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TECHNICAL MEMORANDUM

Date: April 20, 2020 Project #: 17453.010

To: Deedee Fraley (City of Bend)

From: Scott Beaird, PE, Ryan Casburn, EI, and Lee Rodegerdts, PE (Kittelson)

Project: Bond-Reed Market-Brookswood Roundabout Metering Pilot Test (1TBRB)

Subject: Evaluation of Field Results

INTRODUCTION

This technical memorandum documents a pilot test of a roundabout metering system at the Bond Street/Reed Market Boulevard/Brookswood Street roundabout in Bend, Oregon.

This memorandum is organized into the following sections:

- Introduction
- Field Test Configuration
- Data Collection Protocol
- Metering Test Patterns
- Field Observations and Analysis
- Summary and Conclusions
- References

In summary, we find that the metering signals at the Bond/Reed Market/Brookswood roundabout were generally beneficial during the peak periods, particularly during the AM peak. However, careful attention to design details and metering signal logic will be needed to avoid creating unintentionally long queues.

FIELD TEST CONFIGURATION

The metering test was conducted using a set of temporary traffic signals, the type used for two-way, one-lane operations during bridge construction and other similar activities. These temporary traffic signals were placed approximately 100 feet from the yield line, one on each of the four approaches. A temporary stop line was placed at 140 feet from the yield line (40 feet from the signal), supplemented with a STOP HERE ON RED (arrow) sign placed on a Type II barricade. In order to emphasize the requirement to yield at the roundabout, a secondary YIELD sign was placed on a Type II barricade on the splitter island. A sample of this setup for the northbound Brookswood Boulevard leg is shown in Figure 1.

Figure 1 - Temporary Signal Set-up

Additionally, further upstream of the signal, a portable changeable message sign (PCMS) showed two sets of messages (shown in Figure 2):

- For non-test days and for non-test approaches on test days, the PCMS alternated between "TRAFFIC CONTROL CHANGE" and "MON 3/2 THRU FRI 3/6."
- On test days for those approaches with active metering, the PCMS alternated between "METERING SIGNAL ACTIVE" and "YIELD AT RNDABOUT".

Figure 2 - PCMS Boards

Due to scheduling and equipment procurement, the field test was constrained to occur over four days during the AM and PM peak periods. These were assigned as follows:

- Monday, March 2 (Non-test day): Metering signals in place but not active.
- Tuesday, March 3 (Test day): Metering signals active.
- Wednesday, March 4 (Non-test day): Metering signals in place but not active.
- Thursday, March 5 (Test day): Metering signals active.

The test and non-test days were alternated to provide time for the project team to review the results of each day and adapt the testing or measurement protocol to the following days. The AM test period was set at 7:30 to 8:45 AM for all four days. For the PM test period, the test periods were set at 4:15 to 5:45 PM for Monday and Tuesday; for Wednesday and Thursday this was expanded to 3:30 to 5:45 PM. This is discussed later in this document.

DATA COLLECTION PROTOCOL

Two forms of field data were collected:

- Queuing data: Field marks were placed on each entry leg into the roundabout, starting at the entrance line and marked at 25-foot increments. A human observer would mark the queue length at one-minute intervals on the minute.

- Volume data: Cameras recorded the entry-circulating conflict point for each roundabout entry, and traffic volumes were extracted in 5-minute increments for both entry flows and conflicting traffic flows.

During data collection, the queuing data proved challenging in some cases. Some of the challenges experienced include the following:

- On the earliest test days, the queue length occasionally extended beyond the field markings.
- In some cases, the queue length grew so rapidly that the human observer was unable to catch up to it for a precise recording.
- In some cases, the queue length extended through an intersection and split across two legs.

As a result, the queue length is a good indicator but is either approximate or missing for some time periods.

METERING TEST PATTERNS

The metering signal timing was based on VISSIM analysis documented previously. In the AM peak period, northbound Brookswood and eastbound Reed Market were both metered. In the PM peak period, southbound Bond and westbound Reed Market were both metered. For both time periods, both metered legs were stopped at the same time. After a number of seconds, the downstream (northbound or southbound) signal was turned green. After additional time elapsed, the upstream (westbound or eastbound) signal was turned green.

The signal timing on Thursday was updated based on the lessons learned on Tuesday. One of these lessons is the need to dynamically start metering when the queue begins to build. Based on this, on Thursday, only the upstream meter (eastbound or westbound) was used until the opposite leg queue began to grow. The upstream meter was pulsed (15 seconds green, 15 seconds red) for this initial condition. Once the westbound (AM) or eastbound (PM) queue began to grow, then the metering signalization was changed to be similar to the Tuesday phasing. Once the queue decreased, the metering went back to the original pattern. The phase changes are documented in Appendix A.

TUESDAY AM

The signal metering started around 7:30 AM. The pattern had both the northbound and eastbound turn red at the same time. During this period, the northbound turned green first letting those vehicles flush before the eastbound vehicles arrived at the intersection.

By around 7:45, it was clear the northbound queue was growing faster than desired. At this point, the red time for the northbound signal was decreased. Following this, red time for the westbound was increased, also to increase the northbound flow. By 8:15, the northbound queue had continued to grow. The northbound meter was left in green to clear the queue for a period of time. After this period of time, the meters were returned to the sequence pattern with the updated timing. The pattern is shown below in Figure 3.

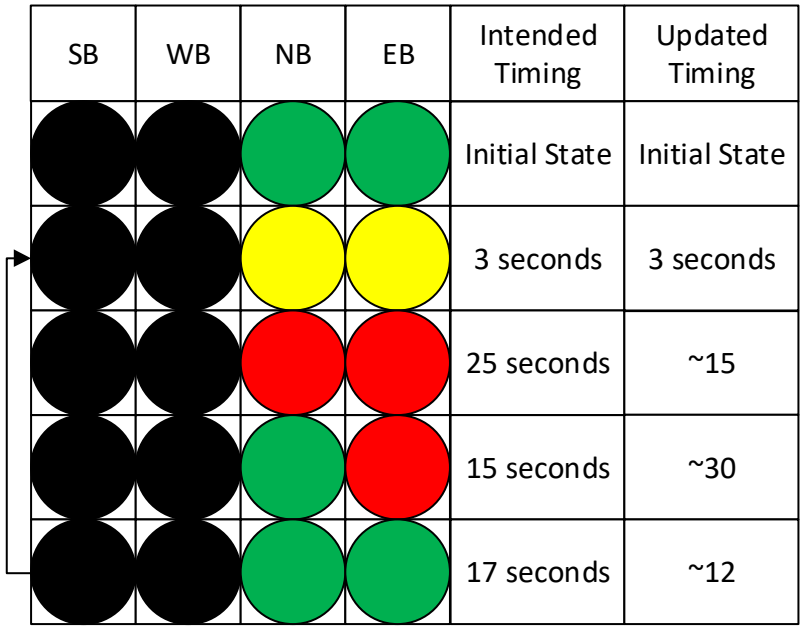


Figure 3 - Tuesday AM Signalization Plan

TUESDAY PM

The signal metering started around 4:15 PM. The pattern had both southbound and westbound going red at the same time with southbound turning green before the westbound. This operated with the same pattern as the AM except it was rotated 180 degrees. On Tuesday, the eastbound and southbound queues had already begun to grow before the meters were activated. There were more changes to signal patterns than in the AM in an attempt to catch up to this queue while reducing the impact to the metered approaches. The pattern used is shown below in Figure 4.

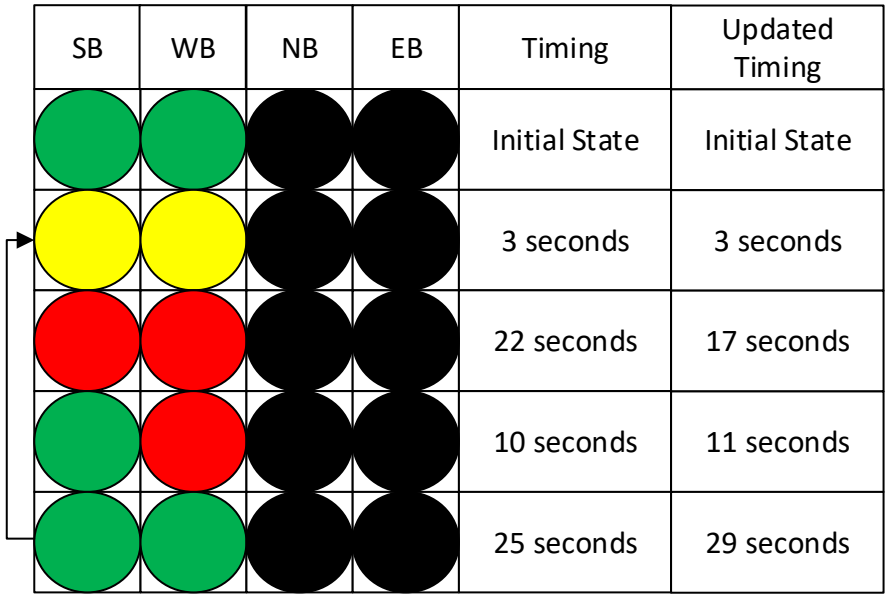


Figure 4 - Tuesday PM Signalization Plan

THURSDAY AM

Learning from the Tuesday test, the metering pattern was adjusted to improve performance. Initially, using a 30-second cycle length, only the eastbound signal was used. The eastbound signal was pulsed with 15 seconds of red time and 12 seconds of green time (3 second yellow). This was intended to give more unconflicted time to the northbound by bunching the eastbound vehicles. Once the westbound queue grew to about 800 feet, the signals were switched to sequence 2, which was identical to the intended timing on Tuesday. This timing is shown below in Figure 5.

