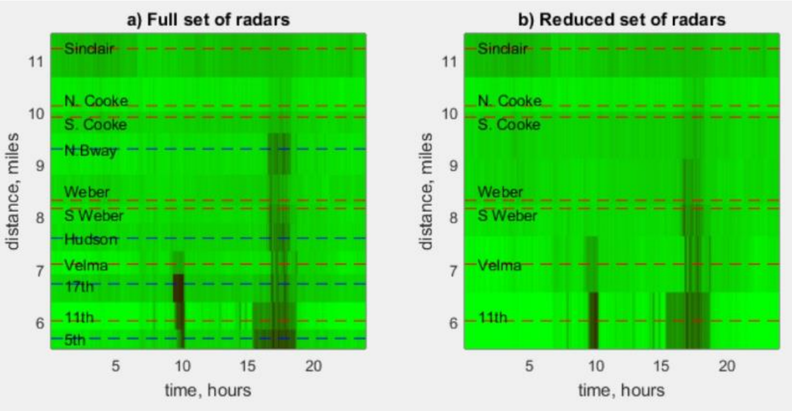
Investigating the Feasibility of Coordinated Ramp Metering Along Freeway Corridors in Ohio



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16. Abstract

Freeway corridors in most of Ohio’s major cities exhibit recurring and non-recurring congestion. Traffic responsive metering is particularly attractive due to its ability to dynamically respond to the inevitable fluctuations in traffic. ODOT has ramp meters in operation on two urban freeway corridors in the state. However, performance of these meters in the field and their efficacy at managing congestion was unknown at the start of this study. This research pursued several objectives: (1) assessing the performance of the current system, (2) ensuring good performance from a traffic responsive metering system, (3) investigating the operation of the coordinated ramp metering system, and (4) work with ODOT to improve the performance of the ramp metering system.

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Executive Summary

Freeway corridors in most of Ohio's major cities exhibit recurring and non-recurring congestion. This congestion imposes excessive delay on both commuters and commercial transport, with negative impacts in terms of fuel consumption and vehicle emissions. Ramp metering is an important tool for controlling the flow into the freeway to mitigate or even prevent the freeway congestion. Ramp meters might be set to time of day operations, controlled remotely, or respond to the traffic. Traffic responsive metering is particularly attractive due to its ability to dynamically respond to the inevitable fluctuations in traffic. ODOT has ramp meters in operation on two urban freeway corridors in the state. These meters run either according to a daily schedule or under locally traffic responsive plans, where the meter operates according to the occupancy sensed by a remote traffic microwave sensor (RTMS) unit typically placed about 500 meters upstream of the ramp of interest. Meters are currently programmed to respond to a trigger of mainline occupancy whenever occupancy values climb above a certain threshold. However, performance of these meters in the field and their efficacy at managing congestion was unknown at the start of this study. This research pursued several objectives: (1) assessing the performance of the current system, (2) ensuring good performance from a traffic responsive metering system, (3) investigating the operation of a coordinated ramp metering system, and (4) work with ODOT to improve the performance of the ramp metering system.

Most of the existing ramp metering schemes are designed to use occupancy as the input because occupancy is the most reliable measure of traffic state from single loop detectors. But ODOT has moved away from loop detectors. It would be cost effective to consider the out-of-pavement data sources that ODOT already has, including SpeedInfo and INRIX; though, both of these systems have their own idiosyncrasies that would need to be worked around. It is also important to keep in mind that the performance of ramp metering depends on the objectives, e.g., ramp metering at low levels serves to break up platoons entering from traffic signals even if it does not reduce the net inflow to the freeway. This study consists of the following six tasks, with the major findings of this study listed by task:

Task 1: Assess the performance of the current system

Based on the data available to us, the system is generally in good shape. The largest problem was already known, that of non-operational radar sensors. Obviously, whenever the sensors are not providing valid data, the system cannot respond to the traffic conditions.

Task 2: Quantify the performance of the existing ramp metering system

We investigated the performance of the existing system. Here too, the system is generally in good shape. However, ODOT should consider special treatment to respond differently to recurring congestion and non-recurring congestion. Another factor that should be examined is how to adapt the ramp metering algorithm when one or more radar sensors are not operational.

Task 3: Work with ODOT to assess the importance of any system deficiencies

While we looked for major system deficiencies, none were found beyond those listed under the other tasks.

Task 4: Work with ODOT to improve the existing ramp metering system

One potential limitation of the existing ramp metering system is that it is memory-less. So the metering rate for the next cycle comes strictly from the most recent recorded conditions during the previous cycle. This task examined ways of reducing the volatility of the occupancy measurements using various forms of low pass filtering. We also considered the use of speed data from INRIX or the legacy SpeedInfo systems. Unfortunately, these systems only report speeds while the current ramp metering system only uses occupancy, so this work also developed a simple approach to convert from speed to occupancy.

Task 5: Investigate the benefits of the coordinated ramp metering system

This task explored several ideas to improve the service of the ramp metering system that are beyond the current capabilities of the existing system.

Task 6: Meetings with ODOT, quarterly reports, final report, and all other reporting

This task consists of regularly scheduled and impromptu meetings with ODOT, compiling information and documenting our research for the various reports.

1 Project Background

Freeway corridors in most of Ohio's major cities exhibit recurring and non-recurring congestion. This congestion imposes excessive delay on both commuters and commercial transport, with negative impacts in terms of fuel consumption and vehicle emissions. The pattern of congestion depends on the roadway geometry. Typically, inbound (morning) congestion exhibits the worst conditions at the upstream end of the queue since as one moves upstream from the bottleneck each successive on-ramp consumes a portion of the capacity that would otherwise be available further upstream. By the same logic, often the inbound bottleneck will form shortly upstream of an add lane, where capacity increases. While the outbound (evening) congestion often exhibit the opposite pattern, with the worst conditions occurring near the bottleneck in the case of a lane drop, since after each successive off-ramp a larger percentage of the traffic is bound for the capacity-limited flow at the bottleneck.

Ramp metering is an important tool for controlling the flow into the freeway to mitigate or even prevent the freeway congestion. More aggressive metering systems severely limit inflow to preserve high-speed conditions while others may only serve to break up platoons of entering vehicles so that merging is safer and more efficient. Ramp meters might be set to time of day operations, controlled remotely, or respond to the traffic. Traffic responsive metering is particularly attractive due to its ability to dynamically respond to the inevitable fluctuations in traffic. The simplest form of traffic responsive ramp metering relies upon a sensor at the metered ramp to determine the target inflow rate, i.e., the metering rate. While local responsive metering can achieve some local optimal outcome, as noted above, conditions at a given location also depend on the inflows and outflows far upstream and downstream of that location. Which leads to corridor wide coordinated ramp metering that seeks to balance the demands throughout a corridor to provide a more comprehensive control scheme.

ODOT has ramp meters in operation on two urban freeway corridors in the state. A communications network is also in place that allows ODOT personnel to remotely control and monitor the meters. Not all interchanges in these corridors are metered. Existing meters run either according to a daily schedule or under locally traffic responsive plans, where the meter operates according to the occupancy sensed by a remote traffic microwave sensor (RTMS) unit typically placed about 500 meters upstream of the ramp of interest. Meters are currently programmed to respond to a trigger whenever mainline occupancy values climb above a certain threshold. Each RTMS unit reports speed, occupancy and flow at 20 second intervals to the given ramp meter controller. These data are also supposed to be available to the TMC, but for the duration of the study the reporting to the TMC was unreliable and most of the data never came through, precluding performance analysis and suggesting the possibility that the controller itself is not receiving all the necessary data. However, performance of these meters in the field and their efficacy at managing congestion was unknown at the start of this study. This research pursued several objectives: (1) assessing the performance of the current system, (2) ensuring good performance from a traffic responsive metering system, (3) investigating the operation of the coordinated ramp metering system, and (4) work with ODOT to improve the performance of the ramp metering system.

2 Research Context

Ramp metering has been a topic of extensive research since the first experiments in Chicago during the 1960's. Ramp metering has become standard practice in many forms. As mentioned above, there are four basic types of ramp metering: time of day, manually set, locally traffic responsive, and coordinated ramp metering. This work is focused on the latter two forms. In terms of the traffic responsive metering the issue for this study is not so much the theory of metering per se, but the data quality and evaluating whether the meters are doing what they are supposed to be doing. In the absence of independent measures (as well as lack of access to the actual measures), it is not possible to assess the state of the system, but it is known that inaccurate data will degrade performance. Such applied problems rarely get published in the literature, and to the extent that there are relevant publications, the focus is on detector performance rather than ramp metering. This type of applied work is about finding the right combination of resources to solve the problem in the most cost effective manner.

Coordinated ramp metering is an active research area that seeks to exploit the benefits of coordination between ramp meters. Perhaps the most prominent coordinated ramp metering algorithm is HERO (Papageorgiou et al., 2006; Papamichail and Papageorgiou, 2008; Papamichail et al., 2010; Bhouri et al. 2013) that coordinates across local ALINEA ramp metering deployments (Papageorgiou et al., 1991; Papageorgiou et al. 1997). Though there have been numerous other coordinated ramp metering deployments, including Portland, Oregon (Ahn et al., 2007), the Twin Cities in Minnesota (Cambridge Systematics, 2001; Hourdakis and Michalopoulos, 2002), and Denver, Colorado (Lipp et al., 1991) to name a few. All of the coordinated ramp metering schemes require real time data from the field, typically with at least one detector station per on-ramp. If anything, compared to local responsive systems these coordinated systems are even more dependent on accurate data. These schemes were first developed via theory and simulation assuming near perfect traffic detection, and thus, once deployed they do in fact need such near perfect traffic detection.

Most of the existing ramp metering schemes are designed to use occupancy as the input because occupancy is the most reliable measure of traffic state from single loop detectors. But ODOT has moved away from loop detectors. The RTMS does a poor job emulating loop detectors on a per vehicle basis (Coifman, 2006) but can do a sufficient job in aggregate (Coifman, 2005). It would be cost effective to consider the out-of-pavement data sources that ODOT already has, including SpeedInfo (Kim and Coifman, 2017) and INRIX (Kim and Coifman, 2014); though as noted in the cited works, both of these systems have their own idiosyncrasies that would need to be worked around but do not preclude their use (e.g., both exhibit a lag between the actual observations in the field and when they are reported, and at any given moment the INRIX data might be imputed rather than actually measured). It is also important to keep in mind that the performance of ramp metering depends on the objectives, e.g., ramp metering at low levels serves to break up platoons entering from traffic signals even if it does not reduce the net inflow to the freeway. On the other hand, if some ramps have meters and some do not, that will incentivize drivers to go to the latter. Here too, at low levels of metering the benefits probably will not cause many drivers to switch on-ramps, but as the ramp delays increase it will likely become necessary to add meters to all on-ramps. Fortunately, that investment does not need to come up front and this approach offers the ability to only add what is needed, when it is needed.

This study consists of the following six research tasks:

Task 1: Assess the performance of the current system

The state and performance of the existing ramp meters was not fully known. So, the first task of this research was to gather information on the performance of the system. This task employed the existing sources of traffic data, which included the RTMS sensors used for responsive ramp metering and INRIX traffic data.

Task 2: Quantify the performance of the existing ramp metering system

With the traffic data in hand, we assessed the congestion in the currently metered corridor from the traffic data. The delays were quantified at the finest resolution available from the data, at a per-junction level for the RTMS used in the existing metering scheme and a finer resolution for the INRIX traffic data.

Task 3: Work with ODOT to assess the importance of any system deficiencies

There are many potential problems in the ramp metering system, ranging from the inability to use traffic responsive ramp metering in the absence of the necessary traffic monitoring infrastructure, to the possibility that the RTMS sensors are not performing as specified. The impact of the challenges could be small, e.g., perhaps the time of day metering is sufficient for the ramps involved, and perhaps the RTMS are providing sufficient data to the respective controllers in the field even if they are not transmitting those data to the TMC. Or they could be large, e.g., perhaps the time of day metering is degrading the performance of the entire corridor. We worked with ODOT to value and prioritize any deficiencies in the existing system that were found in the course of the study.

Task 4: Work with ODOT to improve the existing ramp metering system

The analysis in Task 2 revealed which interchanges are performing as desired and which are not. Our analysis included a spatiotemporal factor, since congestion at one location typically arises in response to increased demand from upstream or reduced capacity downstream. This task sought to provide a tune-up for the existing system, e.g., to assess whether the time of day meters should be adjusted to come on at a different time of day or establishing new criteria to determine when to activate the manually activated meters.

Task 5: Investigate the benefits of the coordinated ramp metering system

This task used the data collected for the other tasks to help ODOT evaluate and improve the ramp metering scheme. Given the practical realities of the roadside environment, priority was given to robustness over complexity. Furthermore, with the shift to out-of-pavement measurement, there is an opportunity to revisit the ramp metering paradigm and re-cast it in terms of those measures readily available from the newer sensor technologies employed by ODOT, e.g., SpeedInfo and INRIX. So rather than rely on accurate measurements of occupancy at a handful of detector stations to determine the ramp metering rates, it could prove to be far more beneficial to assess speed throughout the corridor as the primary trigger to determine metering rates.

Task 6: Meetings with ODOT, quarterly reports, final report, and all other reporting

This task consiststed of regularly scheduled and impromptu meetings with ODOT, compiling information and documenting our research for the various reports.

3 Research Approach

3.1 Task 1: Assess the performance of the current system

The state and performance of the existing ramp meters was not fully known at the start of this project. So the first task of this research was to gather information of the system. The work used speed, flow, and occupancy from the operational radar sensors used for traffic responsive ramp metering in the I-71 corridor between I-670 and I-270. The work also used INRIX speed data for validation. See Appendix A for a report on Task 1 submitted during the study.

Two types of data were used to perform task 1. The first data set used is the INRIX speed data which is available for the entire length of I-71 in Columbus for any time period over the past several years. The second data set used is the radar data downloaded on an on-demand basis and furnished to us by ODOT. We worked with radar data from two time windows. The first time window is Oct. 27th to Nov 27th, 2017 (referred as the November data set) and the second time window is Feb. 12th to Mar 12th, 2018 (referred as the March data set). The November data set has data from five radar sensors in both northbound (NB) and southbound (SB) directions. These ten directional radar sensors were the only ones operational in the corridor at the time. The March data set is more comprehensive with data from 12 radar sensors in the NB direction and from 10 radar sensors in the SB direction.

It appears that some of the radar stations have their directions reversed in the data archive (e.g., 17th Ave in the most recent radar data set, and S. Weber in the older data set). Fig. 1 shows the speed summary plots generated the operational radars on I-71 on a typical day from the March data set. These summary plots show the speed by shade (dark = slow, light = fast) as a function of distance (along the vertical axis) and time (along the horizontal axis) for the corridor over 24 hrs. For the NB summary plots, traffic moves from bottom to top, while in the SB plots, the traffic moves from top to bottom. The NB summary plot from the radar shows evening congestion (dark region after 13:00 at the bottom of the plot) upstream of the lane drop at 11th Ave. The plot also shows an unexpected bit of NB congestion around 9:00 at the 17th Ave radar sensor. Compared to the corresponding plot from the INRIX data, the afternoon congestion is consistent, but the morning congestion is absent. The SB summary plot from the radar shows morning congestion upstream of the add-lane at 11th Ave. Once more the radar plot is consistent with the INRIX plot, with the exception of 17th Ave. It appears that the directional data at 17th Ave is reversed in the data archive, and after swapping directions at this site the correspondence with the concurrent INRIX data has greatly improved. This error was consistently observed at 17th Ave in the March data set. A similar error was observed at S. Weber in the November data set, however, in that case it was not consistent, the directional swapping error would be present one day and gone the next. If these errors are present in the archive, care should be taken to make sure that the errors are only limited to the data archive so that similar errors are not impacting traffic control.

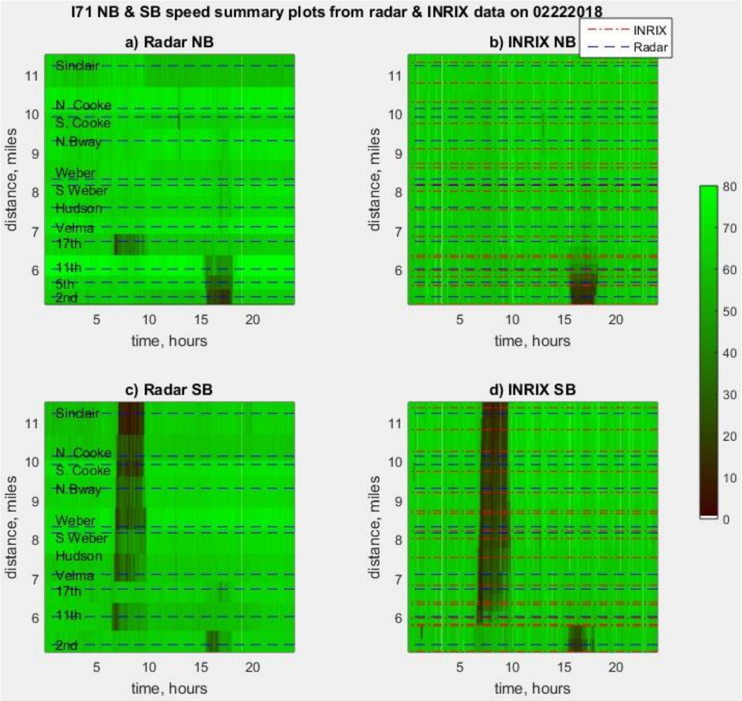

Figure 1, I71 NB & SB speed summary plots for radar and INRIX data on 02222018. Radar data plots are on the left, concurrent INRIX data plots on the right, NB on the top with traffic moving upwards, SB on the bottom with traffic moving downwards

In addition to the reversal of directions in the archived data, for the November data set, it appears that the radar at S Weber consistently overestimates the flows and occupancies by about 1.5 times larger than the flows at the neighboring locations in spite of no major off-ramps downstream of S Weber. On a similar note, the flows at this radar are overestimated in the SB direction as well. The overestimation of flows also appears to happen at S Weber and North of North Broadway radars as observed from the March data set (see section A.3.2 in the appendices).

Assessment of the working of the ramp metering algorithm formed a major portion of this project. The algorithm as employed currently by ODOT takes the occupancy data from a few radars either at the ramp meter location or downstream as inputs and gives a metering rate to regulate the traffic entering from the on-ramp into the study corridor. In order to assess the performance of the radar, it will be pertinent to compare the metering rates that the algorithm suggests with the actual metering rates that were implemented. While we requested the event log of the metering rates from the ramp meters, ODOT was not able gather these data.

3.2 Task 2: Quantify the performance of the existing ramp metering system

We examined the performance of the corridor over an extended period of time to understand the dynamics in the corridor. On most days with congestion there was an extended bottleneck that formed in the vicinity of 11th Ave in both directions. See Appendix B for a report on Task 2 submitted during the study.

The metering rates as calculated by the existing ramp metering algorithm employed by ODOT can vary due to different factors and this section examines the sensitivity of the metering rates as a function of three important factors. First, the ramp metering algorithm calculates rates as a function of the mainline occupancy, but the occupancy varies as a function of speed. Secondly, the existing algorithm calculates the metering rates as a function of the weighted occupancy of the sensors downstream of the ramp meter with the weights typically varying inversely as the distance of the sensor from the ramp meter. So, the meters are more sensitive to congestion close to the onramp; however, in many cases it might prove desirable to start metering before queues from further downstream grow back to the onramp. Thirdly, the calculated metering rates from the existing algorithm could vary depending on the number of radars that are operable at the moment. Yet in November 2017, several radar sensors were inoperable, so it is important to understand how the ramp metering algorithm behaves given degraded inputs due to one or more radar sensors being off line.

Fig. 2a shows the NB speed profiles generated from INRIX data for 26 weekdays in November 2017 and February 2018 and it can be seen that there are three distinct groups emerge. Fig. 2b shows the speed profiles generated from the median speed at a given location for the three groups shown in Fig. 2a, representing strictly free flow (profile 1), a recurring bottleneck at 11th Ave. (profile 2), and a recurring bottleneck at Cooke Rd. (profile 3). Synthetic profiles 4-6 are generated from the profiles 1-3, respectively, to simulate a hypothetical incident near the Hudson St. onramp. The metering rates are calculated for the ramp meter at the 11th Ave on-ramp for the six speed profiles in Fig. 2b using the weights currently used by ODOT for the six detectors currently used by the ramp metering algorithm. The six (full set of) downstream radar detectors are at 11th Ave, 17th Ave, Velma, Hudson, S. Weber and Weber. While there were more than six INRIX detectors that were spanning the length covered by the full set of radars, the speeds at the six radar locations were interpolated from the INRIX speed profiles given in Fig. 2b. As an example, Fig. 2c shows the estimated occupancies using the occ-v relationship given in Section 3.4 for the six speed profiles in Fig. 2b. The curves are only shown for the region covered by the six radar detectors that are used to set the metering rate at the 11th Ave. meter. Fig. 2d repeats this process except the window is shifted upstream to the 5th Ave. onramp.[1] Once the occupancies are calculated, the corresponding ramp metering rates can be found from the look-up table that the ODOT uses, as given in Table 1.

Each of the speed and occupancy profiles in Fig. 2b-d captures a static state, but that state is representative of traffic conditions with or without the various recurring and non-recurring bottlenecks, i.e., there will be small fluctuations from one sample to the next, but the overall state should not change much if we looked at successive measurements. The point of this exercise is to illustrate how the metering rates change in response to large deviations (e.g., between "no active bottlenecks" and a non-recurring incident).

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[1] The treatment at 11th Ave. follows the metering algorithm in place, whereas the treatment at 5th Ave. deviates from the current algorithm. In reality the ramp meter at 5th Ave only uses five radar sensors, one of which is not shown on the schematic because we never had data from that sensor. The modification is done to illustrate the impacts on the metering rates when recurring queues interact with non-recurring queues. For this illustration, we use the weighting from the 11th Ave ramp meter.

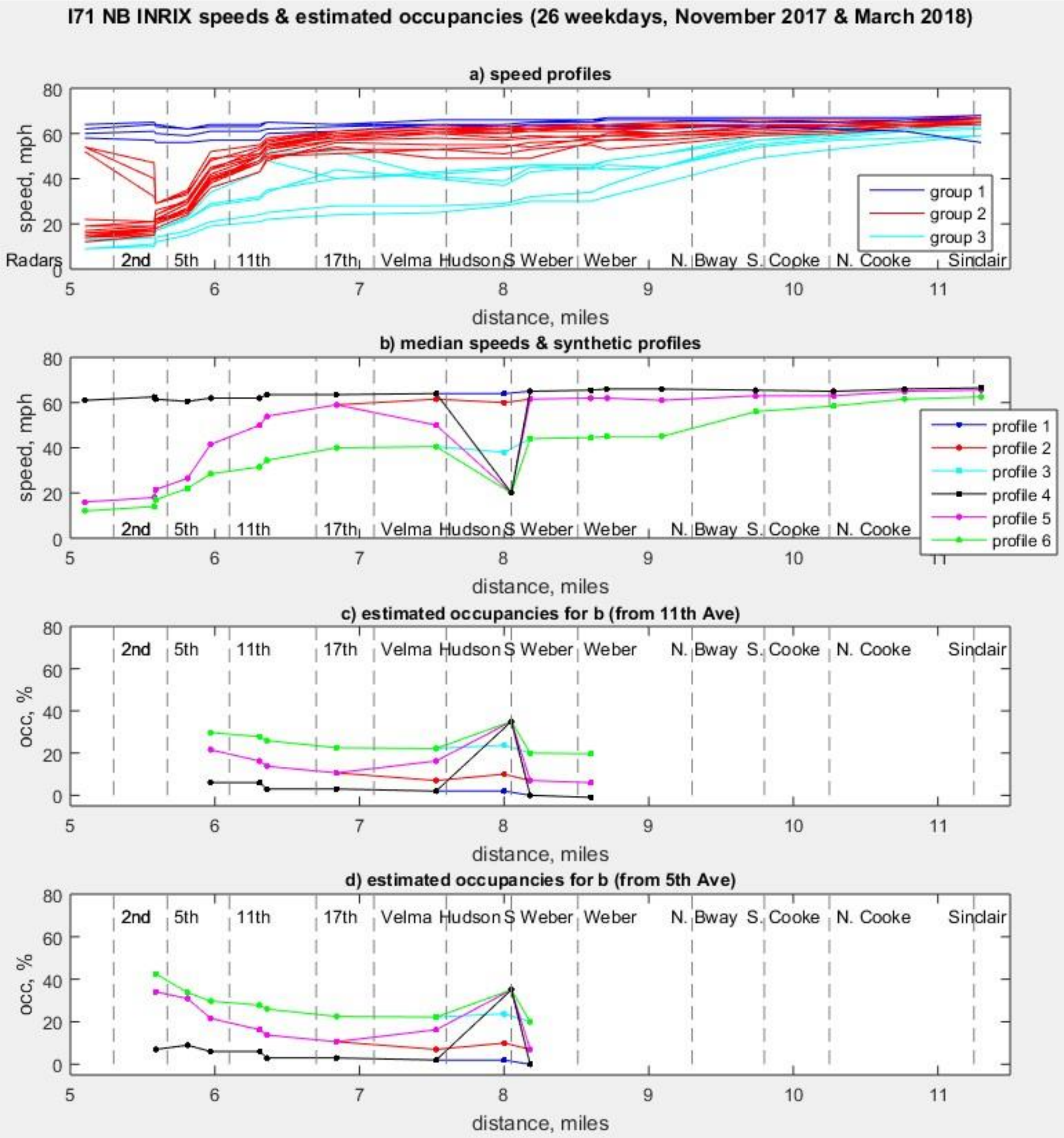

Figure 2, I71 NB a) speed profiles along the corridor using INRIX data for 26 weekdays in November 2017 and March 2018, b) six speed profiles generated as the group-wise median at a given location for the three groups in part a and three synthetic speed profiles to simulate an incidents near the radar detector at Hudson Street, c) estimated occupancies for the six speed profiles seen in part b over the spatial range used to establish the metering rate at 11th Ave, d) repeating part c only shifting upstream by one radar detector.

Table 1, Central Ramp Metering Rates

Occupancy (%)	**Metering Rate (vph)**
14	No action
15	1150
17	1025
19	900
21	775
31	650
33	475
35	300

To assess the impact of the different speed profiles on the metering rates metering rates were first calculated for the current weights (weighting scheme 1) used by ODOT at the 11th Ave on-ramp in the first row of Table 2 for the six occupancy profiles shown in Fig. 2c. The weights given in the second column are for the six radars from upstream to downstream in that order. The last six columns show the resulting metering rate for each of the six profiles. The meter is off for profiles 1 and 2 due to the high speeds (low occupancy) throughout the monitored section, while profile 3 has a metering rate of 775 vph due to the low speeds (high occupancy) throughout all six detectors. The meter is also off for profile 4 even though two of the distant radar sensors see the queue from the incident. In this case the weights are not large enough for the metering algorithm to respond. Profile 5 the combination of the elevated occupancy at the 11th Ave radar and the incident is enough for the ramp meter to turn on at 1025 vph, while profile 6 (superimposing the incident onto profile 3) does not change from the non-incident condition. The algorithm will not respond to queuing that is strictly downstream of the furthest detector at Weber. Some thought might want to be given to how to weight detectors depending on where they fall relative to recurring queues, e.g., perhaps a stronger response should be given to non-recurring congestion from profiles 4 and 5 by giving greater weight to detectors downstream of recurring queues (such re-weighting should likely be done in parallel to the existing weighting rather than in place of). In fact, to accommodate non-recurring congestion, it may be beneficial to also account for detectors further downstream (again, running in parallel rather than in place of the current weighting).

Table 2, Metering rates at 11th Ave as a function of different combinations when treating the speed profiles as instantaneous speeds at the respective locations. Note that in the reduced set "x" denotes a radar detector that is not operational and thus, is not included by the algorithm in the weighting scheme.

Weighting scheme	**Weights**	**Radars**	**Profile #**					
			1	**2**	**3**	**4**	**5**	**6**
1	(20, 18, 14, 6, 4, 2)	Full Set	N.A.	N.A.	775	N.A.	1025	775
2	(8, 10, 6, 6, 30, 40)	Full Set	N.A.	N.A.	775	N.A.	1025	775
3	(8, 10, 8, 8, 10, 30)	Full Set	N.A.	N.A.	775	N.A.	N.A.	775
4	(6, 6, 10, 8, 30, 40)	Full Set	N.A.	N.A.	775	N.A.	1025	775
1-R	(x, x, 14, x, 4, 2)	Reduced	N.A.	N.A.	775	N.A.	1025	775

Table 2 rows 2 to 5 explore different weighting schemes that give greater priority to the downstream radar sensors for the calculated ramp metering rate. Scheme 2 assigns the highest weights to the last two radars namely S. Weber and Weber, but because the highest weighted location is downstream of the incident it results in the same metering rates as scheme 1. Scheme 3 has the most even weighting across the detectors, with a slight bias to the furthest downstream detector (which again, is beyond the incident), so in this case the input is not enough to turn the meter in for profile 5. Scheme 4 is very similar to scheme 2 and yields similar results. Finally, to assess the impact of data outages on the metering rates, the last row in Table 2 uses the current weighting scheme of ODOT for the 11th Ave ramp meter but considers the data only from a reduced set of radars (Velma, S Weber & Weber) that were operable in November 2017. The six profiles yield results identical to scheme 1 because the three detectors that are off line generally did not see any of the recurring congestion.

Repeating this exercise at the 5th Ave meter, Fig. 2d shows that the on-ramp is now well within the recurring queue. For comparison sake to illustrate the interactions between the recurring and non-recurring queues we hold the weights constant to that at the 11th Ave meter, even though the actual weighting at 5th Ave is different. Table 3 shows that this time using the original weighting scheme the meters are off for profile 1 (no congestion), on for profile 2 and 3, which see high occupancy at the highest weighted detector, and then this pattern repeats for the three incident profiles because the queueing from the incident receives such little weight. In scheme 2 the shift to favoring the downstream detectors causes the meter to turn off for profile 2 (recurring bottleneck with the queue ending in the vicinity of the second radar detector) and a slightly less restrictive metering rate for profile 3 (moderate congestion throughout that slowly decreases as one moves downstream). In this case, the meters turn on for profile 4, where the queues are mostly at the downstream end where the weighting is most sensitive. scheme 3 and 4 are similar to scheme 2 both in terms of weighting and in terms of the resulting metering rates.

Finally, to assess the impact of data outages on the metering rates, the last row in Table 3 considers the data only from a reduced set of radars that were operable in November 2017. Although there is recurring queuing at the onramp, the ramp meter does not turn on for scheme 2 because none of this queuing is observable with the detectors off line. Profile 3 shows a less restrictive metering rate than when using the full set of scheme 1 because the most congested detectors at the upstream end are missing. Profile 4 does not respond to the incident, while profiles 5 and 6 respond more strongly to the incident than they did in scheme 1 because of the missing detectors.

This exercise has sought to demonstrate the negative impacts of missing data (e.g., scheme 1-R for profile 2 in Table 3) and the differing impacts between recurring and non-recurring congestion. By giving greater weight to the downstream detectors, schemes 2-4 in Table 3 showed the ramp metering responding to the non-recurring congestion in profile 4. It may prove beneficial to run different weighting schemes in parallel to separately look for recurring congestion (favoring closer detectors) and non-recurring congestion (favoring further detectors).

Table 3, Metering rates at 5th Ave as a function of different combinations when treating the speed profiles as instantaneous speeds at the respective locations.

Weighting scheme	**Weights**	**Radars**	**Profile #**					
			1	**2**	**3**	**4**	**5**	**6**
1	(20, 18, 14, 6, 4, 2)	Full Set	N.A.	775	650	N.A.	775	650
2	(8, 10, 6, 6, 30, 40)	Full Set	N.A.	N.A.	775	900	775	650
3	(8, 10, 8, 8, 10, 30)	Full Set	N.A.	N.A.	775	900	775	650
4	(6, 6, 10, 8, 30, 40)	Full Set	N.A.	N.A.	775	900	775	650
1-R	(x, x, x, 14, x, 4)	Reduced	N.A.	N.A.	775	N.A.	1025	775

3.3 Task 3: Work with ODOT to assess the importance of any system deficiencies

This task involved working with ODOT to assess system deficiencies such as inaccuracies, archiving errors and outages in the radar data. Task 1 involved assessing the performance of the current system and suggested ODOT to fix inaccuracies and archiving errors as the radar data are taken as inputs to the ramp-metering algorithm.

Even if these two deficiencies are fixed, data outages can still happen any time and have an impact on the metering rates calculated by the ramp-metering algorithm employed in the study corridor. In order to assess the impact of outages on the generated metering rates, it was necessary to understand the working of the algorithm to simulate the rates. As a first step towards understanding the algorithm, the location of the various ramp meters, the locations of the associated mainline radars for each ramp meter along with their weights were collected from ODOT. For each ramp meter, ODOT has a mapping scheme whereby each ramp meter bases its rate on few mainline sensors at the ramp meter location and a few sensors immediately downstream of the ramp meter. The algorithm generates the metering rates using a look-up table for weighted occupancy of all the radars associated with the ramp meter. Typically, the weights of a given radar sensor is inversely proportional to its distance from the ramp meter. This look-up table for occupancy-ramp metering rate for the central metering scheme was also collected from ODOT. The existing algorithm uses 1-min data and hence the metering rates are generated for every minute using the 1-min weighted occupancy.

Once the working of the algorithm was understood, a MATLAB program was written to simulate the algorithm. Using this program, metering rates for the ramp meters in the study corridor were generated for the March dataset with the full set of 22 radars. Similarly, the metering rates for the ramp meters in the corridor were generated for the March dataset with the reduced set of 11 radars that were operable in November. The results showed that the ramp metering rates differ depending on the number of radars that were available to provide data.

The impact of data outages on the metering rates also depend on the location of the ramp meter in question. The greatest impact of data outage will happen when a) the data from the closest radars (that have greater weight) are missing and b) the freeway at the ramp meter location experiences congestion that is not seen further downstream. Alternatively, the impacts were negligible if the data outage happens at a radar that is far (but still at a location that could influence speeds at the ramp meter location) and if the ramp meter is at a location that has relatively higher speeds. These inferences are valid only when we still use discrete occupancy-metering rate look-up table. This way, the importance of data outages was assessed and the possible impacts of outages on the ramp metering rates were ascertained.

3.4 Task 4: Work with ODOT to improve the existing ramp metering system

This section considers two advances that could improve the existing ramp metering system. First, the work considers simple low pass filters to smooth out the input occupancy data. Secondly, the work considers a means to convert INRIX speeds in to occupancy that could be input directly to the existing ramp metering algorithms.

Low-pass filters on metering rates

Low pass filtering is effectively a weighted average of recent measurements. This work only considers the simplest low pass filtering: longer sample periods, moving average, and exponential filtering. Generally low pass filtering sacrifices a little responsiveness to reduce volatility. Starting with our raw, 1 min occupancy data from a typical day for the northbound 11th Ave on-ramp using the data from the full set of radars on 21st Feb, 2018, Fig. 3a shows the resulting metering rates. The metering rates for a given sample are calculated from the occupancies reported from the most recently completed sample period. In fact the data we are using with 1 min sampling period is aggregated from the raw 20 sec sampled radar data that is not recorded by ODOT. Intuitively, a 1 min sample should be less volatile than the three 20 sec samples contained therein since a surge in the first 20 sec could cancel a lull in the second 20 sec. This less volatile 1 min sample comes at the cost of not updating traffic conditions at the end of the first two 20 sec sampling periods, thus increasing the response time. Fig. 3b aggregates the 1 min occupancy data to 5 min samples, reducing the volatility further, but with a longer response time. Fig. 3c finds a moving average of the one minute data, so the results at t=5 min is the arithmetic average of minutes 1-5; while the result at t=6 min is the arithmetic average of minutes 2-6, and so forth. The moving average has the benefit that it updates at the same rate as the original data (compare to Fig. 3b) while preserving the reduced volatility (compare to Fig. 3a). The moving average will be slower to respond to real changes than the raw data since an increase in occupancy only needs to persist for a portion of a minute to impact Fig. 3a but has to persist for several minutes to impact Fig. 3c. Fig. 3d calculates the moving median using the same samples input to moving mean in Fig. 3c. The median is considered here because it is less sensitive to outliers than the mean; however, we did not observe any extreme outliers in the data that would disrupt the mean so the results are similar to (or possibly slightly worse than) the moving average in Fig. 3c. The one potential drawback of all of these approaches is the need to store the intermediate samples. If the ramp metering system does not have the ability to recall the data from the past few minutes then none of the moving window approaches could be applied to the existing system without injecting an intermediate processor to re-aggregate the data. On the other hand, the fixed time averaging could be easily implemented simply by changing the sampling period that the sensors are operating at.

The second type of low pass filter we considered is the exponential filter, that is simply a weighted average of the current input, r, and most recent output, a, as shown in Equation 1, where p denotes the proportion that comes from the current input. The lower the value of p, the greater the reduction of volatility by reducing the impact of the most recent observation at the expense of reducing the response time to real changes in the background state (similar to the tradeoffs when finding a moving average). The exponential filter is attractive for applications with limited memory since it only requires knowledge of the current state of the system and most recent input to calculate the next state. Fig. 4a-d shows the results for the data from Fig. 3a with different values of p.

$$a(i+1) = r\,(i+1) * p + a\,(i)\,(1-p);\ 0 \le p \le 1 \qquad (1)$$

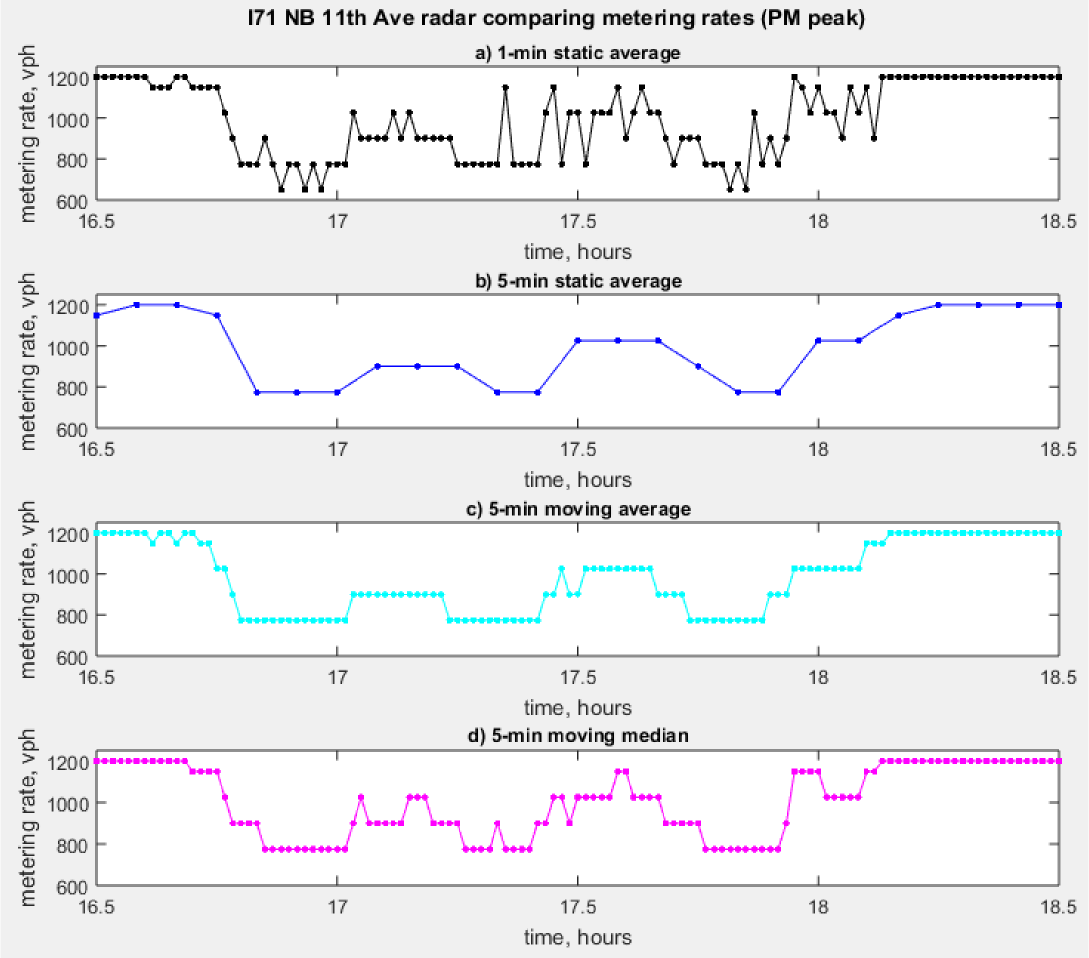

Figure 3, I-71 northbound at 11^{th} Ave comparing metering rates resulting from different low pass filters during a typical PM peak.

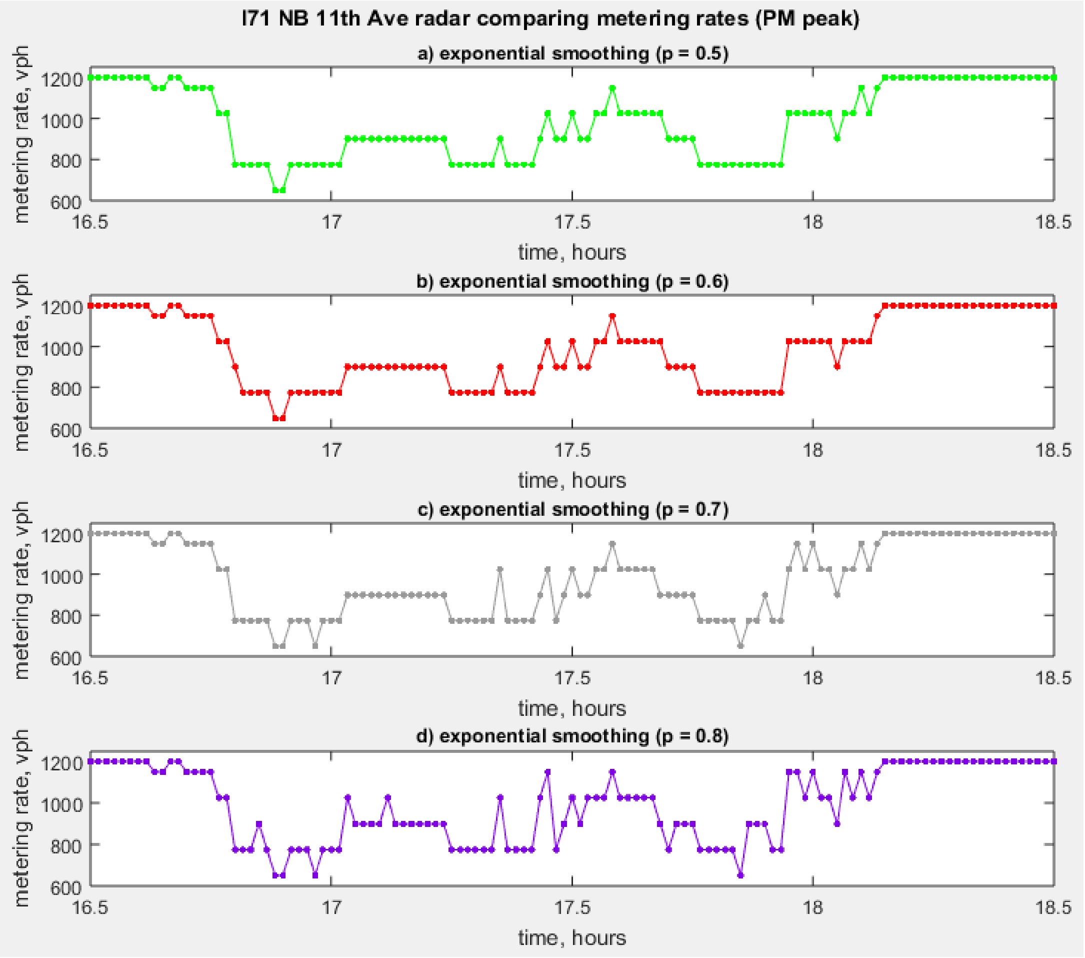

Figure 4, I-71 northbound at 11th Ave comparing metering rates resulting from exponential low pass filters during a typical PM peak.

Estimating occupancy from INRIX speeds

While there are only a few corridors in Ohio equipped with sensors to measure occupancy, and those occupancy sensors can be off line for extended periods, the complete coverage of INRIX (Kim and Coifman, 2014) or the legacy SpeedInfo (Kim and Coifman, 2017) deployed throughout the state can be an attractive alternative to fill in holes in coverage either due to short term power loss or long term loss of a sensor due to a traffic accident. Though as noted in the cited works, both of these systems have their own idiosyncrasies that would need to be worked around but do not preclude their use (e.g., both exhibit a lag between the actual observations in the field and when they are reported, and at any given moment the INRIX data might be imputed rather than actually measured). Unfortunately, INRIX and SpeedInfo only report speeds while the current ramp metering system only uses occupancy. Based on classical traffic flow theory, we derived the function in Fig. 5 to map from reported INRIX speeds on I-71 to equivalent occupancy. The function is defined as follows:

If $v < 20$ mph, then $occ = 85 - 2.5*v$;

Or if $v \geq 20$ mph & $v < 60$ mph, then $occ = 47.5 - 0.625*v$;

Or if $v \geq 60$ mph, then $occ = 130 - 2*v$;

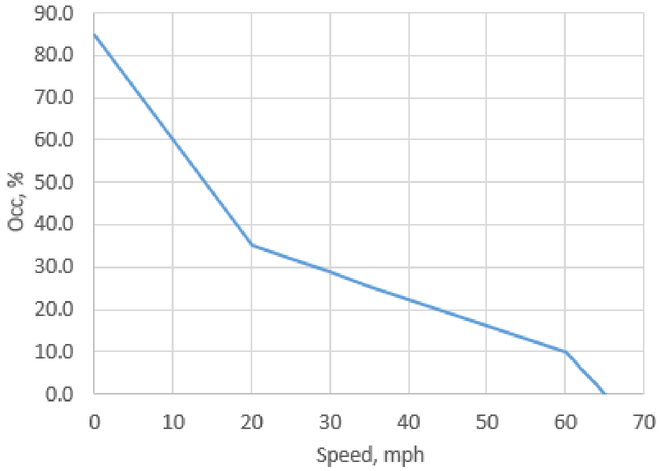

Figure 5, Occupancy-Speed relationship used for estimating occupancy from INRIX speeds

Fig. 6 and Fig. 7 show examples of the estimated occupancy from INRIX data against the measured occupancy from the radar sensors. Fig. 6a shows the speed from the radar sensor at 11th Ave on 21st February, 2018 and at the INRIX sensors immediately upstream (denoted u/s) and downstream (denoted d/s) of the 11th Ave radar sensor on the same day.[2] Fig. 6b shows the occupancy as obtained from the radar sensor and the occupancy estimated from speeds for the two INRIX sensors from Fig. 6a using the relationship shown in Fig. 5. Fig. 7 repeats the comparison of Fig. 6 for the radar sensor at 17th Ave. Both figures show that during the low flow of late night and early morning the calculated occupancy from INRIX speeds are volatile, but that is because under these low flow conditions there is little direct correlation between flow and occupancy. What is important is that the calculated occupancy remains below the threshold of the ramp metering algorithm. The occupancy estimate during the rest of the day appears to be rather close to the measured value of occupancy from the radar sensor. So the occupancy estimated from INRIX speeds could potentially be used in the ramp metering algorithm as a substitute for the occupancies measured from the radar sensors. Note, however, that the function in Fig. 5 will likely need to be recalculated based on the speed limit of the site and "turn-on" occupancy value for the ramp metering algorithm.

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[2] Note that Fig. 6a shows that the radar appears to be overestimating speed, which may be as simple as an incorrect adjustment factor, in any event, the radar speed is not used by the ramp metering algorithm, only the occupancy.

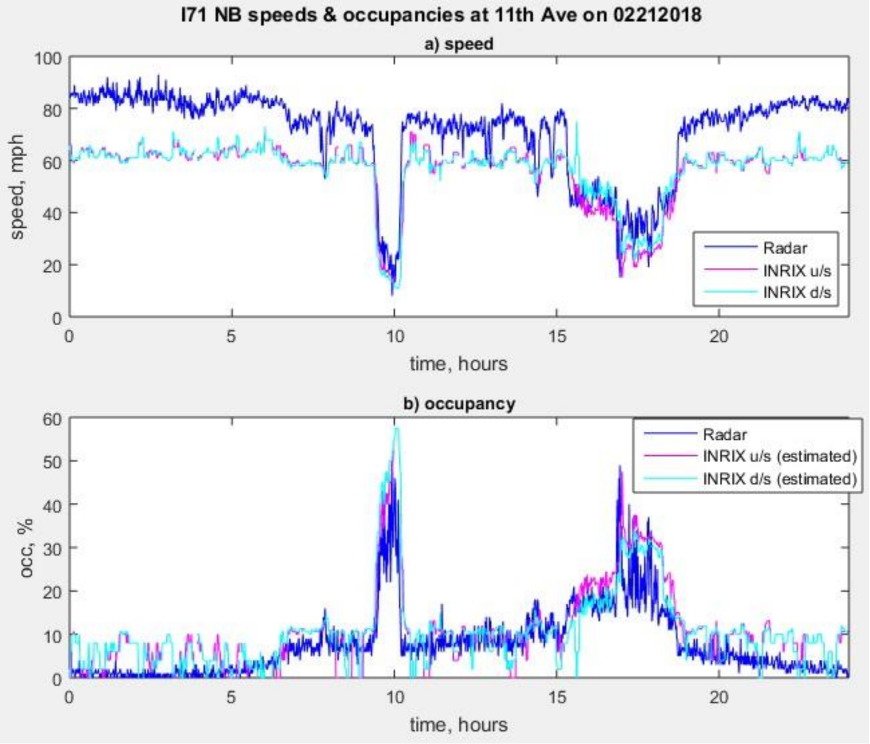

Figure 6, I71 NB speeds & occupancies from radars and INRIX sensors at 11th Ave. Note that the radar is likely overestimating speed at this location.

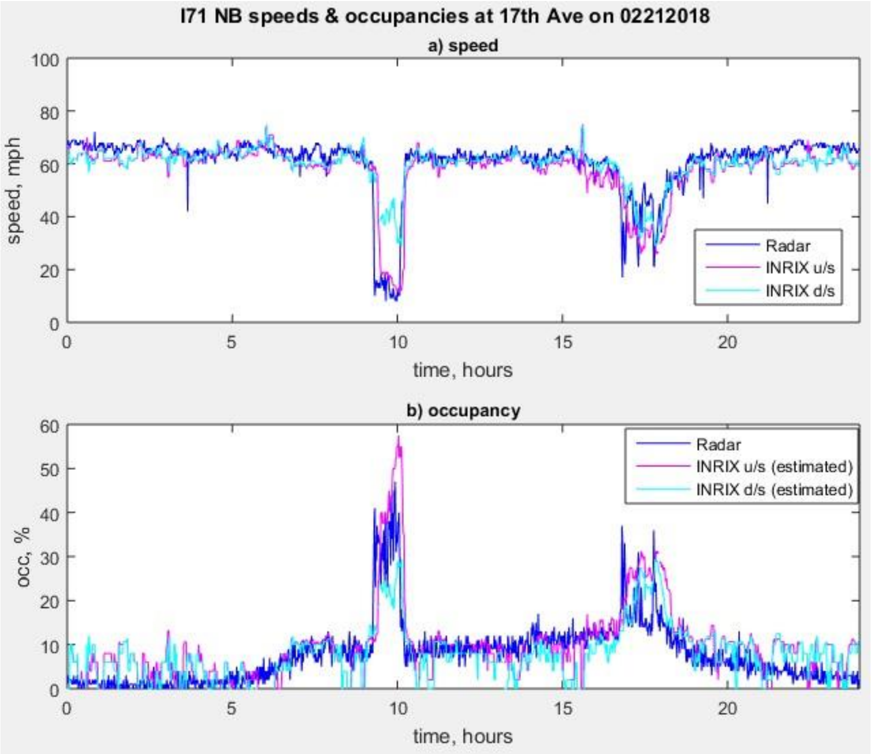

Figure 7, I71 NB speeds & occupancies from radars and INRIX sensors at 17th Ave

3.5 Task 5: Investigate the benefits of the coordinated ramp metering system

Northbound evening peak

Typical speeds range from about 20 mph at the I-670 interchange to about 30 mph shortly upstream of the lane drop at 11th Ave. Speeds then increase to about 50 mph passing 11th Ave. These relatively high speeds (and the associated lower occupancies) could easily be misinterpreted as coming from free flowing traffic. However, speeds continue to increase over the next 1.5 mi to about 60 mph at Hudson St. as one passes beyond two on-ramps that each provide about 5-10 veh/min. The on-ramps consume capacity that would otherwise be available to the queue upstream of 11th (there are also three off-ramps in this stretch, but their outflow is below that of the inflow). While a net inflow of 10 veh/min might not seem like much, that equates to 600 vph, or more than 8% of the flow that passes Hudson St. In other words, the demand from these on-ramps appear to be contributing to the congestion upstream of 11th, but the local occupancies are below the threshold for ramp metering. From a purely traffic flow standpoint it would be worth considering metering in this region to increase the throughput of the lane drop.

In general, such a coordinated ramp metering algorithm should turn on if traffic is queued at a given on-ramp or if conditions immediately downstream of an on-ramp are near capacity (irrespective of speed). The algorithm should also assess the length of the queue upstream of the on-ramp and how long it takes a vehicle to traverse the queue. From what we know of the current ramp metering system on I-71, it is unlikely that such an approach could be deployed, but aspects of this approach could be incorporated (e.g., accounting for the extent of queuing upstream of a ramp).

The situation is compounded by a high demand off-ramp at Hudson St, if the flow exiting at this ramp can be increased then conditions should improve for the vehicles that remain on the freeway. Presumably the vehicles passing through the lane drop at 11th are more likely to exit at Hudson (compared to those vehicles that enter downstream of the lane drop). The more vehicles that exit at Hudson the greater the effective flow past Hudson (i.e., the sum of mainline and off ramp flows at Hudson), which provides a second factor that would benefit from more restrictive ramp metering between 11th Ave and Hudson St.

Rather than rely on traffic responsive ramp metering, when a queue is present upstream of the lane drop at 11th, it might be worth considering a ramp metering rate that frequently generates a queue of (at most) 1-2 vehicles on the on-ramps from 11th and 17th. We believe such control is beyond the current automated system, so a simple experiment could be conducted to explore the potential benefit:

1. choose a one hour window during the afternoon peak when recurring congestion is expected
2. for each of the next three days with recurring congestion choose either the first, second, or third 20 min interval during the chosen hour and manually operate the ramp meters at 11th and 17th to maintain a short queue (e.g., rest in red, turn to green 10 sec after first vehicle arrives, and green every 3 sec thereafter until the queue has cleared, and then repeat)
3. look at the mainline flows at Hudson and at 11th over the following three 20 min periods: immediately before the test, during the test, and immediately after the test. If across the three days the mainline flow

at 11th consistently increases during the test period compared to the prior and following 20 min periods then consider further investigation.

4. the corresponding flows at Hudson should also be examined to make sure that nothing unusual is seen there, e.g., a downstream queue growing in to the segment. If possible, the off-ramp flows at Hudson should also be collected to see if the OD theories also come in to play, resulting in higher outflows (if no detectors are available for the ramp, then perhaps by pointing a CCTV camera at the off-ramp and recording the video for the one hour period).

Southbound morning peak

The nature of congestion during the morning peak is different than that from the evening. In this case, the additional lane starting at 11th Ave comes from an on-ramp with demand far below the capacity of a single lane, so mainline vehicles can spill in to the new lane just past 11th Ave. In which case the mainline should be at the capacity of the three lanes as it passes 11th Ave. Moving upstream at 17th Ave some of the mainline capacity is used to serve the on-ramp demand, leaving, say 96% of the capacity to the mainline upstream of the ramp (assuming 5 veh/min from the on-ramp and 2400 vphpl on the mainline). In the absence of metering, the Hudson on-ramp could contribute up to 1/2 of the flow in the shoulder lane, or 1/6 of the available capacity downstream of that ramp, leaving 0.96 * 0.83 = 79% of the capacity at 11th for the mainline upstream of Hudson. If there were no off-ramps the available capacity would continue to drop as one moves upstream of each successive on-ramp. In reality, the off-ramp at Hudson relieves some of the pressure since the exiting vehicles do not have to pass the subsequent on-ramps, so some capacity is restored upstream of the off-ramp at Hudson. For most of the interchanges upstream of Hudson on a typical day the inflow should be greater than the outflow during the morning peak, thus reducing the available capacity as one moves upstream of each subsequent interchange. Since demand exceeds capacity, each drop in available capacity corresponds to a drop in speed. So, the worst traffic conditions should be seen at the tail of the queue. From the perspective of a driver they encounter the lowest speeds as they join the queue, speeds should slowly improve as they pass each successive interchange until they pass 17th Ave, where the congestion seemingly disappears without any clear source or perceptible problem.

From the perspective of coordinated ramp metering, the worst occupancies are seen at the tail end of the queue since occupancy is inversely proportional to speed, and if all ramps are treated equally, the most restrictive metering rates will be applied at the tail of the queue. So like the northbound evening peak, given sufficient detection, communications, and processing power, it might make sense to consider a more sophisticated traffic responsive metering algorithm that uses the real time measurements to balance the per-vehicle delay caused by a given on-ramp with the per-vehicle delay experienced at that onramp. However, if one assumes that there is no change in the ramp demands given new metering rates, then this strategy simply swaps delay from vehicles at one ramp to vehicles at another ramp; the flow past 11th Ave should not change since this section will remain at capacity regardless of where vehicles enter the freeway.[3] We identified a promising lead for inbound queues, Kim and Cassidy (2012) suggests that releasing burst of demand from the on-ramps shortly upstream of the most restrictive point can cause a secondary bottleneck that actually increases the throughput at the most restrictive point. Translating this to I-71, it is conceivable that releasing pulses of high flows from the on-ramp at Hudson might actually increase the flow past 11th. ODOT may want to consider exploring this possibility, e.g., conducting an experiment to manually control the meters for about 20 min a day over 3 days similar in magnitude to the one offered for the northbound traffic.

3.6 Task 6: Meetings with ODOT, quarterly reports, final report, and all other reporting

This task proceeded as planned, with monthly teleconferences, quarterly reports, and several interchanges with the technical liaisons between the various administrative meetings. Interaction with the technical liaisons included email requests for data or other information, as well as telephone and in person meetings to gain an understanding of the existing system.

4 Research Findings, Conclusions, and Recommendations for Implementation of Research Findings

Task 1: Assess the performance of the current system

Based on the data available to us, the system is generally in good shape. The largest problem was already known, that of non-operational radar sensors. Obviously, whenever the sensors are not reporting valid data, the system cannot respond to the traffic conditions. We found some apparent scaling errors for some of the radar sensors, it would be beneficial for ODOT to periodically review a typical day of data from all radar sites to make sure consistent speeds, flows and occupancies are being reported. We also found a few locations where the directions were swapped in the data archive. It is not possible for us to tell if this error is limited to just the data archive. ODOT should consider periodically reviewing the performance of the radar sensors, e.g., when one direction is queued and the other direction is free flowing (morning or evening peak) they should check in real time to see that the reported data are consistent. Finally, since it was not possible to collect the log reports, we were unable to assess the output of the actual ramp metering system itself.

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[3] Caveat: In reality the ramp demands should change in response to different metering strategies, but the shift would not necessarily improve conditions on the freeway, so there is no simple assessment of their impacts. For now, we assume that in the short term the change in ramp demands would be small. The biggest impacts, however, could come from expediting those vehicles that exit within the queue, e.g., at Hudson, to maximize the total outflow from the queue (not simply the flow past the most restrictive point at 11th Ave). But such a strategy requires knowledge of the origin-destination patterns and detailed analysis to favor the on-ramps with more flow that exits within the queue, which is beyond the scope of the current study.

Task 2: Quantify the performance of the existing ramp metering system

We investigated the performance of the existing system. Here too, the system is generally in good shape. However, ODOT should consider special treatment to respond differently recurring congestion and non-recurring congestion. The current algorithm settings typically give greatest weight to the radar sensor at the metered on-ramp and then the weight decay at successive sensors as one progresses further downstream. This approach seems as good as any for recurring congestion. If it is possible to run two or more metering algorithms for a given meter and choose the most restrictive output, then it would be beneficial to separately consider non-recurring congestion, e.g., by giving greater weight to the radar sensors further downstream, to reduce the mainline demand approaching a growing queue. Another factor that should be examined is how to adapt the ramp metering algorithm when one or more radar sensors are not operational. For example, the on-ramp at northbound 5th Ave is typically in a recurring queue during the afternoon that starts around 11th Ave. If none of the sensors are working between 5th and 11th, the algorithm will only use the operational sensors (all of which are downstream of the recurring queue in this case) so the meter at 5th will not restrict the traffic even though a mainline queue might be present at the on-ramp. In this case, for the short term, perhaps the best solutions are either going to time of day metering or have the TMC staff regularly check the location and manually adjust the metering rate. Meanwhile, the non-operational radar sensor should be restored to operational status as soon as possible.

Task 3: Work with ODOT to assess the importance of any system deficiencies

While we looked for major system deficiencies, none were found beyond those listed elsewhere in this section.

Task 4: Work with ODOT to improve the existing ramp metering system

One potential limitation of the existing ramp metering system is that it is memory-less. So the metering rate for the next cycle comes strictly from the most recent recorded conditions during the previous cycle. If the radar sensors are polled every 20 sec, the metering rate can exhibit large jumps from one cycle to the next. While it would be nice to conceive of a ramp metering system that forecasts the evolving traffic conditions, that would require an investment in something far more sophisticated than what is currently in use. That said, ODOT should consider the possibility of smoothing the data to reduce volatility in the metering rates. The simplest approach would be setting the radar sensors to a longer sampling period, perhaps consider 5 min. However, the longer the sampling period the less responsive the system will be to the onset or conclusion of congestion. If the data were clean, on average one should expect to see the state change on average in one half of the sampling period, potentially taking another sampling period to verify (5-10 min with 5 min sampling periods). For the 20 sec or 1 min data, one likely has to wait several minutes to rule out noise (something the current system does not do). Low pass filtering can both reduce the volatility and improve the responsiveness to eliminate the need to wait another sample to confirm a large change in state. We considered several simple low pass filters, including a moving average and an exponential filter.

We also considered the data availability issue when one or more radar sensors are off-line or conceivably, for corridors without radar sensors. While there are only a few corridors in Ohio equipped with sensors to measure occupancy, and those occupancy sensors can be off line for extended periods, the complete coverage of INRIX (Kim and Coifman, 2014) or the legacy SpeedInfo (Kim and Coifman, 2017) deployed throughout the state can be an attractive alternative to fill in holes in coverage either due to short term power loss or long term loss of a sensor due to a traffic accident. Though as noted in the cited works, both of these systems have their own idiosyncrasies that would need to be worked around but do not preclude their use (e.g., both exhibit a lag between the actual observations in the field and when they are reported, and at any given moment the INRIX data might be imputed rather than actually measured). Unfortunately, INRIX and SpeedInfo only report speeds while the current ramp metering system only uses occupancy, so this work also developed a simple approach to convert from speed to occupancy.

Task 5: Investigate the benefits of the coordinated ramp metering system

This task explored several ideas to improve the service of the ramp metering system that are beyond the current capabilities of the existing system. For example, applying light metering at stations just downstream of the northbound lane drop at 11th Ave. should facilitate traffic exiting at Hudson, thereby helping reduce the magnitude and duration of queuing upstream of 11th. Whereas the southbound queuing in the morning suffers from the fact that conditions improve as one moves further and further downstream, with only mild recurring congestion upstream of the add lane at 11th Ave. Conditions worsen as one moves upstream because each successive onramp consumes some of the available capacity. So drivers encounter the worst conditions as they enter the queue and then the congestion seemingly vanishes as the reach the actual bottleneck. In this case benefits might be realized by taking a slightly more restrictive metering rate for the onramps immediately upstream of the add lane than the rates used elsewhere.

References

Ahn, S., R. L. Bertini, B. Auffray, J. H. Ross, and O. Eshel. (2007) Evaluating benefits of systemwide adaptive ramp-metering strategy in Portland, Oregon. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2012,* TRB, National Research Council, Washington, D.C., pp. 47–56.

Bhouri, N., H. Haj-Salem, and J. Kauppila. (2013) Isolated versus coordinated ramp metering: Field evaluation results of travel time reliability and traffic impact. *Transportation Research Part C*, Vol. 28, pp. 155–167.

Cambridge Systematics. (2001) Mn/DOT Ramp Metering Study. Final report. Minnesota Department of Transportation.

Coifman, B. (2005) "Freeway Detector Assessment: Aggregate Data from the Remote Traffic Microwave Sensor," *Transportation Research Record 1917*, 2005, pp 149-163.

Coifman, B. (2006) "Vehicle Level Evaluation of Loop Detectors and the Remote Traffic Microwave Sensor," *ASCE Journal of Transportation Engineering*. Volume 132, No 3, pp 213-226.

Hourdakis, J., and P. G. Michalopoulos. (2002) Evaluation of ramp control effectiveness in two Twin Cities freeways. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1811*, TRB, National Research Council, Washington, D.C., 2002, pp. 21–29.

Kim, K. and Cassidy, M.J., (2012). A capacity-increasing mechanism in freeway traffic. *Transportation research part B: methodological*, *46*(9), pp.1260-1272.

Kim, S., Coifman, B. (2014) "Comparing INRIX speed data against concurrent loop detector stations over several months," *Transportation Research Part C*, Volume 49, pp 59-72.

Kim, S., Coifman, B., (2017) "Assessing the performance of SpeedInfo Radar Traffic Sensors" *Journal of Intelligent Transportation Systems*. Vol 21, No 3, 2017, pp179-189.

Lipp, L. E., L. J. Corcoran, and G. A. Hickman. (1991) Benefits of central computer control for Denver ramp-metering system. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1320*, TRB, National Research Council, Washington, D.C., pp. 3–6.

Neudorff, L., McCabe, K. (2015) Active Traffic Management Feasibility and Screening Guide, FHWA, FHWA-HOP-14-019

Papageorgiou, M., H. Hadj-Salem, and J. M. Blosseville. (1991) ALINEA: A Local Feedback Control Law for Onramp Metering. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1320*, TRB, National Research Council, Washington, D.C., pp. 58–64.

Papageorgiou, M., H. Hadj-Salem, and F. Middelham. (1997) ALINEA Local Ramp Metering - Summary of Field Results. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1603*, TRB, National Research Council, Washington, D.C., pp. 90–98.

Papageorgiou, M., I. Papamichail, and partners of the Information Society Project EURAMP (2006) *Network-wide ramp metering*, Deliverable 3.3, Report for the European IST Office, Brussels, Belgium, (IST-2004-507645).

Papamichail, I., and M. Papageorgiou (2008) Traffic-Responsive Linked Ramp-Metering Control. *IEEE Transactions on Intelligent Transportation Systems*, Vol. 9, pp. 111–121.

Papamichail, I., M. Papageorgiou, V. Vong, and J. Gaffney. (2010) Heuristic ramp-metering coordination strategy implemented at Monash Freeway, Australia. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2178*, TRB, National Research Council, Washington, D.C., pp. 10–20.

Appendix A- Task 1: an Assessment of the Existing Traffic Monitoring Used

A.1. Executive Summary

- This task examined the performance of the existing traffic monitoring. The work used speed, flow, and occupancy from the operational radar sensors used for traffic responsive ramp metering in the I-71 corridor between I-670 and I-270. The work also used INRIX speed data for validation.
- It appears that some of the radar stations have their directions reversed in the data archive (e.g., 17th Ave in the most recent radar data set, and S. Weber in the older data set). If these errors are present in the archive, care should be taken to make sure that the errors are only limited to the data archive so that similar errors are not impacting traffic control.
- At least two of the radar sensors reported excessively high flows for an extended period. We believe this is the result of a calibration factor and since the flows are not used for ramp metering control, it should not have any direct impact. However, the presence of any perceptible error might be indicative of less obvious errors. While we do not know the exact source of the error, we suspect it might simply the number of lanes used when calculating vphpl.
- The older data often shows periods with no data. It is believed to be due to the archival process rather than a sensor or communications failure.
- It is our understanding that the ramp metering system makes control decisions based strictly on the current conditions. If our understanding is correct, ODOT may want to consider the trade-offs. On the one hand, a short sampling period potentially offers a faster response time, on the other hand, the shorter the sample period the greater the volatility. If ODOT experiences rapid changes in metering rates, they may want to consider using longer sampling periods for the radar sensors. If there is an option to store and use recent history, one could also consider low pass filtering techniques to reduce the volatility with less reduction in responsiveness.

A.2. Description of the Data

Two types of data were used to perform task 1. The first data set used is the INRIX speed data which is available for the entire length of I-71 in Columbus for any time period over the past several years. The second data set used is the radar data downloaded on an on-demand basis and furnished to us by ODOT. We worked with radar data from two time windows. The first time window is from Oct. 27th to Nov 27th, 2017 (referred as the November data set) and the second time window is from Feb. 12th to Mar 12th, 2018 (referred as the March data set). The November data set has data from five radar sensors in both northbound (NB) and southbound (SB0 directions. These ten directional radar sensors were the only ones operational in the corridor at the time. The March data set is more comprehensive with data from 12 radar sensors in the NB direction and from 10 radar sensors in the SB direction, Fig. A-1.

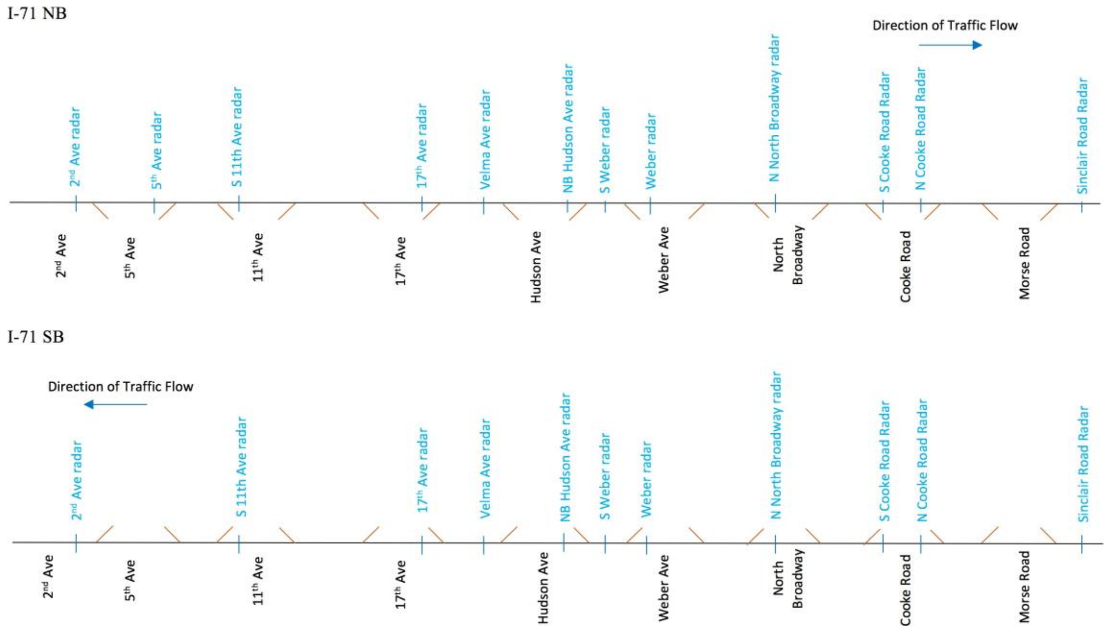

Figure A-1, I-71 NB & SB schematics showing the operable radar sensors in the March data set.

A.3. Data Analysis

The analysis in this report has been done using both the November and the March data set. Radar sensors on the corridors were calibrated against the INRIX data and for consistency, the radars were also evaluated against each other.

A.3.1. Calibrating radar against concurrent INRIX data

Fig. A-2 shows the speed summary plots generated the operational radars on I-71 on a typical day from the March data set. These summary plots show the speed by shade (dark = slow, light = fast) as a function of distance (along the vertical axis) and time (along the horizontal axis) for the corridor over 24 hrs. For the NB summary plots traffic moves from bottom to top, while in the SB plots the traffic moves from top to bottom. The NB summary plot from the radar shows evening congestion (dark region after 13:00 at the bottom of the plot) upstream of the lane drop at 11th Ave. The plot also shows an unexpected bit of NB congestion around 9:00 at the 17th Ave radar sensor. Compared to the corresponding plot from the INRIX data, the afternoon congestion is consistent, but the morning congestion is absent. The SB summary plot from the radar shows morning congestion upstream of the add-lane at 11th Ave. Once more the radar plot is consistent with the INRIX plot, with the exception of 17th Ave. It appears that the directional data at 17th Ave is reversed in the data archive. If these errors are present in the archive, care should be taken to make sure that similar errors are not impacting traffic control. Fig. A-3 repeats the comparison on the same day, only this time the data from the two directions at 17th Ave are swapped. The correspondence with the concurrent INRIX data has greatly improved.

This error was consistently observed at 17th Ave in the March data set. A similar error was observed at S. Weber in the November data set, however, in that case it was not consistent, the directional swapping error would be present one day and gone the next. The bottom of the NB and SB summary plots in Fig. A-4 show this error. Fig. A-5 show the results after swapping the directions at this sensor, and the error is no longer evident. Fig. A-6 shows the summary plots on a different day. In this case, there is no error evident in the morning, but the directions swap at S. Weber before the evening peak.

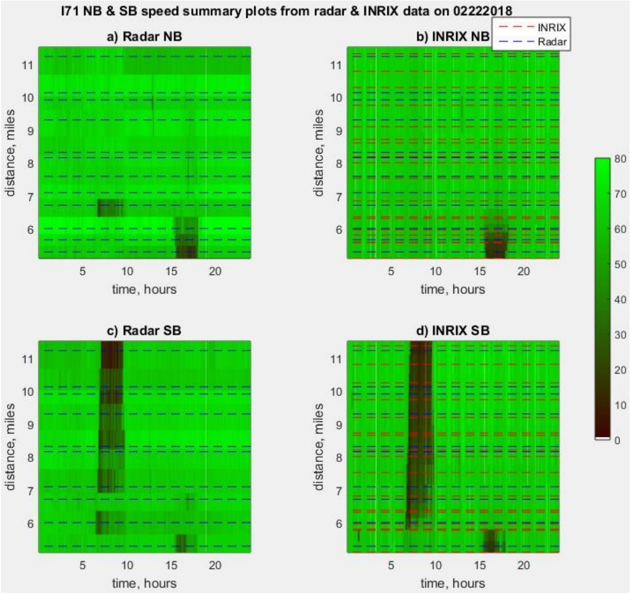

Figure A-2, I-71 NB & SB speed summary plots for radar & INRIX data on 2/22/2018. Radar data plots are on the left, concurrent INRIX data plots on the right, NB on the top with traffic moving upwards, SB on the bottom with traffic moving downwards.

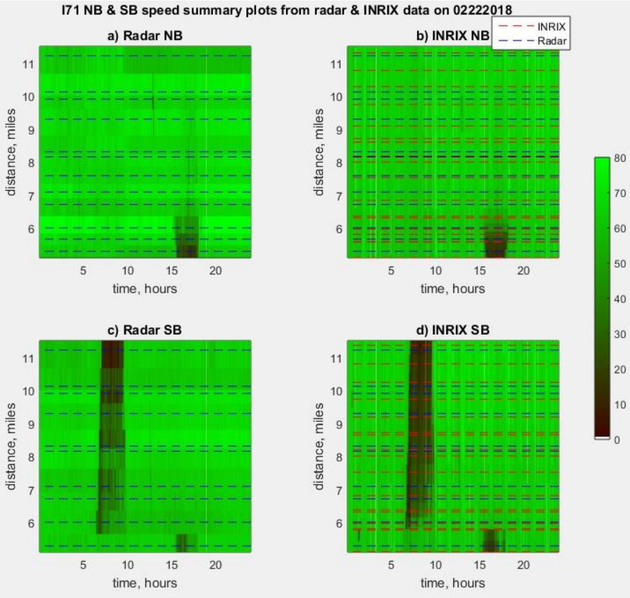

Figure A-3, I-71 NB & SB speed summary plots for radar & INRIX data on 2/22/2018 after swapping directions at 17th Ave.

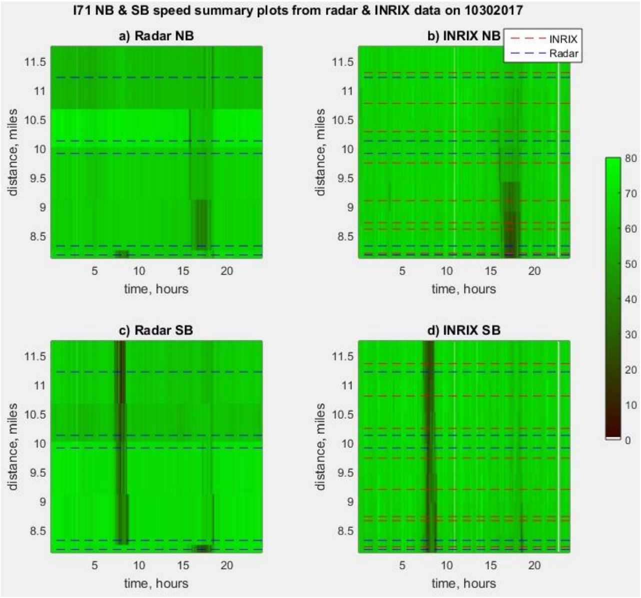

Figure A-4, I-71 NB & SB speed summary plots for radar & INRIX data on 10/30/2017.

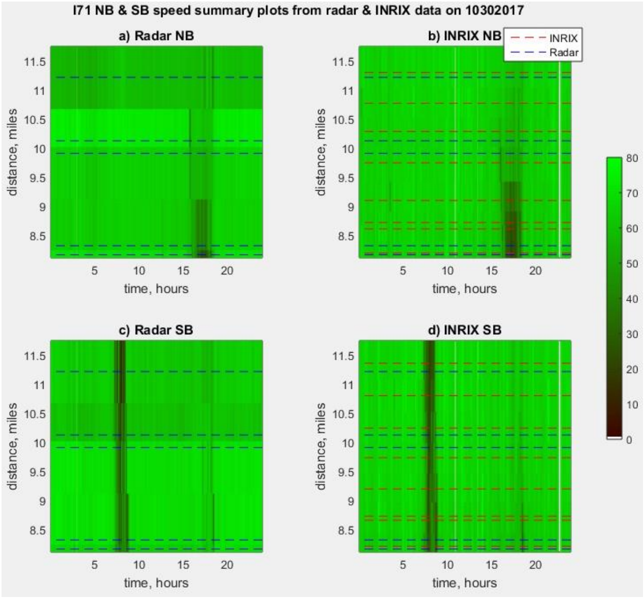

Figure A-5, I-71 NB & SB speed summary plots for radar & INRIX data on 10/30/2017 after swapping directions at S Weber

A.3.2. Consistency check across radar sensor units, comparing time-series flows and occupancies

The reversal of directions in the archived data only becomes evident in the speed summary plots if one radar exhibits congestion at a time when only the opposite direction should be congested. However, since these errors are in the traffic state, we check the other measures of the traffic state: flow and occupancy. Fig. A-7 repeats the analysis of Fig. A-2 on another day that did not show much congestion, as a result, there is no apparent problems at 17th Ave since all of the data from this radar is free flowing in both directions for the entire day. Fig. A-8, shows the time series flow at all of the radar sensors for this day, sorted by direction. Almost all of the radar sensors show an expected increase in SB flow during the morning peak (inbound commuters) and no such peak NB, but at the 17th Ave radar shows the behavior swapped, with a peak in the reportedly NB morning flows and no such peak in the SB flows. Thus, the error persists even when it is not evident in uniformly high speeds over the entire day.

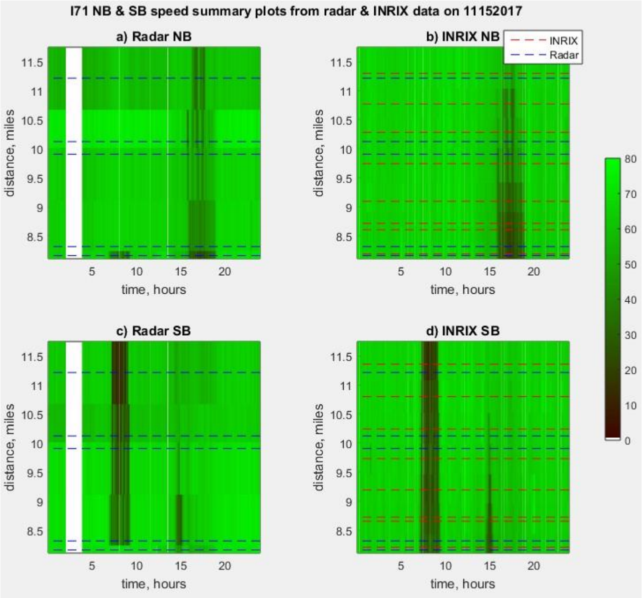

Figure A-6, I-71 NB & SB speed summary plots for radar & INRIX data on 11/15/2017

A.3.3. Calibrating flows and occupancies by comparing neighboring radar sensors

In addition to the reversal of directions in the archived data, for the November data set, it appears that the radar at S Weber consistently overestimates the flows and occupancies as shown in Fig. A-9. This figure shows that the S Weber flows are about 1.5 times larger than the flows at the other four locations in spite of no major off-ramps downstream of S Weber until the radar at Sinclair which is the northern most radar in the NB direction among the five radars shown in Fig. A-9. On a similar note, the flows at this radar are overestimated in the SB direction as well. Fig. A-10 is the counterpart of Fig. A-9 but plotting the occupancy instead of flows. It appears that the occupancy at this radar is not overestimated in the same way.

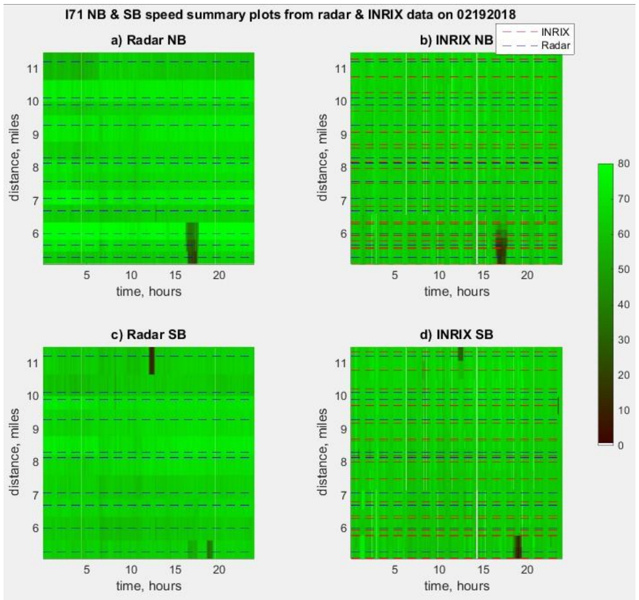

Figure A-7, I-71 NB & SB speed summary plots for radar & INRIX data on 2/19/2018

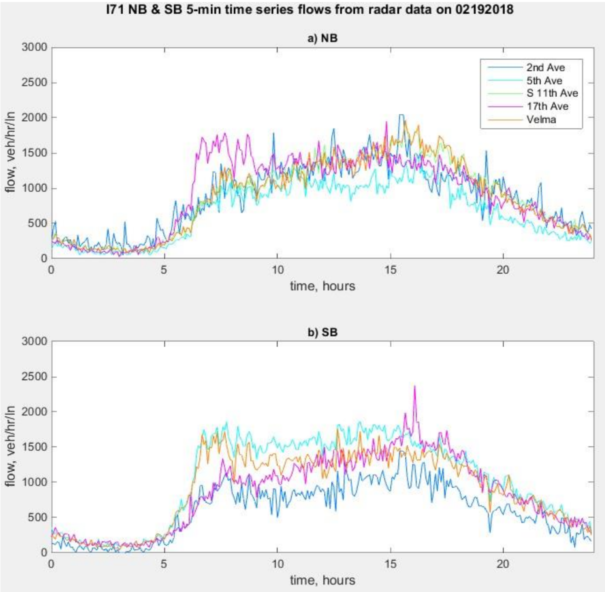

Figure A-8, I-71 NB & SB time series flow plots from radar data on 2/19/2018

The overestimation of flows also appears to happen at S Weber and North of North Broadway radars as observed from the March data set. Fig. A-11 below shows that the flows from the two radars in the NB direction are about 1.5 times larger than the other radars. The same is the trend in the SB direction of the S Weber radar. The reason for a scaling factor of 1.5 or 3/2 is possibly because of counting the number of lanes as 2 while in fact there are 3 lanes at the station (the radar sensors appear to report flows in vphpl looking at the daily maximum reported flows). Another day for which the same trend is observed is shown in Fig. A-12.

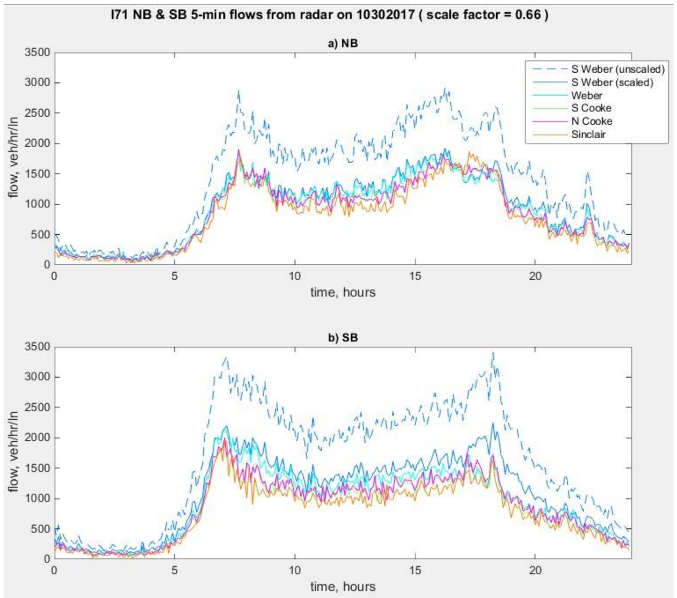

Figure A-9, I-71 SB time series flows from the five radars on 10/30/2017

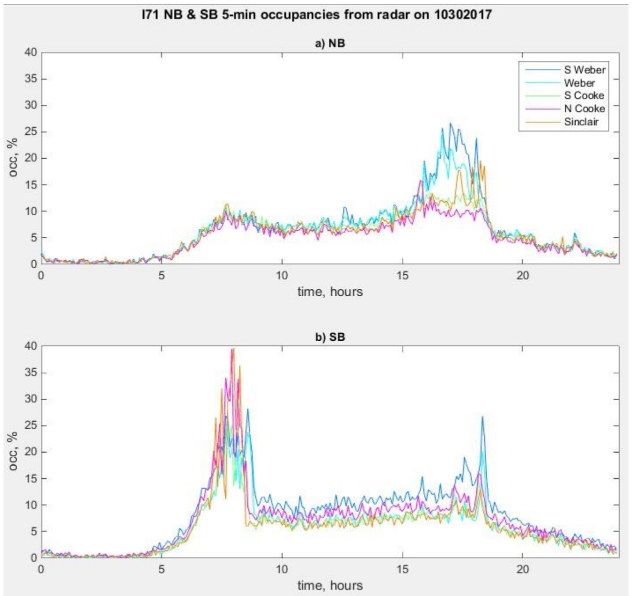

Figure A-10, I-71 SB time series occupancies from the five radars on 10/30/2017

Investigating the corresponding occupancies as shown in Fig. A-13 & A-14, consistent with the expected direction of peak period flows, it appears that the radars at 2nd, Ave, 5th Ave and S 11th Ave experience far higher occupancies than the other radars in the NB direction during the evening peak. On a similar note, the radars at S Cooke, N Cooke and Sinclair in the SB direction experience far higher occupancies during the morning peak (note, as per earlier reported findings, that the data from the 17th Ave radar have had their directions swapped in these figures).

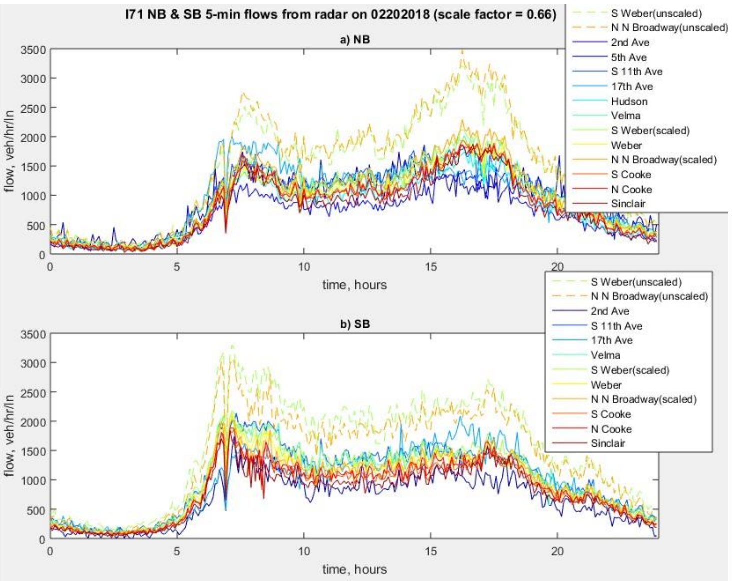

Figure A-11, I-71 SB time series flows from the radars on 2/20/2018

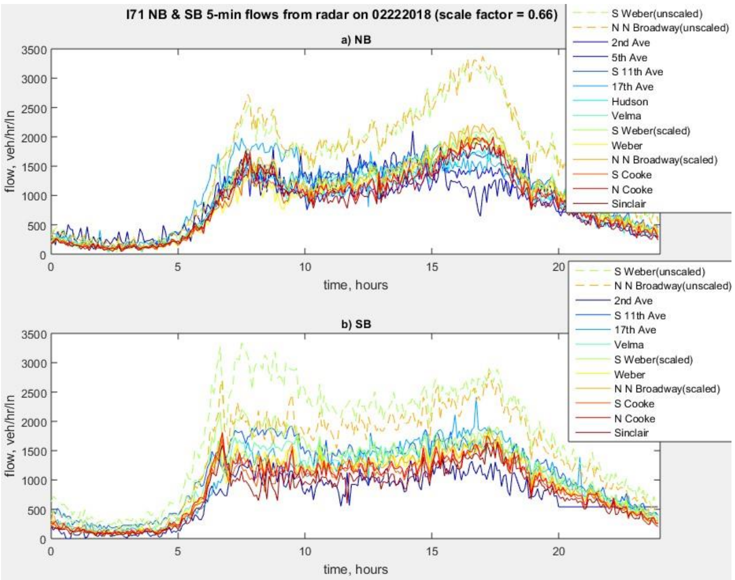

Figure A-12, I-71 SB time series flows from the radars on 2/22/2018

Irrespective of which radars we are looking at there seems to be outages in the archived data on many days in the November data set as shown in Fig. A-15. A similar data outage is evident in the early hours in Fig. A-6 as well.

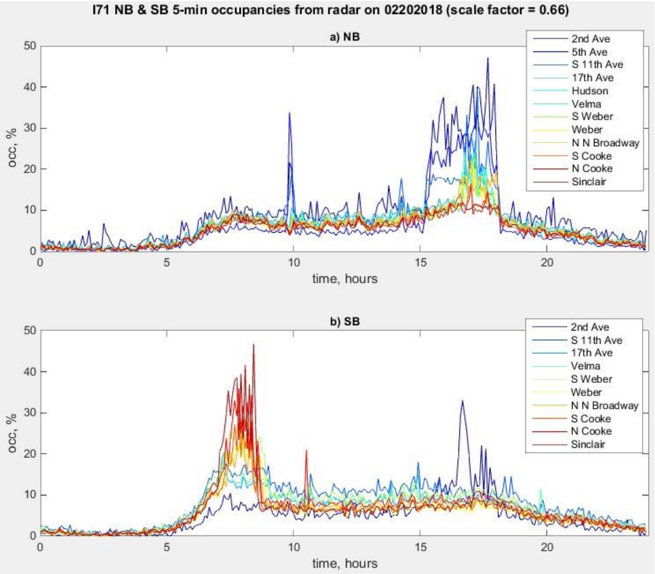

Figure A-13, I-71 SB time series occupancies from the radars on 2/20/2018

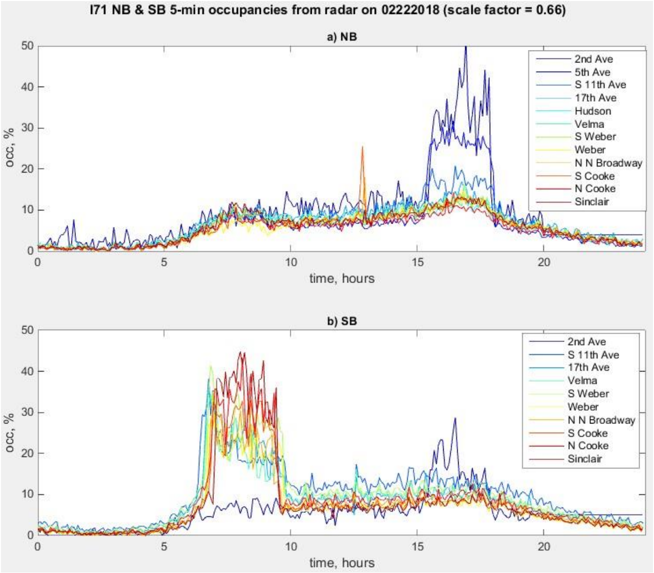

Figure A-14, I-71 SB time series occupancies from the radars on 2/22/2018

A.3.4. Trade-off between data resolution and presence of noise

This report primarily used data reported at 1 min sample periods, the highest resolution available from the data archives. It is our understanding that the ramp metering system makes control decisions based strictly on the current conditions. If our understanding of the algorithm is correct, ODOT may want to consider the trade-offs. On the one hand, a short sampling period potentially offers a faster response time since the sample period is so short, on the other hand, the shorter the sampling period the greater the volatility. Consider the upper plot in Fig. A-16, showing the occupancy from the 1 min samples, in some cases the occupancy jumps by more than a factor of two between one sample and the next. The lower plot in Fig. A-16 shows the same time period, only now using 5 min sampling period, and the volatility is greatly decreased. If ODOT experiences rapid changes in metering rates, they may want to consider using longer sampling periods for the radar sensors. Even better, if there is an option to store and use recent history, one could also consider low pass filtering techniques to reduce the volatility with less reduction in responsiveness, e.g., an exponential filter can be implemented with a single memory unit, or a moving average could be used to combine the lower volatility of the 5 min averages with the responsiveness of a higher sampling frequency.

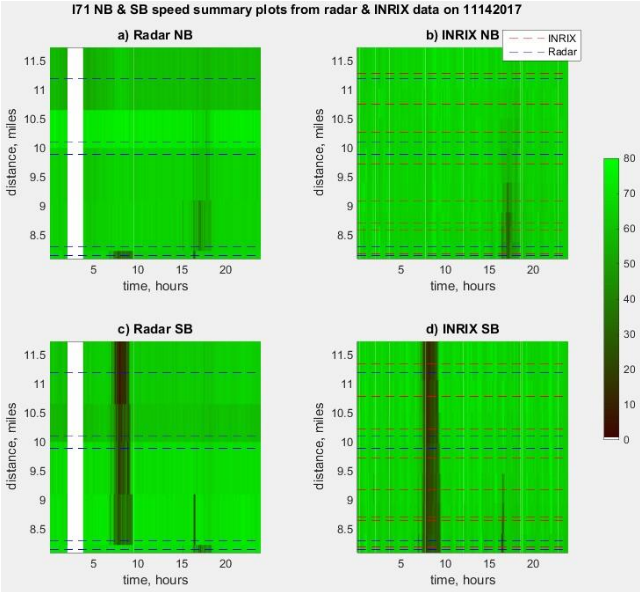

Figure A-15, I-71 NB & SB speed summary plots for radar & INRIX data on 11/14/2017

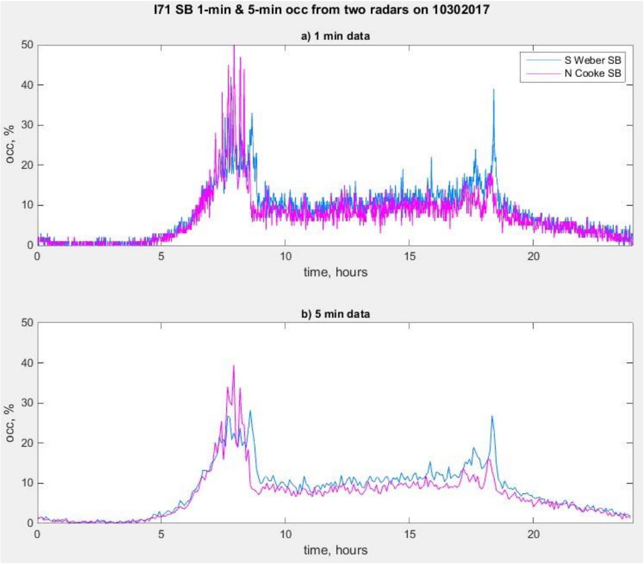

Figure A-16, I-71 SB 1-min and 5-min time series occupancies from two radars on 10/30/2017

Appendix B- Task 2: an Evaluation of the performance of the Actual Ramp Metering Algorithms

This task examined the performance of the existing ramp metering algorithm. The performance of the ramp metering algorithm was tested by coding the algorithm in Matlab and examining the resulting output under various scenarios. The following shows typical results from the algorithm, in this case as applied to the ramp meter located at the 11th Ave ramp on I-71 NB. This ramp meter takes input from the radar at the 11th Ave and five other downstream radars located at 17th Ave, Velma Road, North of Hudson St, South of Weber Road and Weber Road in that order. The weights assigned by ODOT to these six radars is 20, 18, 14, 6, 4 & 2 and these decreasing weights are based on the increasing distance of these radars from the location of the ramp meter. The algorithm as employed by ODOT uses 1 min data and generates the ramp metering rates every minute. The metering rates for the upcoming minute is calculated based on the 1-min occupancies in the previous minute. Using the same procedure used by ODOT, the ramp metering rates are synthetically generated as follows using the central metering rates given as follows.

Table B-1, Central Ramp Metering Rates

Occupancy (%)	Metering Rate (vph)
14	No action
15	1150
17	1025
19	900
21	775
31	650
33	475
35	300

For the ramp meter on the 11th Ave, for a given minute, the weighted occupancy is calculated using the weights given above and the 1-min occupancy of that minute for the six radars in question. Where, w_i is the weight of the radar at location i and occ_i is the occupancy of the radar at location i and i ranges from 0 to 5 where index 0 corresponds to the radar at location of the ramp meter and 1 to 5 correspond to the five radars downstream of 11th Ave on-ramp. In the event that one of the radars is not operational, the weight for that radar is set to zero. The metering rate that corresponds to the occupancy in the table that is closest to the weighted occupancy is set to be the metering rate for the next minute.

Based on this procedure, the ramp metering rates were synthesized for the entire day of 21st February, 2018 which is one of the days in the comprehensive March dataset. