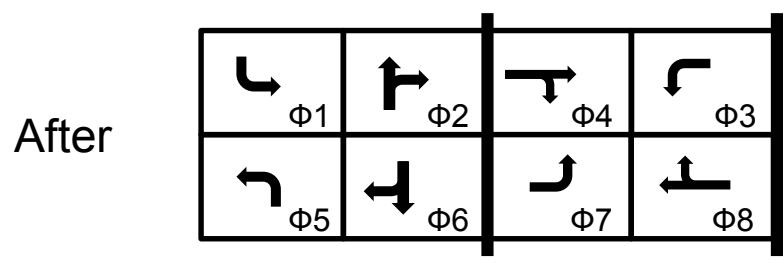
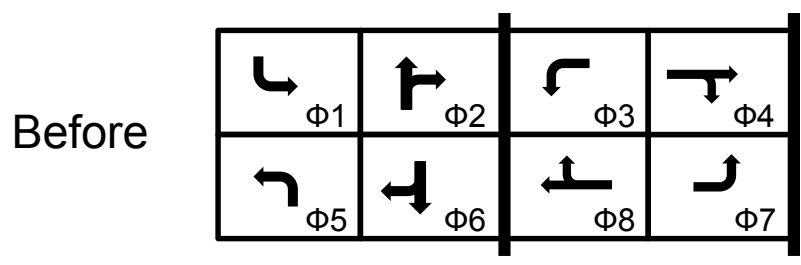


## 5.2 Mitigating Split Failures at US-231 and River Rd.

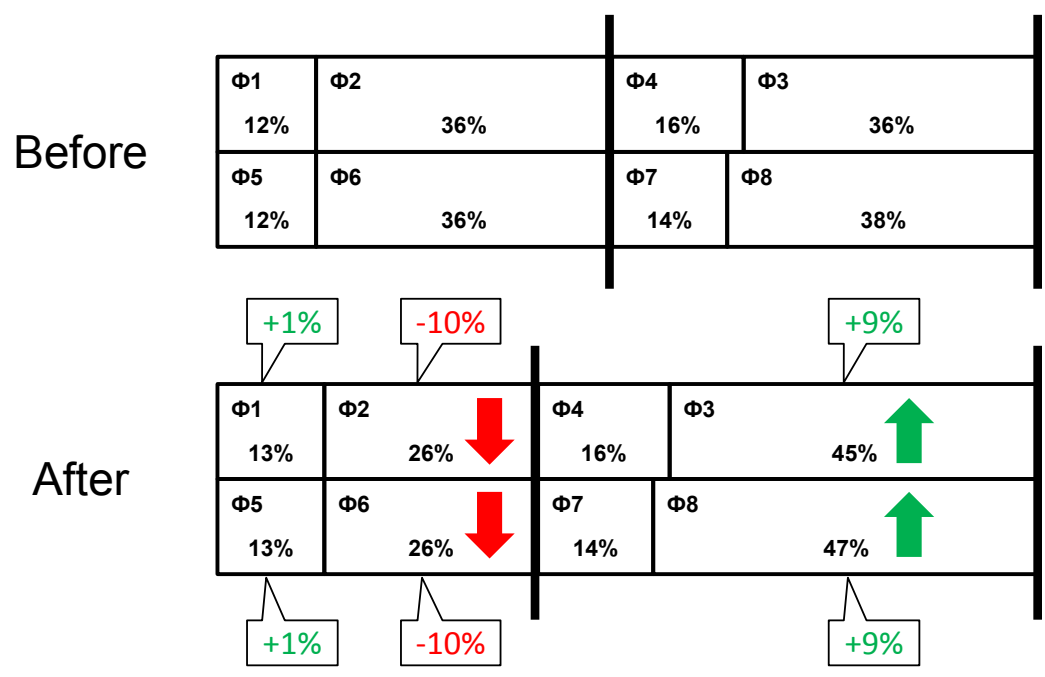
When the intersection of US-231 and River Rd. was changed from free operation to coordinated operation, the maximum duration of the westbound left movement (Phase 3) was reduced because its split time is less than its maximum green time. This led to an increase of split failures on Phase 3, especially during the PM peak when the demand for that movement is highest. Figure 5.3 shows the two solutions that were used to mitigate the split failures, a sequence change (Figure 5.3a) and a split adjustment (Figure 5.3b). Figure 5.4 shows the number of oversaturated splits in 30-minute bins for each phase at the intersection before coordination, after coordination, after the sequence change, and after the split adjustment. Phase 3 is outlined in red and the PM peak is highlighted in blue. Figure 5.5 shows detailed plots of the  $ROR_5$  vs. GOR for minor movements and  $v/c$  ratios for the mainline movements during the PM peak. Phase 3 is outlined in red.

Figure 5.4 and Figure 5.5 illustrate the effects that coordination, the sequence change, and the split adjustment had on the number of Phase 3 split failures during the PM peak on consecutive Thursdays:

- Coordination increased the number of split failures from 1 to 23.
- Changing the sequence of Phase 3 from leading to lagging as shown in Figure 5.3a, which enabled any unused green time from Phase 4 to be transferred to Phase 3 rather than Phase 1, reduced the number of split failures from 23 to 18.
- Making the split adjustment shown in Figure 5.3b further reduced the number of split failures from 18 to 8.



a) Sequence Change (1/27/14)



b) PM Peak (1500-1900) Split Adjustment (2/3/14)

Figure 5.3 Sequence change and split adjustment to mitigate Phase 3 split failures at US-231 and River Rd.

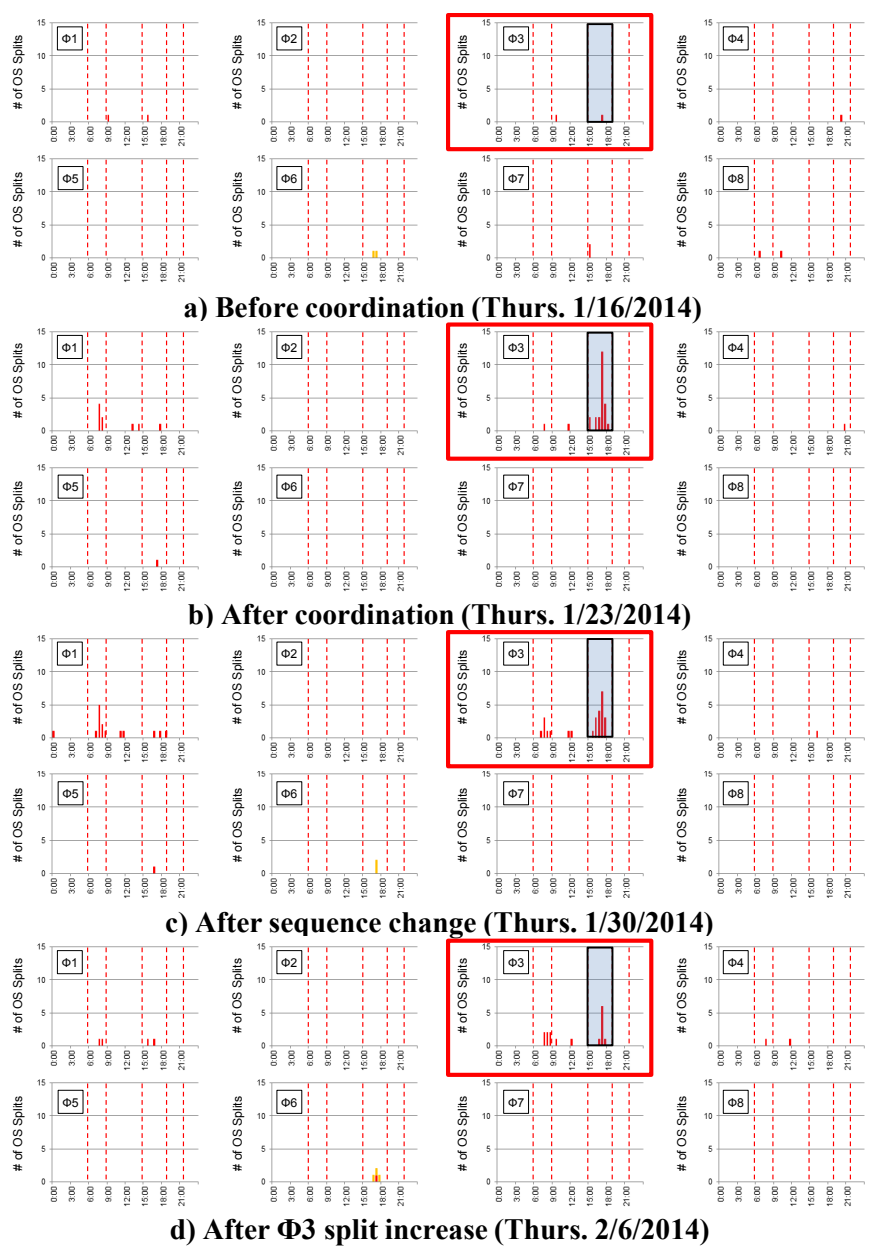
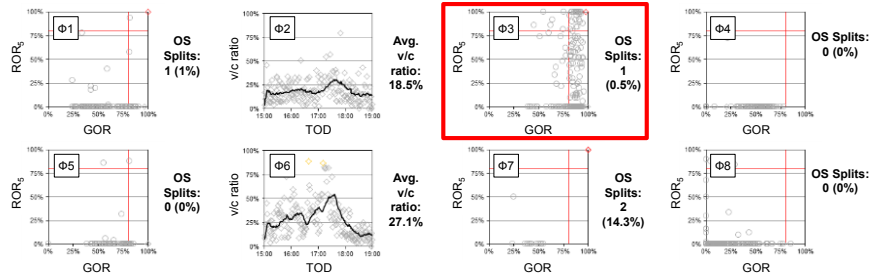
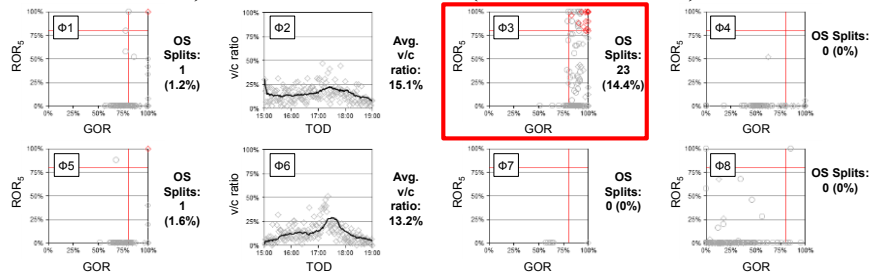


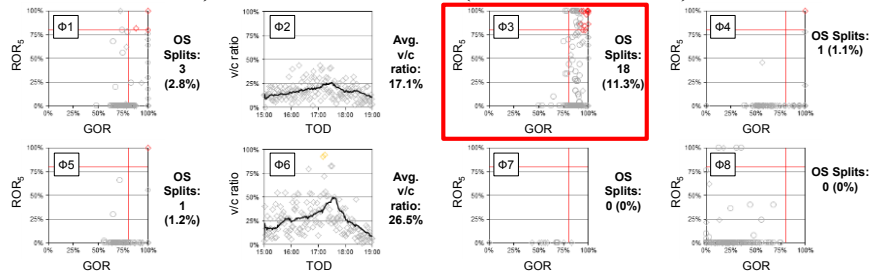
Figure 5.4 Oversaturated splits before and after coordination and after adjustments to mitigate phase 3 split failures at US-231 and River Rd.



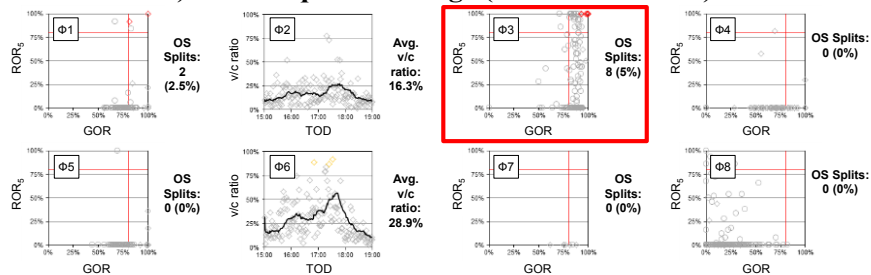
**a) Before coordination (Thurs. 1/16/2014)**



**b) After coordination (Thurs. 1/23/2014)**



**c) After sequence change (Thurs. 1/30/2014)**



**d) After Φ3 split increase (Thurs. 2/6/2014)**

Figure 5.5 ROR<sub>5</sub> vs. GOR and v/c plots (PM peak) before and after coordination and after adjustments to mitigate phase 3 split failures at US-231 and River Rd.

After the operation of Phase 3 had been improved, the performance measures were used to further analyze the intersection's operation by conducting a longitudinal evaluation of its performance. Figure 5.6 shows oversaturated splits in 30-minute bins for each phase on each weekday. Figure 5.7 and Figure 5.8 show detailed plots of the ROR<sub>5</sub> vs. GOR for minor movements and v/c ratios for the mainline movements during the AM peak and PM peak, respectively.

In Figure 5.6, Phase 3 is outlined in red because there is a repetitive pattern of split failures that were still occurring during the AM and PM peaks. Phase 2 is outlined in green because it was consistently undersaturated during the AM and PM peaks. Phase 6 is outlined in yellow because it was consistently nearly saturated during the PM peak.

Taking a closer look at the AM peak (shown in Figure 5.7), Phase 2 (outlined in green) is the dominant mainline movement, but it can afford to yield some green time to Phase 3 (outlined in red) without reaching oversaturation. During the PM peak (shown in Figure 5.8), Phase 6 (outlined in yellow) is the dominant mainline movement, and it doesn't have a lot of excess capacity. Nevertheless, it might be able to yield a small amount of green time to Phase 3 (outlined in red) without experiencing significant adverse effects.

Based on the insight provided by Figure 5.6, Figure 5.7, and Figure 5.8, additional split adjustments were made on February 28<sup>th</sup>, 2014 (see Figure 5.9).

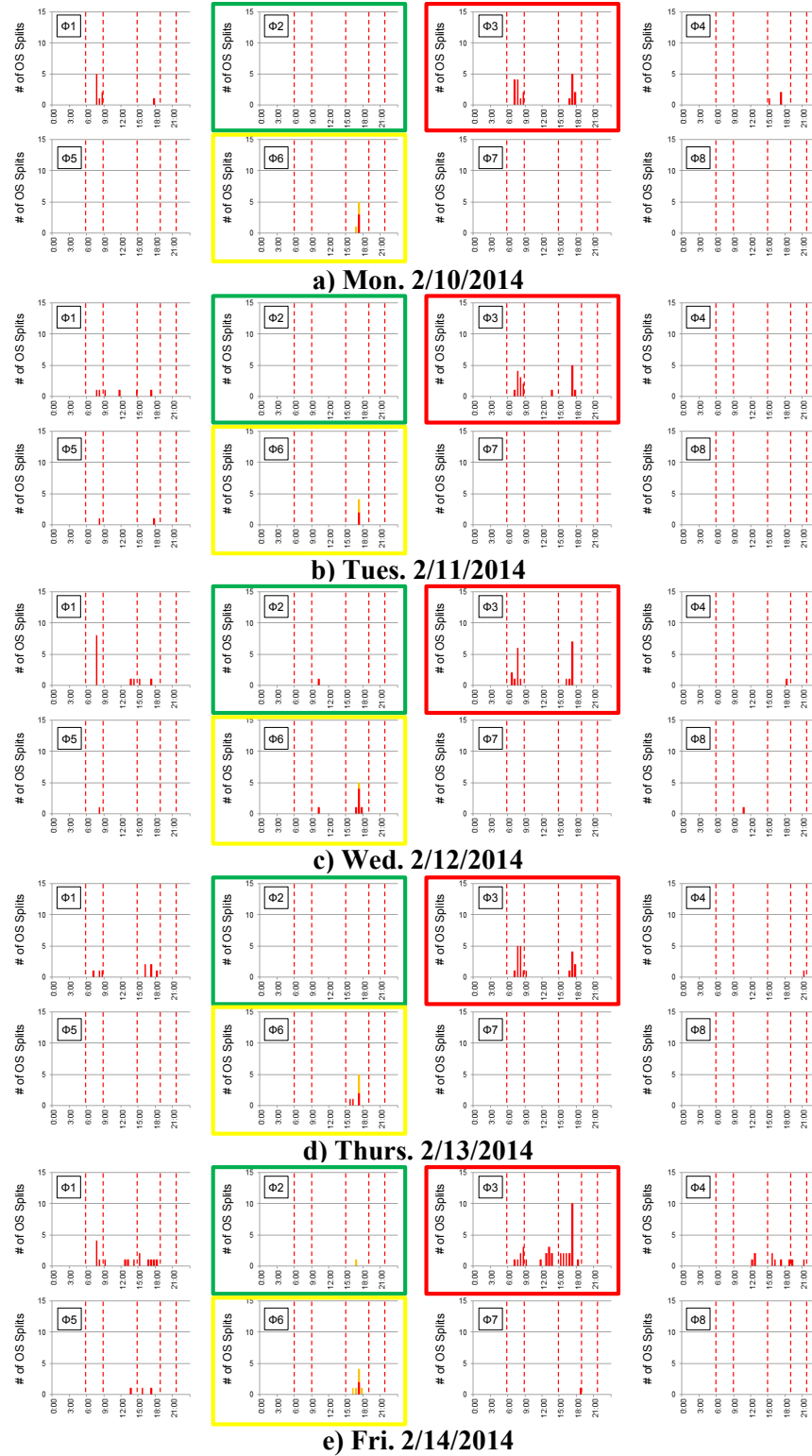


Figure 5.6 Longitudinal comparison of oversaturated splits in 30-min. bins (US-231 and River Rd.)

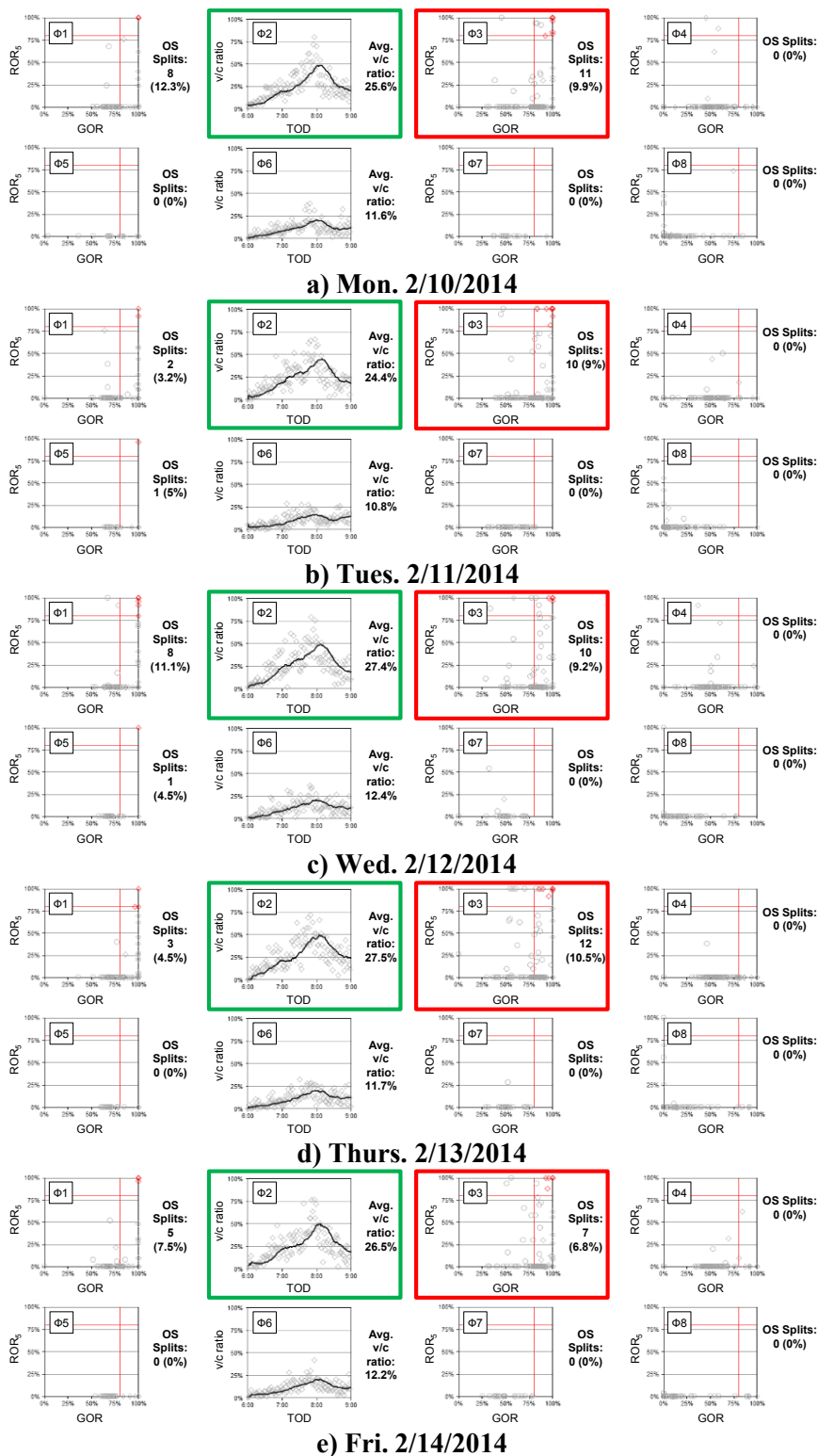


Figure 5.7 Longitudinal comparison of ROR<sub>5</sub> vs. GOR and v/c plots during the AM peak (US-231 and River Rd.)



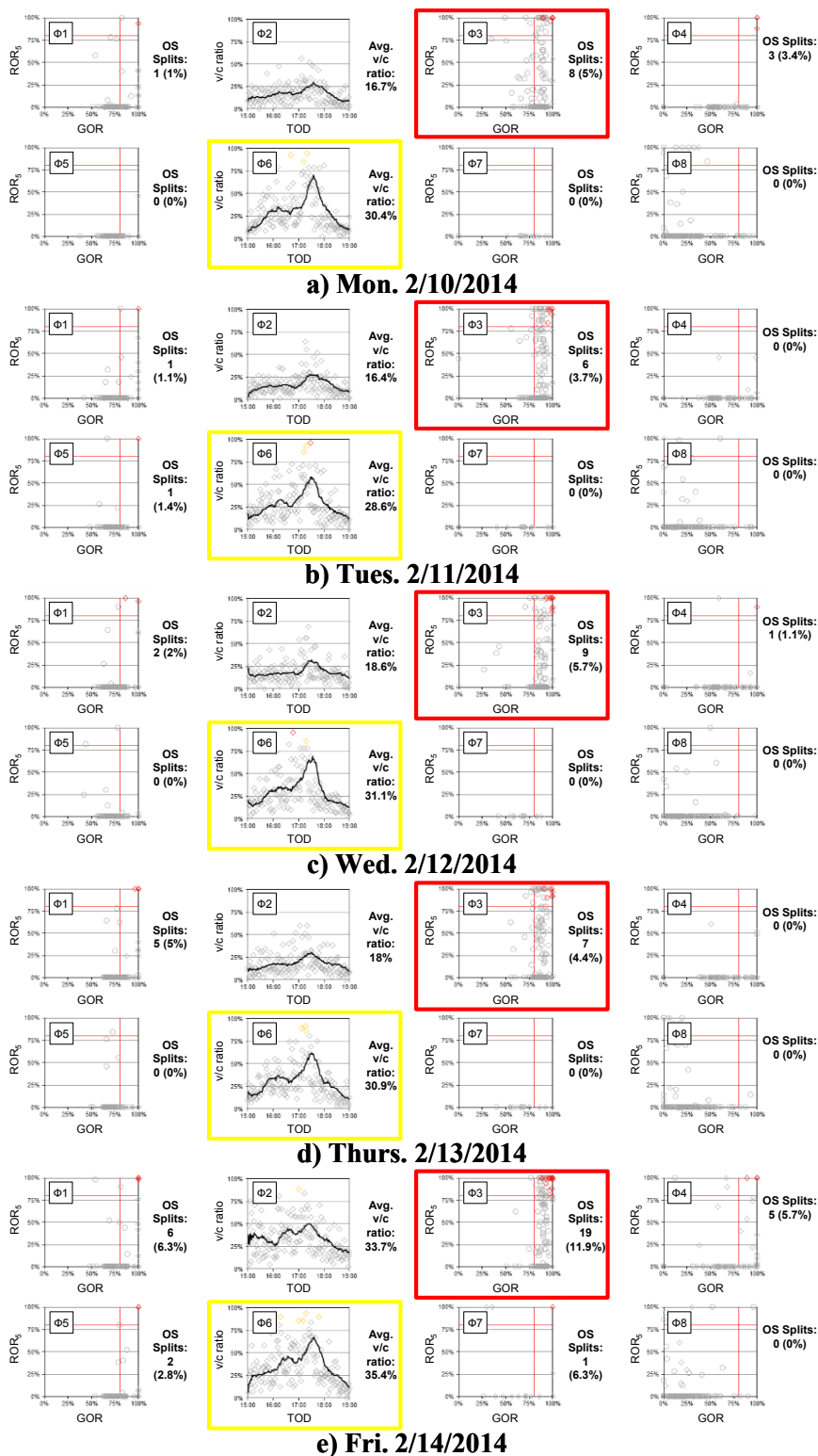


Figure 5.8 Longitudinal comparison of ROR<sub>5</sub> vs. GOR and v/c plots during the PM peak (US-231 and River Rd.)

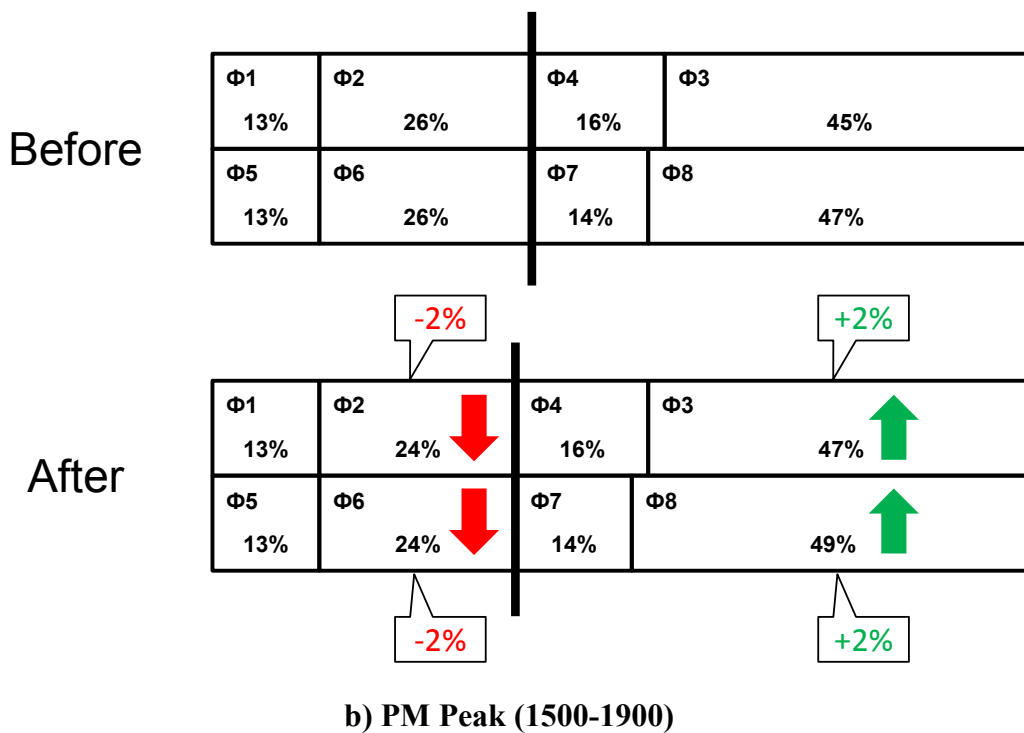
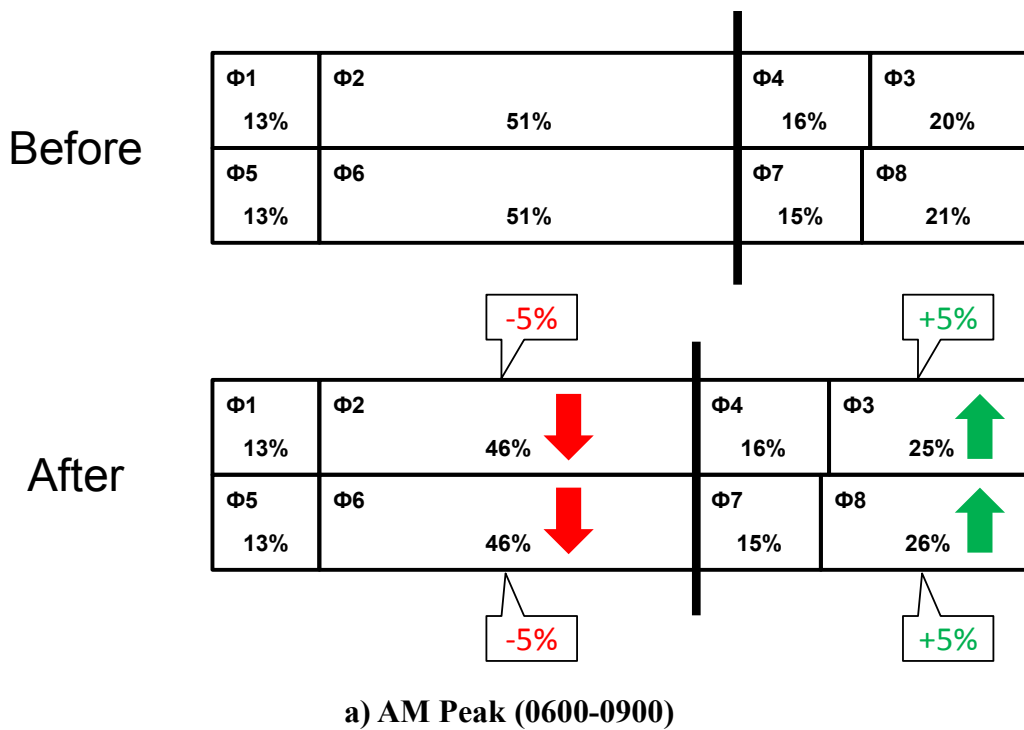


Figure 5.9 Additional split adjustments at US-231 and River Rd. (2/28/14)

Figure 5.10a-b and Figure 5.11a-b both show the number of oversaturated cycles in 30-minute bins before and after the split adjustment. Figure 5.10c-d and Figure 5.11c-d show detailed plots of  $ROR_5$  vs. GOR and v/c ratios before and after the split adjustment during the AM peak and PM peak, respectively. Phase 3 is outlined red in Figure 5.10 and Figure 5.11. The AM peak is highlighted blue in Figure 5.10a-b, and the PM peak is highlighted blue in Figure 5.11a-b.

- Figure 5.10 shows the reduction of Phase 3 split failures from 11 to 0 during the AM peak after taking 5% from the split times of Phases 2 and 6 and giving it to Phases 3 and 8.
  - Figure 5.10 also shows that Phases 2 and 6 were not adversely affected by the split adjustment during the AM peak.
- Figure 5.11 shows the reduction of Phase 3 split failures from 8 to 4 during the PM peak that resulted from taking 2% from the split times of Phases 2 and 6 and giving it to Phases 3 and 8.
  - Figure 5.11 also shows no significant increase in the number of oversaturated or nearly saturated cycles during the PM peak.

The split adjustment made on February 28<sup>th</sup>, 2014 eliminated Phase 3 split failures during the AM peak. However, due to Phase 6 competing for split time, there were still 4 split failures on Phase 3 during the PM peak.

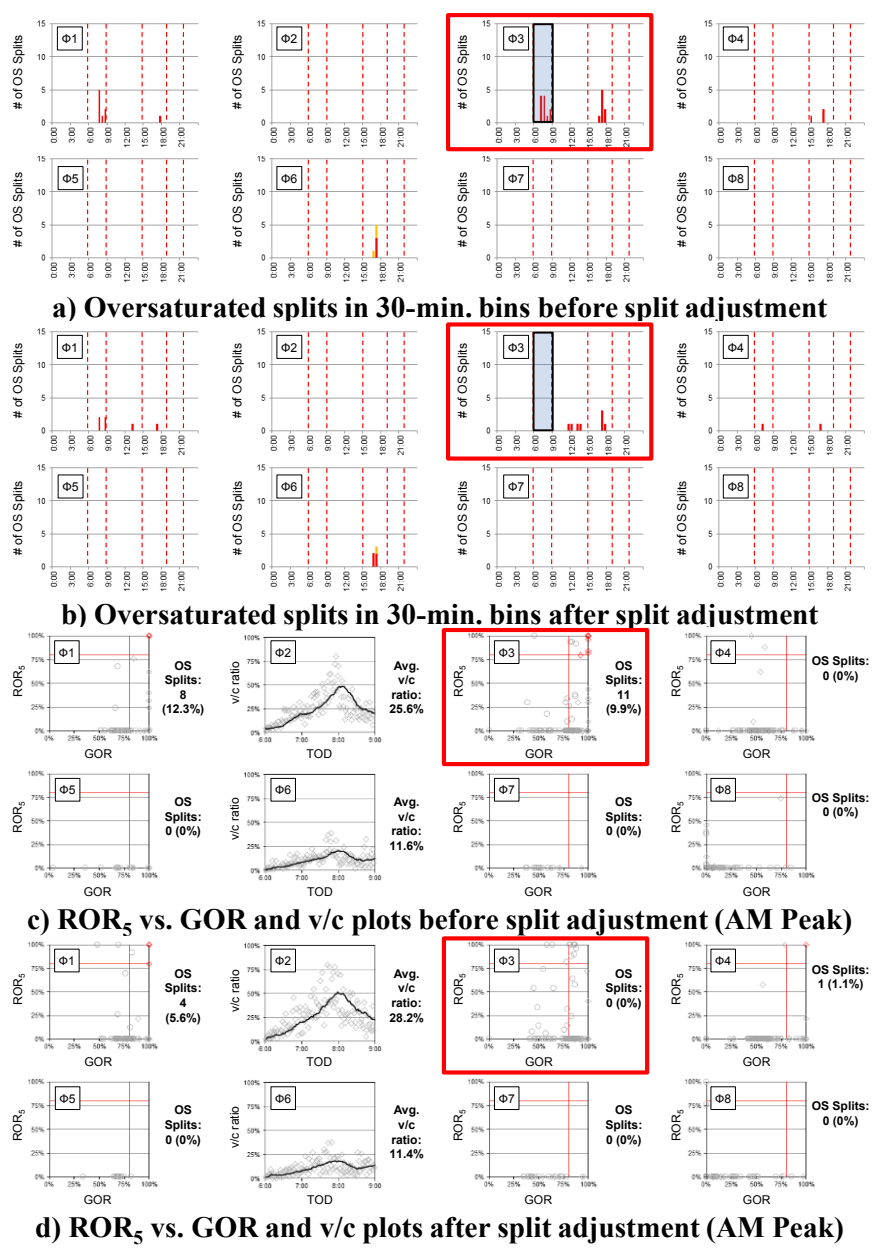


Figure 5.10 Comparison of US-231 and River Rd. during the AM Peak before (Mon. 2/10/2014) and after (Mon. 3/3/2014) split adjustment

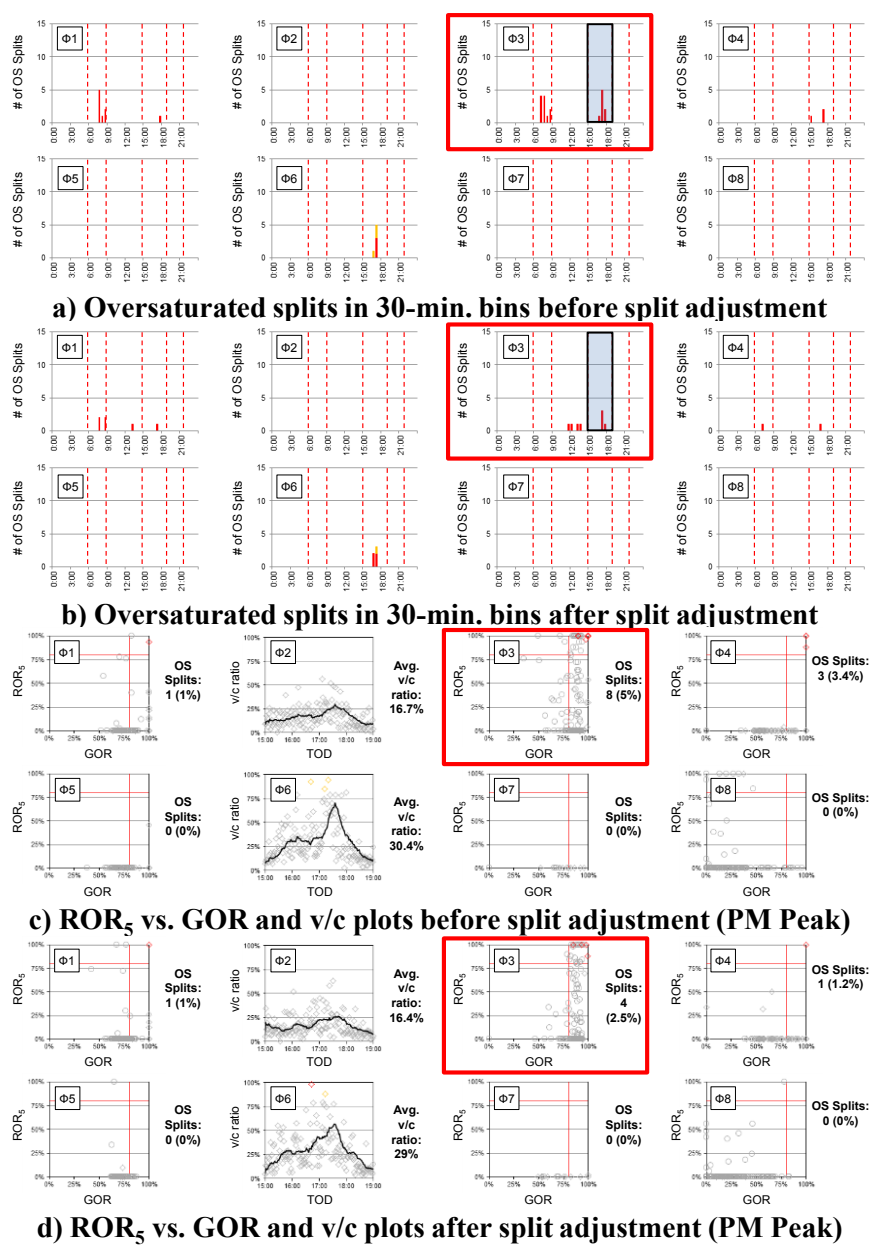


Figure 5.11 Comparison of US-231 and River Rd. during the PM Peak before (Mon. 2/10/2014) and after (Mon. 3/3/2014) split adjustment

## CHAPTER 6. CONCLUSIONS

The performance measures presented in this thesis provide a means for practitioners to efficiently validate complaints from the public reporting that a signal is not providing adequate green time for a particular movement. By combining the GOR, the  $ROR_5$ , 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 3.3, Figure 3.5, Figure 3.6, Figure 3.7, Figure 3.11, Figure 4.1, Figure 4.3, Figure 5.7, Figure 5.8, Figure 5.10c-d, and Figure 5.11c-d) 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 oversaturated splits for each phase (Figure 3.9, Figure 3.10, Figure 3.12, Figure 3.13, Figure 4.2, Figure 5.4, Figure 5.6, Figure 5.10a-b, and Figure 5.11a-b).

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 thesis illustrates the power of this analysis technique through two separate case studies. At US-31 and 126<sup>th</sup> St, 4% of the split time was taken from Phases 2 and 6 and given to Phases 3 and 8 during the mid-day plan (see Figure 3.8). This adjustment resulted in a 55% reduction (116 to 52) of oversaturated splits on Phase 3 and a 65% reduction (43 to 15) of oversaturated splits on Phase 8 during the mid-day plan on consecutive Thursdays (see Figure 3.9). It resulted in a 64% reduction (75 to 27) of oversaturated splits on Phase 3 and a 32% reduction (34 to 23) of oversaturated splits on Phase 8 during the mid-day plan on consecutive Fridays (see Figure 3.12). It also resulted in a reduction of consecutive oversaturated splits on Thursday (see Figure 3.10) and Friday (see Figure 3.13). Meanwhile, the mainline movements from which split time was taken did not experience significant adverse impacts. The v/c ratios increased by a modest amount (see Figure 3.14) and the progression was unaffected (the POG actually increased slightly).

At US-231 and River Rd, a sequence change and two iterative split adjustments were implemented to mitigate split failures on Phase 3. The sequence change (see Figure 5.3a) resulted in a reduction of oversaturated splits from 23 to 18 during the PM peak on consecutive Thursdays (see Figure 5.4). The first split adjustment (see Figure 5.3b) resulted in a reduction of oversaturated splits from 18 to 8 during the PM peak on consecutive Thursdays (see Figure 5.4). The second split adjustment (see Figure 5.9) resulted in a reduction of oversaturated splits from 11 to 0 during the AM peak on two Mondays (see Figure 5.10) and from 8 to 4 during the PM peak on two Mondays (see Figure 5.11).

In terms of potential applications and future directions for this research, there exists a great deal of applicability for state and local transportation agencies to implement the ROR vs. GOR methodology. For example, in the near future, a central system could produce daily automated counts of oversaturated splits for each phase during each timing plan at signalized intersections across the state. A practitioner could then use the system to rank split reallocation opportunities on minor phases at each intersection during each timing plan. Then, a filter could be used to eliminate any opportunities in which one or more of the mainline phases has an average  $v/c$  ratio greater than a certain threshold (e.g. 80%). Finally, the practitioner could use the system to view detailed summaries of the graphical performance measures (such as those shown in Figure 5.10 and Figure 5.11) corresponding to the most promising split reallocation opportunities.



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