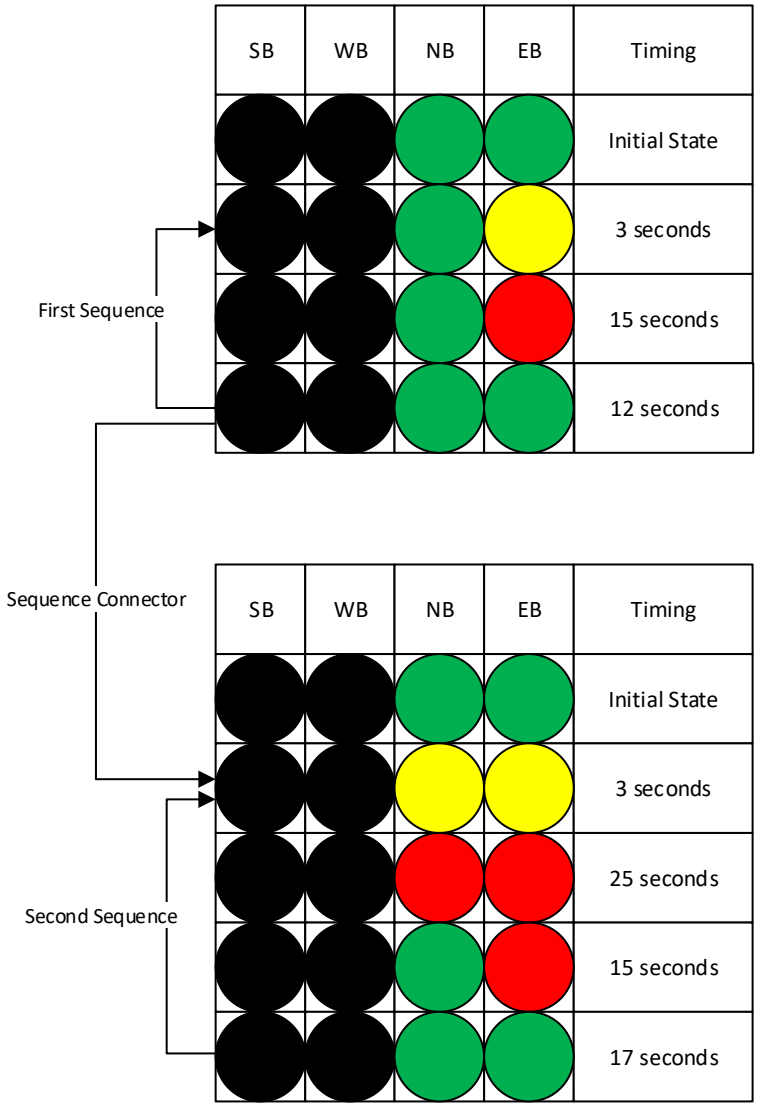


Figure 5 - Thursday AM Signalization Plan

THURSDAY PM

Timing patterns were revised based on lessons learned from the previous days. This included beginning metering at 3:30 PM. The planned timing sequence is shown below in Figure 6.

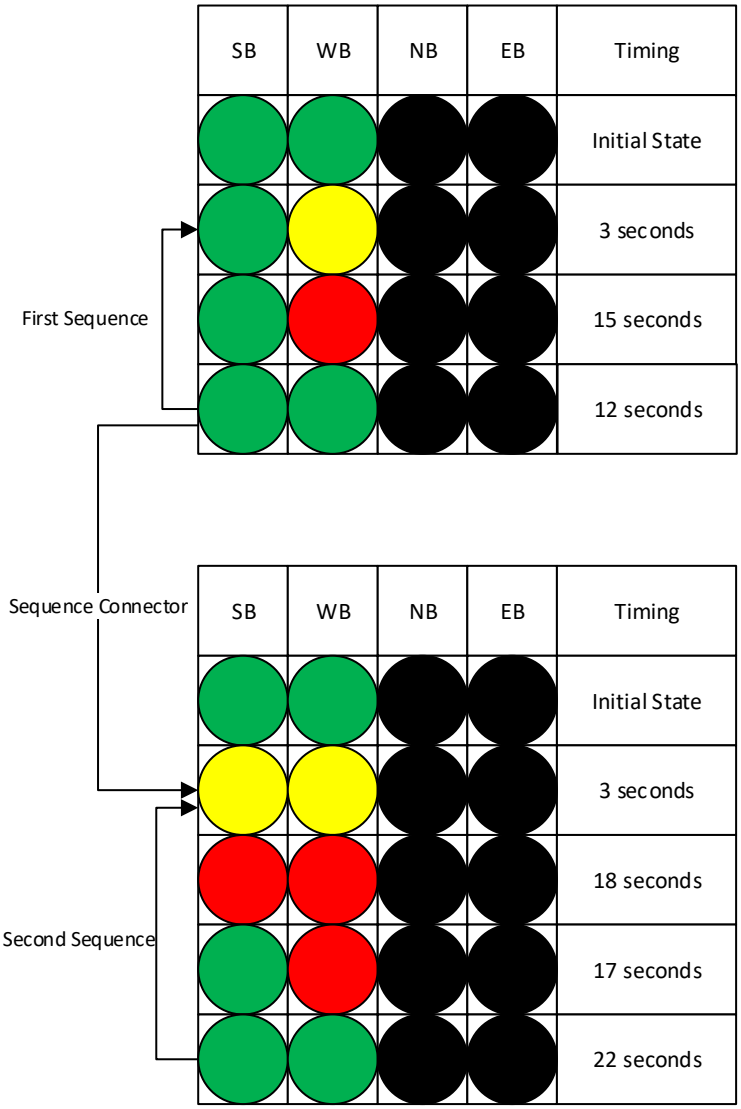


Figure 6 - Thursday PM Signalization Plan

FIELD OBSERVATIONS AND ANALYSIS

SAFETY OBSERVATIONS

The metering operation resulted in no observed safety-related incidents requiring attention. Our team anecdotally noted the following:

- Compliance with the YIELD signs remained the same between non-test and test days, with no significant observations of failure to yield.
- Compliance with drivers stopping for pedestrians on both the entry side and exit side of each splitter island remained the same between non-test and test days. Yielding rates were not measured but are estimated to be well above 90 percent.

- Some drivers did not fully comply with the metering signals, with some red-light running. These generally occurred when a vehicle was stuck in a dilemma zone between the stop bar and a back of queue that extended to the meter. When this driver cleared from that zone, the subsequent one or two drivers behind the stop bar also proceeded. None of these violations resulted in unsafe maneuvers.
- Many drivers were observed using cell phones while driving. These resulted in unnecessary hesitation but no unsafe maneuvers.

NON-TEST OBSERVATIONS

Queuing at the roundabout is unstable during peak hours and can vary significantly from day to day. Figure 7 and Figure 8 illustrate this for the westbound Reed Market and northbound Brookswood legs, respectively, on the two non-test days during the AM peak. This type of queuing behavior is to be expected for a roundabout operating near capacity during peak conditions. In the case of northbound Brookswood in the AM peak, the queuing is particularly magnified during demand surges caused largely by people going to work at the same time or taking children to school at the same time. Because the legs interact with each other at the roundabout, surges in northbound Brookswood traffic impede westbound Reed Market traffic.

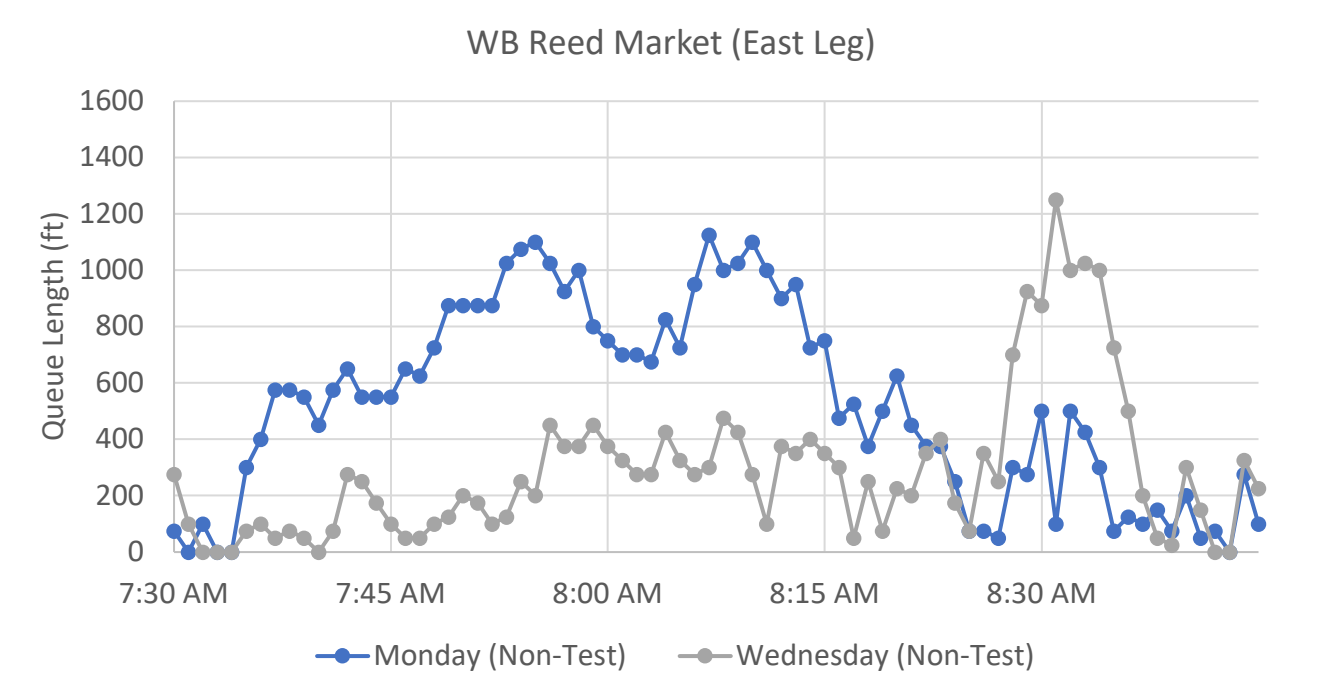


Figure 7 - Non-Test AM Westbound Reed Market

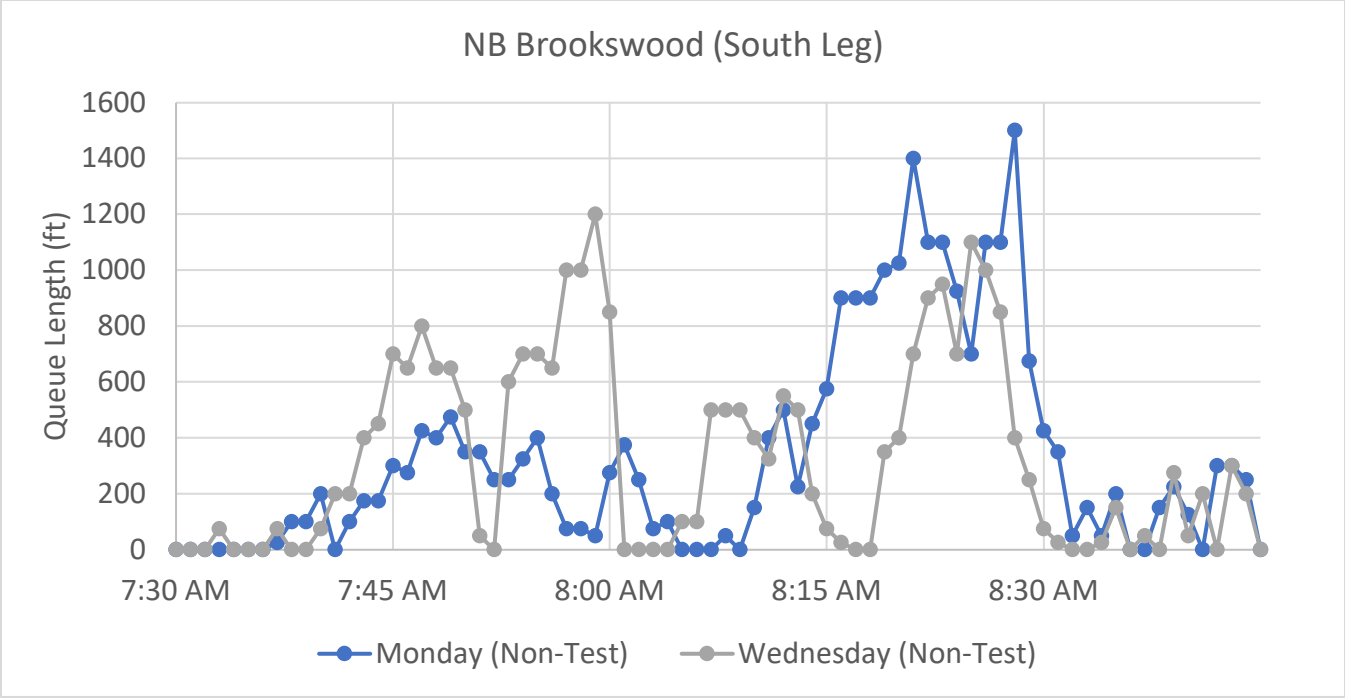


Figure 8 - Non-Test AM Northbound Brookswood

TEST OBSERVATIONS, AM PEAK PERIOD

Metering proved to have some effectiveness in managing the queue formation on westbound Reed Market during the AM peak period. A graph is shown in Figure 9. A few aspects are notable:

- The overall size of the queue was kept manageable, below 400 feet in length, until about 7:55, comparable to the queues on Wednesday, a non-test day, and significantly better than Monday, also a non-test day.
- Once the queue increased rapidly beyond 800 feet, it was possible to modify the metering pattern to rapidly flush the queue. This was initiated at 8:02 and terminated at 8:07. This avoided any sustained queuing back to the Bend Parkway interchange.
- During the 8:15 to 8:45 period, queues were allowed to remain in the 600-foot to 800-foot range as an effort to prioritize managing the queue on northbound Brookswood. A queue clearance sequence was implemented twice during this period—8:17 to 8:27 and 8:30 to 8:32—to further reduce the queue on northbound Brookswood.

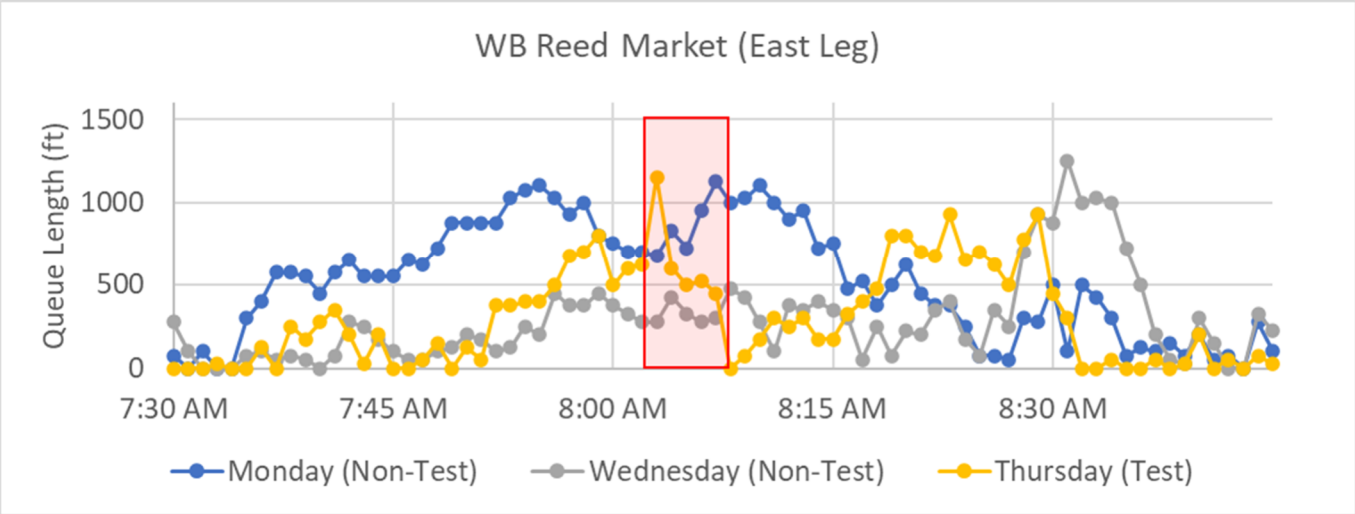


Figure 9 - Test to Non-test comparison on Westbound Reed Market Road

The queuing picture on northbound Brookswood is less clear. A graph is shown in Figure 10. A few aspects are notable:

- Queue spikes occurred every day, test or non-test. These appear to be caused by demand spikes, most likely due to people taking children to school or going to work by a certain time. Again, this is to be expected when an entry is operating at or over capacity.
- During the time of the active queue clearance on westbound Reed Market (8:02 to 8:07, described previously), the queue on northbound Brookswood was allowed to grow (see Figure 11). This was directly a function of the metering, given that Brookswood was shown extended red periods to clear the circulatory roadway to serve the westbound Reed Market entry. During the test, the northbound Brookswood entry was held back a minute or two longer than needed. On the one hand, the westbound Reed Market entry completely cleared, but it was perhaps at the expense of more queuing than necessary on northbound Brookswood.
- Once the metering pattern was switched back at 8:07 to not favor westbound Reed Market, the queue reduced substantially and quickly. This is likely a combination of the metering and a drop in the arriving demand (the end of the demand spike). This is visible in the 8:10 to 8:15 time period. As a result, the queues were similar to those experienced on Wednesday, a non-test day, and somewhat better than on Monday, also a non-test day.

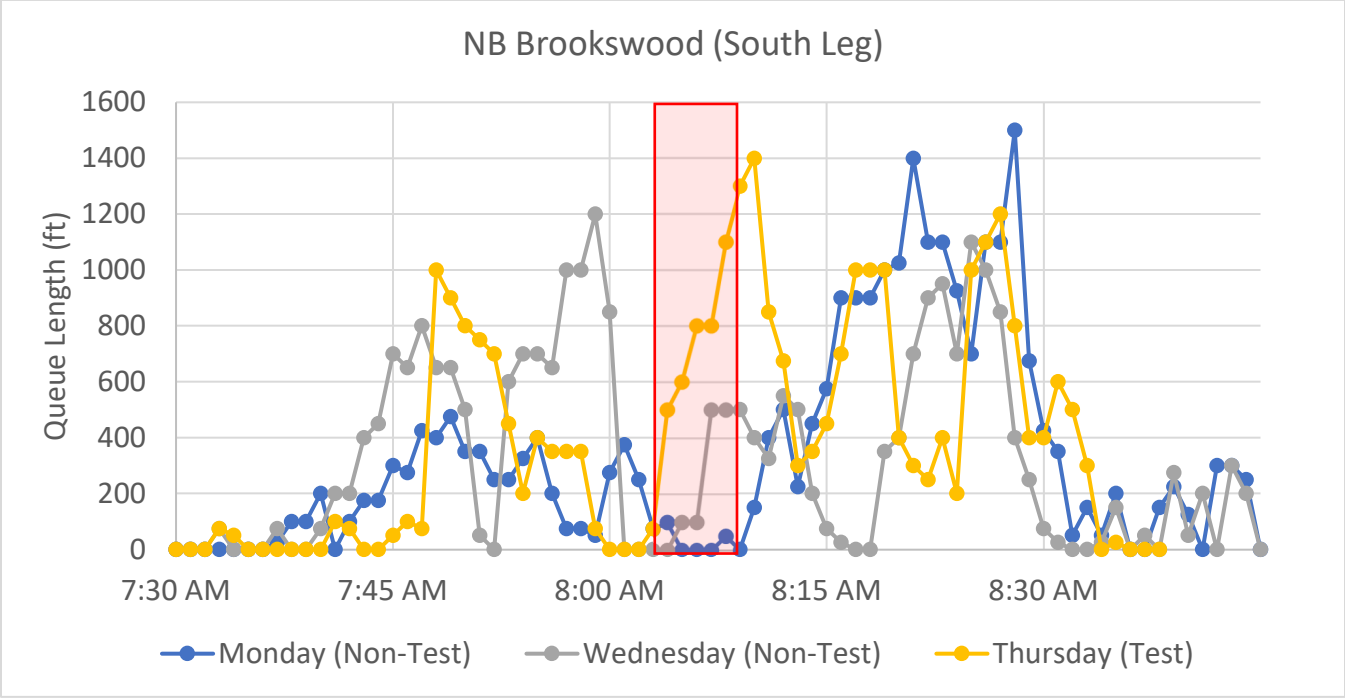


Figure 10 - AM Test to Non-Test Comparison Northbound Brookswood

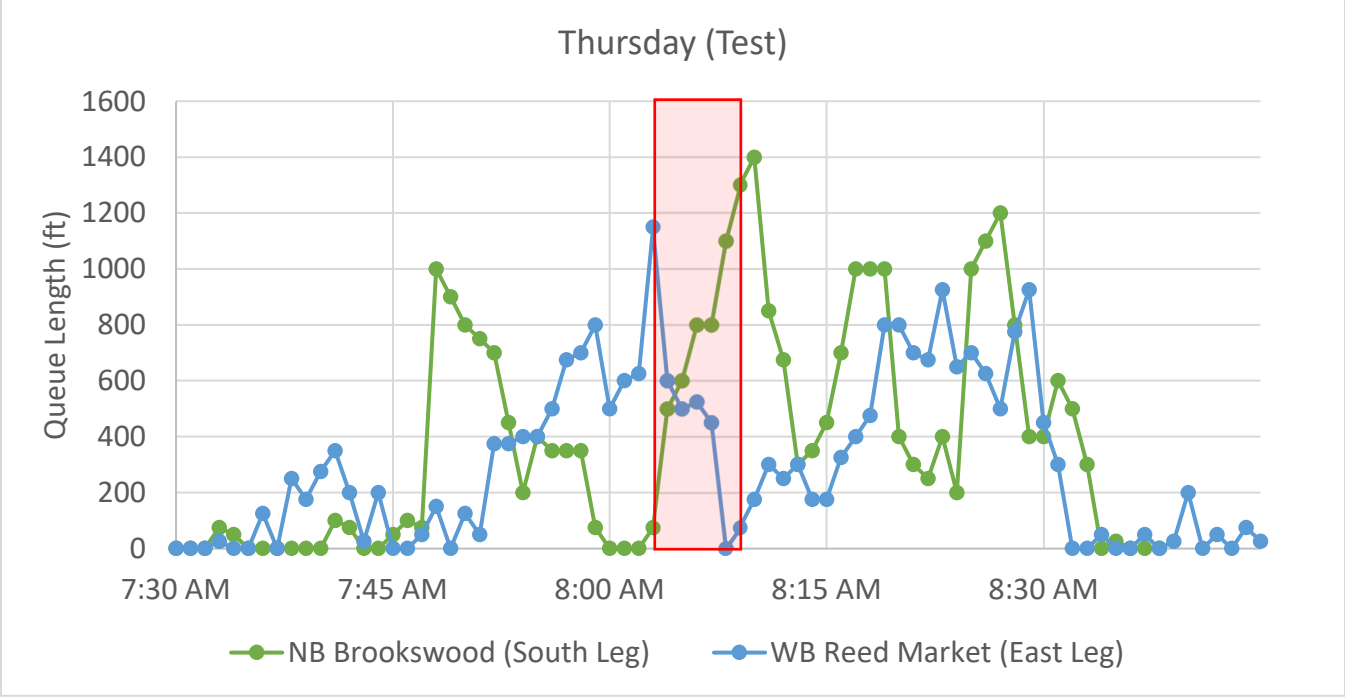


Figure 11 - Thursday AM (Test) Northbound vs Westbound queue comparison

TEST OBSERVATIONS, PM PEAK PERIOD

Metering had more mixed effects during the PM peak period.

For southbound Bond, the biggest lesson learned during the first day of testing was to start the metering pattern earlier in the afternoon. The initial queue on southbound Bond on Monday and Tuesday already exceeded 1,000 feet, and the initial metering plan devised for Tuesday was unsuccessful in reducing the queue. This prompted a decision to beginning data collection earlier on both Wednesday and Thursday and to also implement a revised metering plan earlier on Thursday. The results from this adjustment were mixed but showed some promise. Queuing was initially longer or about the same on Thursday compared to Wednesday despite the metering. However, starting around 5:15, the revised metering pattern produced significantly shorter queues on Thursday than what was observed Monday and Wednesday. This was a result of active monitoring and modifying the metering pattern in real time as the test period progressed. Southbound Bond queuing is shown in Figure 12.

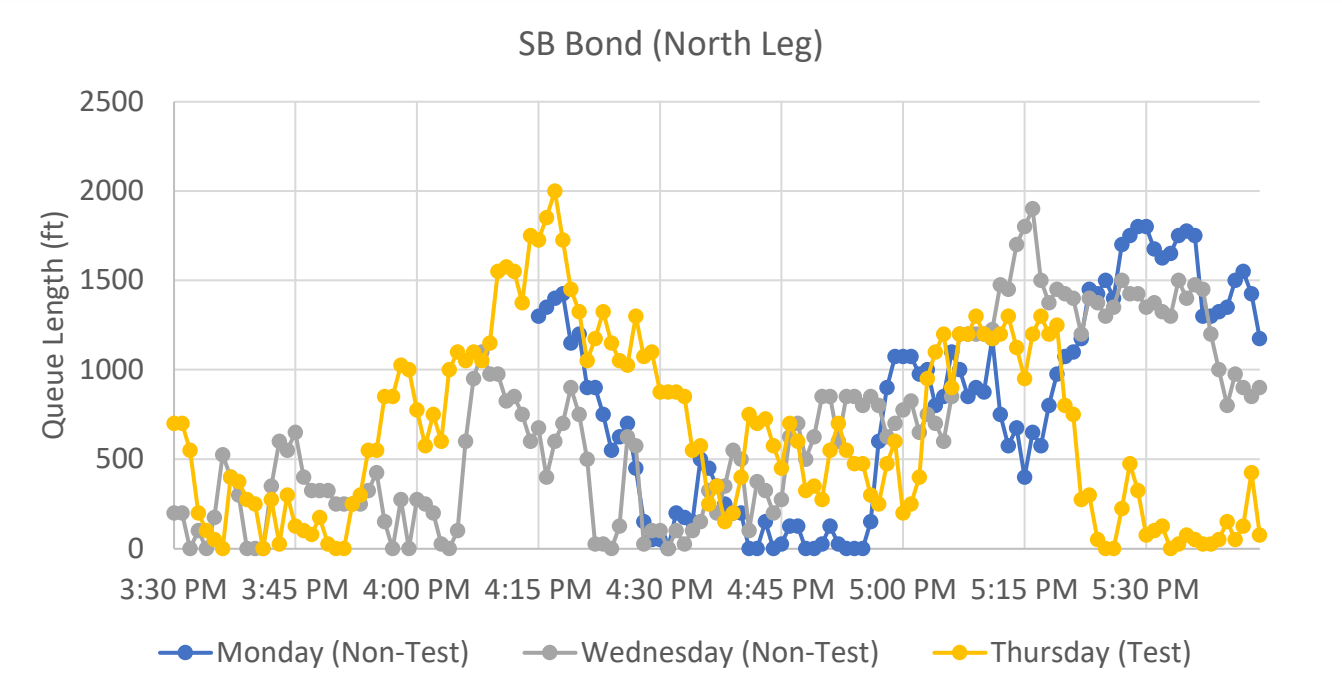


Figure 12 - PM Southbound Bond

For westbound Reed Market, the most notable effect was on the first testing day. The efforts to manage the queue on southbound Bond came at the expense of increased queues on westbound Reed Market, with some queues reaching the Bend Parkway interchange. The adjustments made to the metering patterns used on Thursday kept the queues significantly more manageable, with none exceeding 700 feet. It is notable that these queues are longer than those experienced on non-test days, but this is by design to provide more opportunities for southbound Bond and eastbound Reed Market. Westbound Reed Market queue is shown in Figure 13.

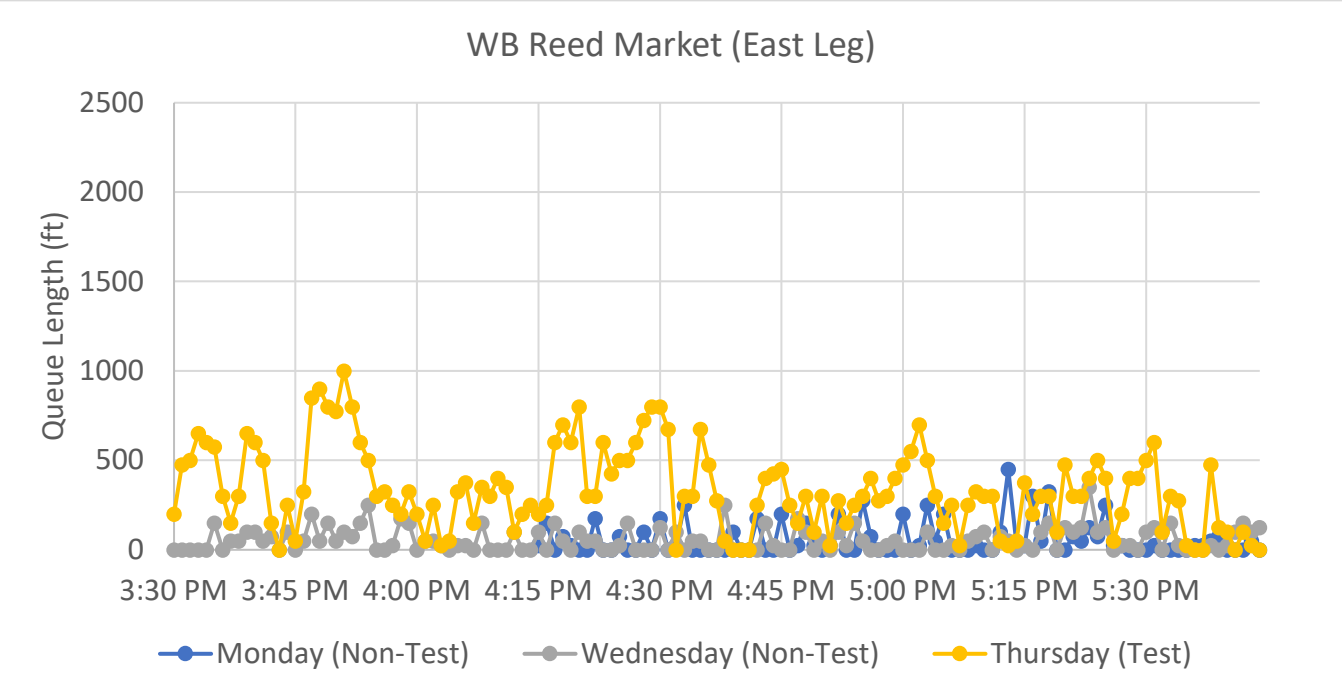


Figure 13 - PM Westbound Reed Market

For eastbound Reed Market, the patterns are more differentiated between whether one looks at Monday versus Tuesday or Wednesday versus Thursday rather than non-test versus test. Both Wednesday and Thursday experienced the greatest queuing from about 4:10 until 4:30. The metering on Thursday seemed to reduce queues compared to Wednesday during the later peak from about 5:10 until 5:25. Eastbound Reed Market queues are shown in Figure 13Figure 14.

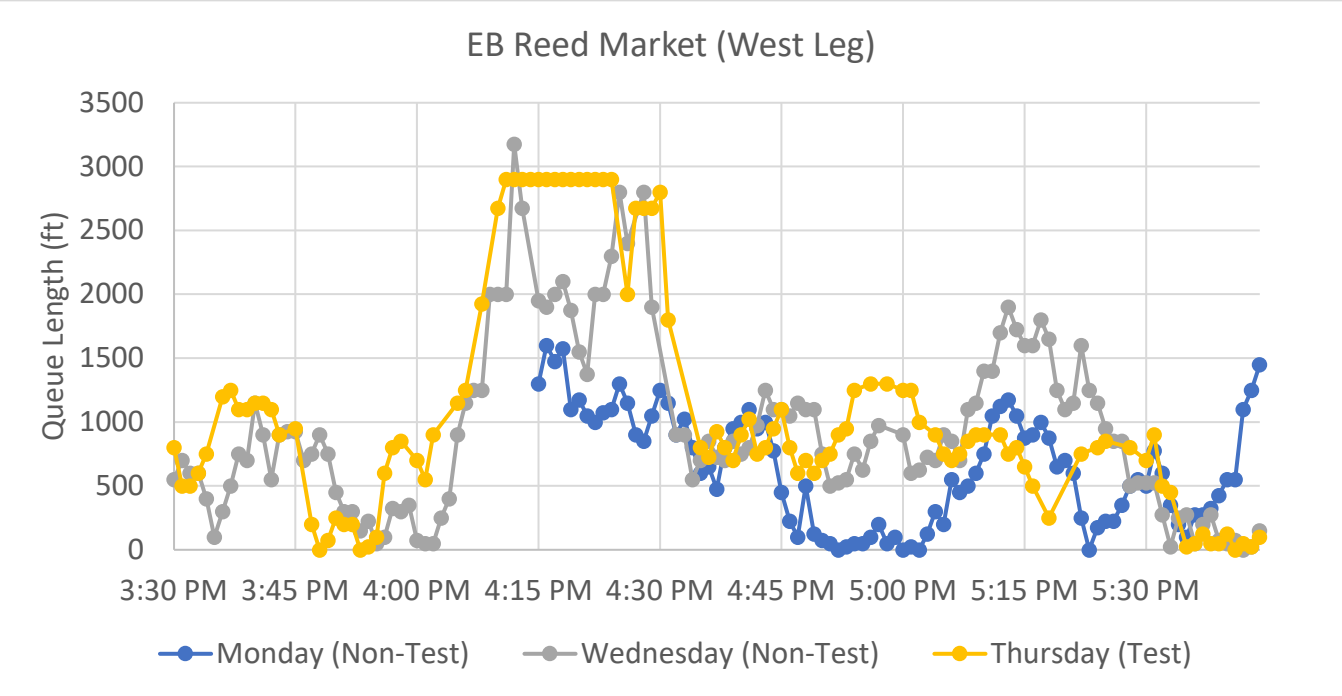


Figure 14 - PM Eastbound Reed Market

CAPACITY

Under queued conditions, the entry flow processed at a particular roundabout entry is a direct measure of its capacity against a measured circulating flow rate. Volume from both non-test and test days were examined to see if any changes in capacity could be measured. These were also compared to two benchmarks: the capacity equation for single-lane roundabouts from the HCM 6th Edition, and the calibrated form of the equation adopted by the City of Bend.

For the AM peak period, the westbound Reed Market and northbound Brookswood entries experienced the most queuing and are plotted below in Figures 15-16. As the volumes increase during the morning peak, the westbound Reed Market entry reaches the capacities predicted by the HCM 6th Edition equation, and the southbound Brookswood entry reaches (and in some cases exceeds) the capacities predicted by the Bend calibration. In both cases, the scatter of data below and to the left of the curve represents non-queued conditions. Of note, no discernable difference can be detected between the non-test and test days, with the exception of a few capacities measured on one test day that exceed both prediction models. Overall, however, the metering signals did not produce a substantive and sustained change in entry capacity.

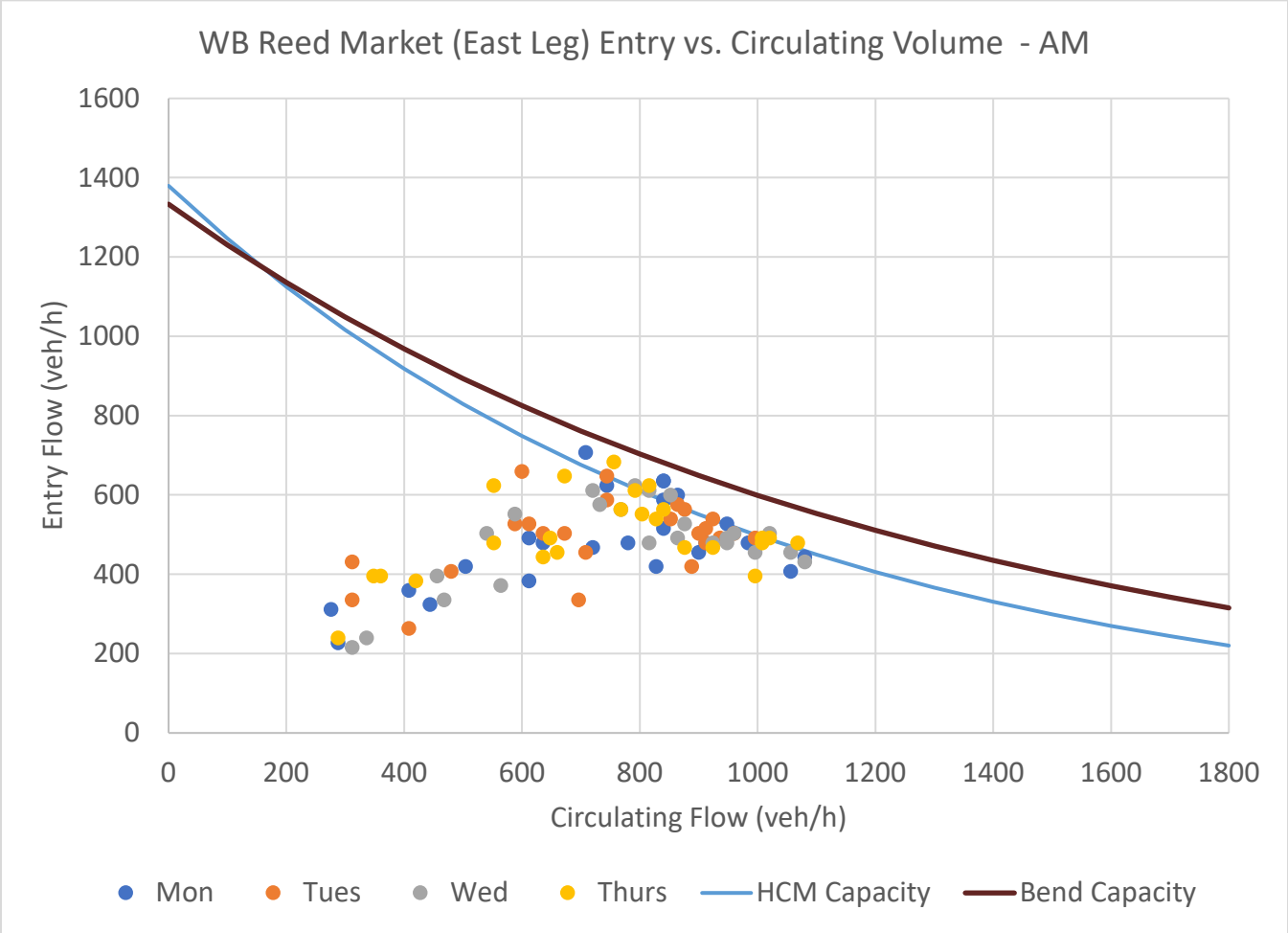


Figure 15 - WB Reed Market Entry vs. Circulating Volume - AM

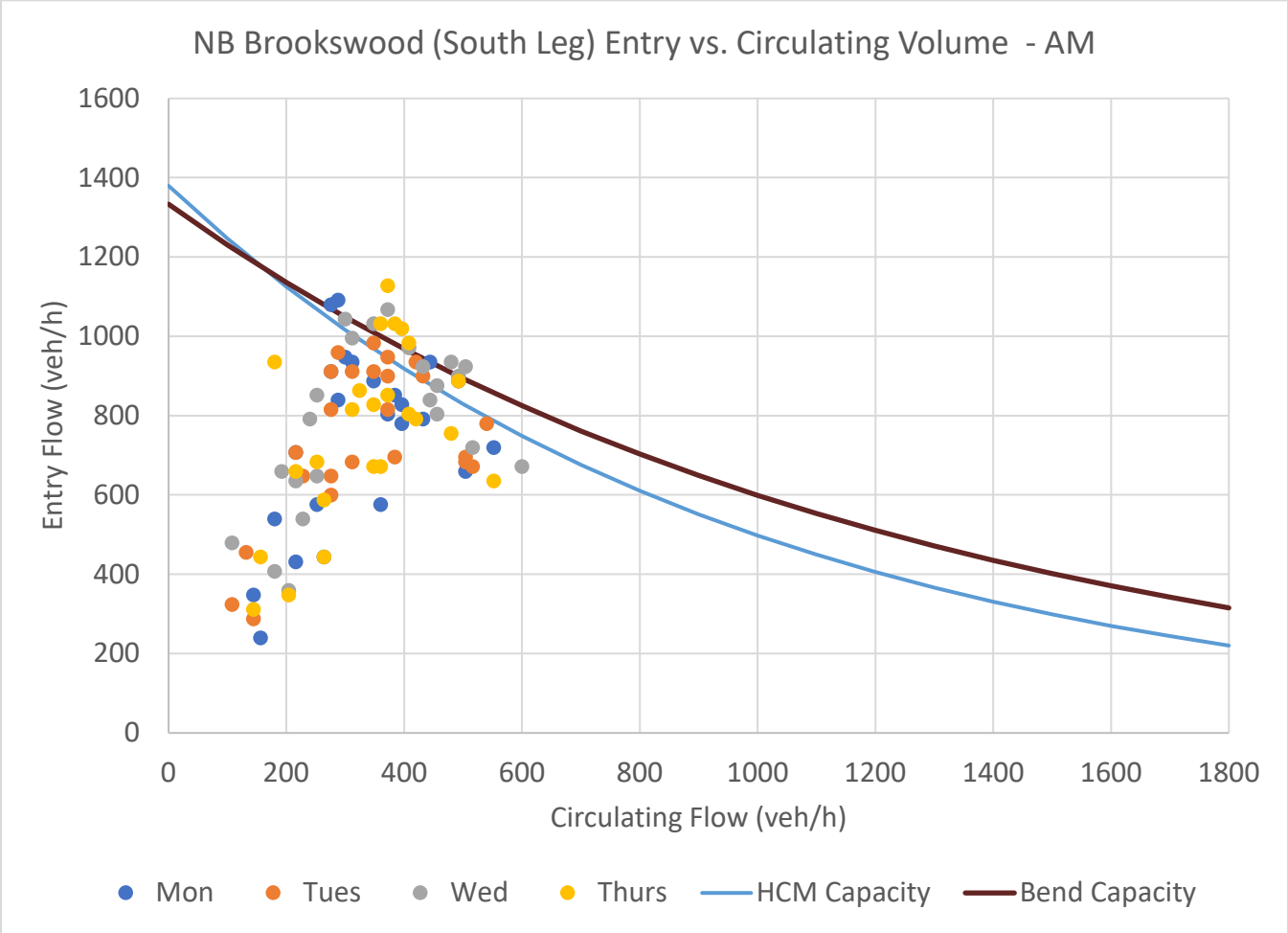


Figure 16 - NB Brookswood Entry vs. Circulating Volume - AM

For the PM peak period, the two approaches studied are the eastbound Reed Market and southbound Bend entries; these are plotted below in Figures 17-18. In both cases, measured volumes track closely with the HCM 6th Edition equation and below the Bend calibration. As with the AM peak, no discernable difference can be detected between the non-test and test days. As such, the metering signals produced no discernable change in entry capacity.

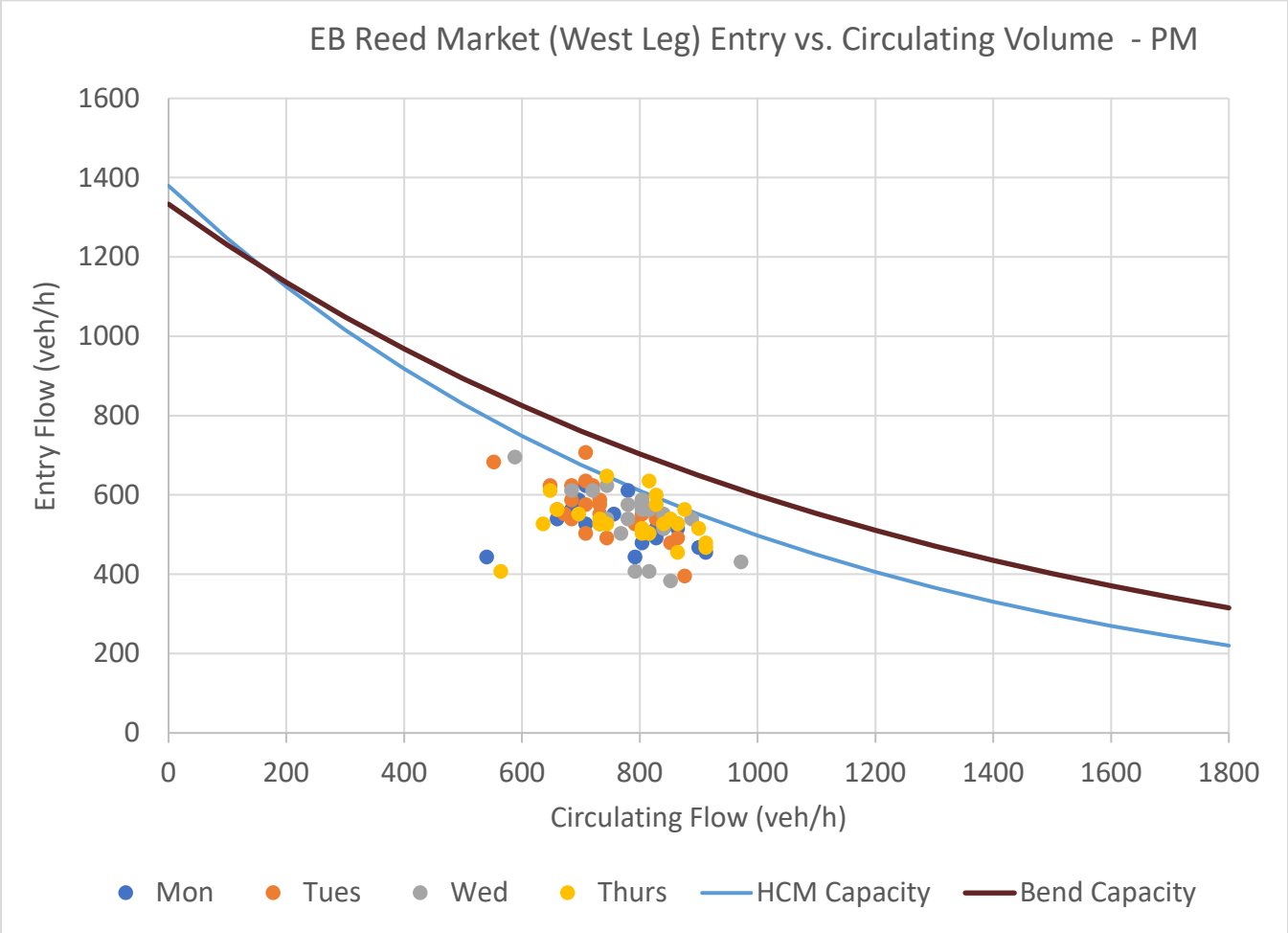


Figure 17 - EB Reed Market Entry vs. Circulating Volume - PM

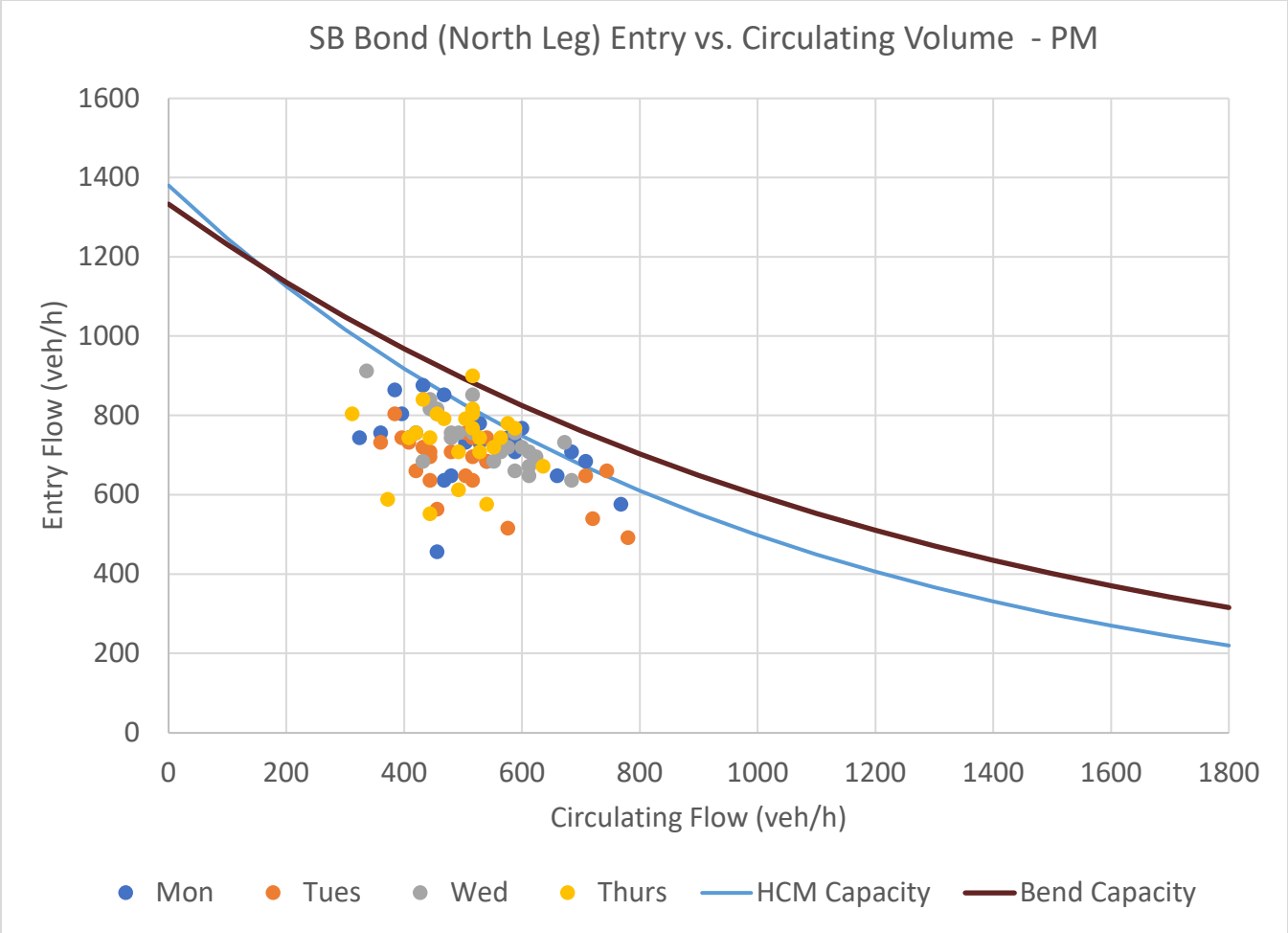


Figure 18 - SB Bond Entry vs. Circulating Volume – PM

CONCLUSIONS AND RECOMMENDATIONS

SUMMARY OF CONCLUSIONS

Based on the analysis in this memorandum, we find that the metering signals at the Bond/Reed Market/Brookswood roundabout were generally beneficial during the peak periods, particularly during the AM peak. However, careful attention to design details and metering signal logic will be needed to avoid creating unintentionally long queues.

Specific conclusions include the following:

- The metering signal operation produced no adverse safety outcomes. Drivers appropriately yielded at the roundabout to vehicles already in the roundabout and to pedestrians in the crosswalks, even if they had a green metering indication. Some drivers proceeded through a red indication, but these incidents did not result in incidents or erratic maneuvers.
- Queue clearance programs need to be initiated quickly to be effective, and they also need to be released quickly to avoid excessively negative effects to other approaches. The nature of the test limited the ability to test truly dynamic timing plans.

- The AM peak period benefits the most from metering due to the queuing challenge being mostly confined to two legs. The metering test demonstrated that it is possible to manage the queue on westbound Reed Market to minimize the likelihood of spillback into the Bend Parkway interchange, while keeping northbound Brookswood manageable.
- The PM peak period is more challenging to meter. A key lesson is that metering needs to begin early enough to keep queues from growing too quickly; this is especially critical on southbound Bond. Metering is limited in its ability to handle simultaneous heavy surges on both southbound Bond and eastbound Reed Market due to the fixed capacity where these two flows join (the eastbound Reed Market entry).
- Metering on more than two approaches, which is what was tested, may be necessary during parts of the day.
- Capacities remained essentially the same with or without metering. There was no measurable increase in throughput during metering operations. The observed improvements were primarily in the managing of queues.

RECOMMENDATIONS

Based on the findings of this evaluation, we recommend the City advance the metering concept into design and implementation. Our recommendation is based on the following benefits:

- The pilot test showed the ability to manage queues using metering signals. More dynamic and developed timing strategies will be more responsive to fluctuations in demand than were able to be replicated during the pilot test.
- The most critical need for queue management from a safety standpoint is during the AM peak when there is a potential for queues to extend onto the Bend Parkway. The pilot test demonstrated the ability to mitigate this queue.
- The implementation of metering signals is estimated to cost significantly less than additional lanes and would not require any right-of-way to be acquired.
- By using metering signals, the City can manage demand during the peak periods while maintaining the safety advantages of a single-lane roundabout throughout the day.
- The above benefits notwithstanding, the benefit of meters may diminish over time as the durations of overcapacity periods increase throughout the day. However, the use of metering signals does not preclude the selective implementation of capacity improvements (e.g., the addition of right-turn bypass lanes) in the future and could be paired with and supportive of capacity improvements.
- Metering signals provide an opportunity to integrate emergency vehicle preemption and improve response times through the intersection. The signal infrastructure would be useful for this purpose even if additional lane capacity is added in the future.
- Metering signals could be used to manage traffic under special circumstances, such as special event traffic or evacuations.
- If additional lane capacity is added in the future and the meters are deemed unnecessary for managing vehicular demand, the equipment and infrastructure could potentially be repurposed (e.g., enhanced pedestrian crossings).
- The metering signals have the potential to provide near-term congestion reduction and defer the more significant investment in the addition of lanes while the City considers potential network improvements (e.g, the Aune Street connection to the Old Mill District or expanded river crossings) that may alter the demand at this intersection.

If the City decides to move forward with the implementation of metering signals, the next phase will be design and logic development. The following aspects are recommended in the design phase:

- The design will include locations of the signal heads, stop bars, signs, and other physical aspects of the metering signals, as well as careful placement of detection to support the dynamic logic needed for the metering.

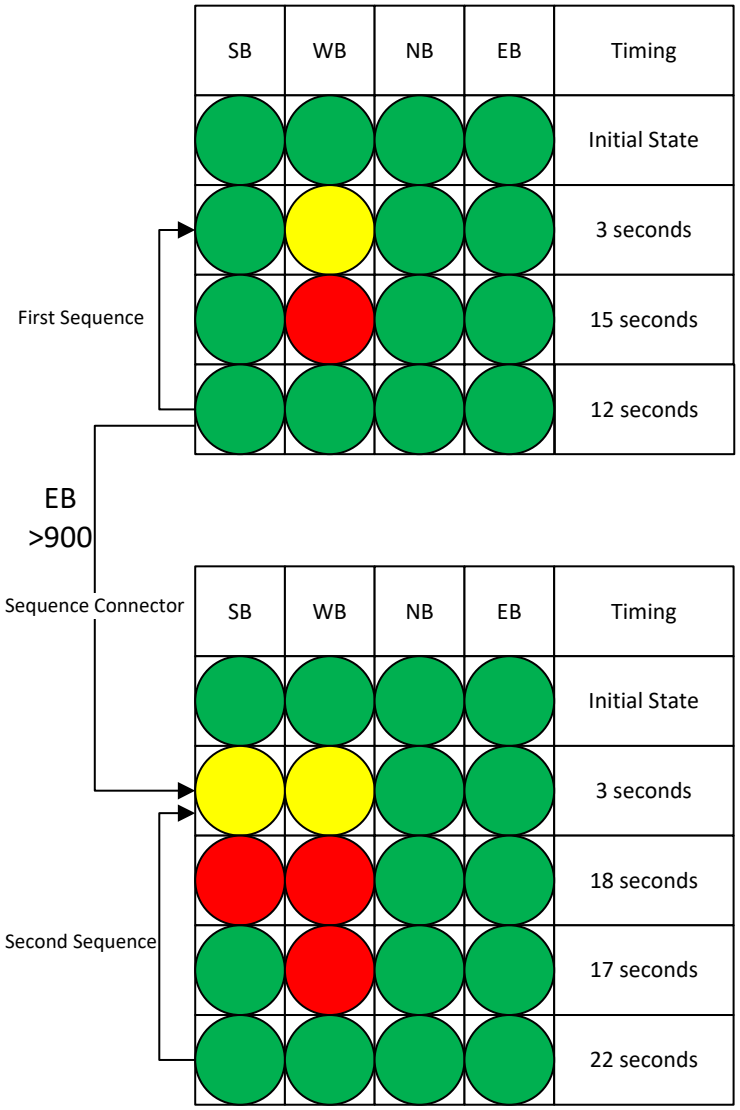
- The logic development for the metering signals should include both programming and simulation of dynamic logic. While a simulation model has already been analyzed before the field test, more simulation will be needed for the logic development. This simulation model can be used as a base, but a few changes will need to be made. First, the signalization logic should be programmed using Software-In-the-Loop (SIL), so the software being programmed can be directly implemented in the field. Some changes to calibration parameters may be valid given the data collected during the field test.
- Finally, emergency vehicles might be considered during this phase to help improve the pre-emption logic that will be field implemented. This was not tested during this testing scenario but is part of the overall design concept.

REFERENCES

1. Transportation Research Board (TRB). *Highway Capacity Manual, 6th Edition.* TRB, Washington, DC, 2016.

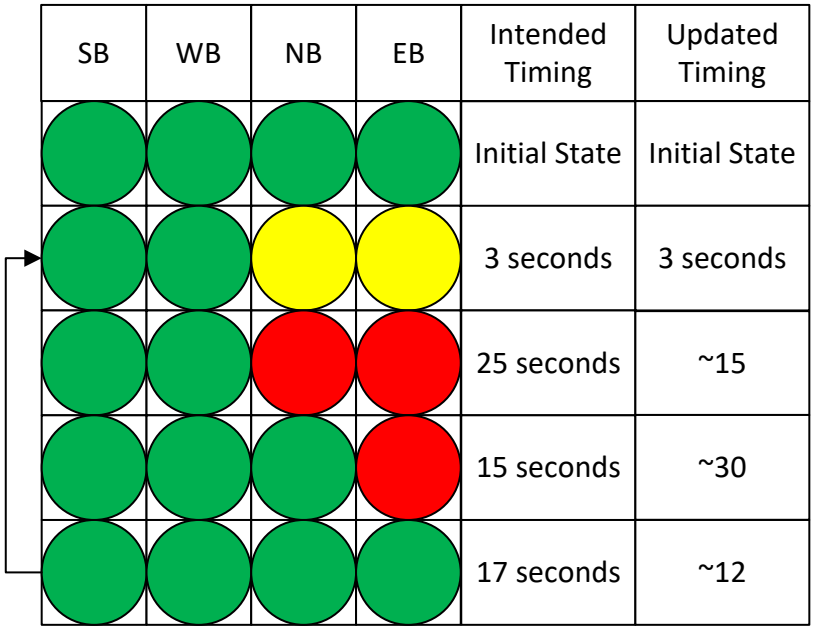
APPENDIX A – METERING PLAN AND FIELD ADJUSTMENTS

PM Day 2 (Thursday)



3:37 – Sequence 2
3.39 – Sequence 1
3:41 – 1 cycle green WB
3:42 – Sequence 2
3:46 – Sequence 1
3:47 – 2 cycle green WB
3:56 – Sequence 1
3:56 – Sequence 2
3:58 – Sequence 1
4:04 – Sequence 2
4:17 – 1 cycle green SB
4:30 – 1 cycle green WB
4:33 – Sequence 1
4:37 – Sequence 2
4:38 – 1 cycle green WB
4:44 – 1 cycle green WB
4:45 – Sequence 1
4:54 – Sequence 2
5:02 – 1 cycle green WB
5:02 – Sequence 1
5:26 – Sequence 2 for 2 cycles
5:31 – WB Green hold

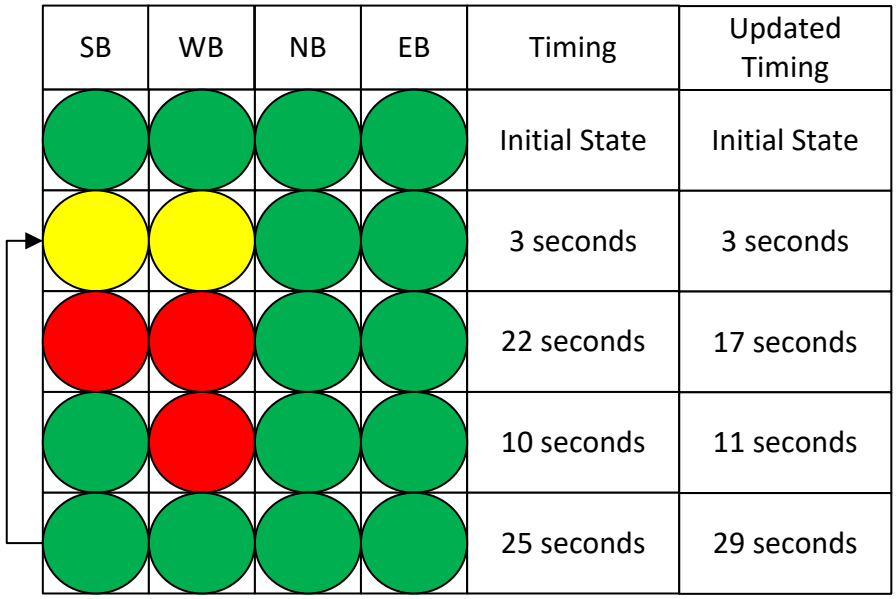
AM Day 1 (Tuesday)



SB	WB	NB	EB	Intended Timing	Updated Timing
				Initial State	Initial State
				3 seconds	3 seconds
				25 seconds	~15
				15 seconds	~30
				17 seconds	~12

7:45 – Green Increase northbound and Red increase Eastbound (approximate new values in Updated timing column
8:15 – Long Flush (Green Hold) northbound

PM Day 1 (Tuesday)

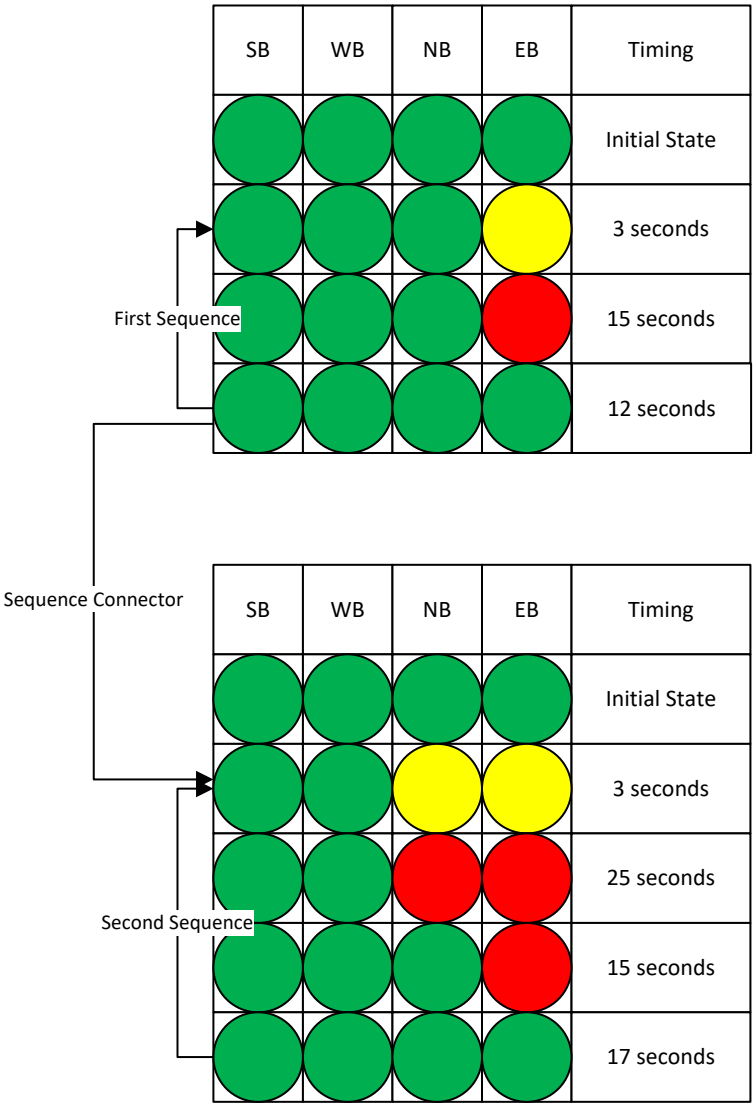


SB	WB	NB	EB	Timing	Updated Timing
				Initial State	Initial State
				3 seconds	3 seconds
				22 seconds	17 seconds
				10 seconds	11 seconds
				25 seconds	29 seconds

4:24 – 2 cycles green WB
4:33 – 1 cycle green SB
4:37 – 2 cycles green WB
4:37 – 4 seconds add Green WB
4:44 – 2 cycles green WB
4:48 – 1 cycles green SB
4:51 – 1 cycle green SB
4:55 – 2 cycles green SB
5:00 – 1 cycle green SB
5:03 – reduce red 5 seconds SB
5:12 – 2 cycle green SB
5:20 – 2 cycle green WB
5:25 – 2 cycle green WB
5:28 – 2 cycle green SB
5:33 – 1 cycles green SB
5:37 – Green hold SB

*final timing shown in updated timing column.

AM Day 2 (Thursday)



8:02 – NB Seq 2 start
8:07 – NB Seq 1
8:17 – Sequence 2
8:27 – Sequence 1
8:30 – Sequence 2
8:32 – Sequence 1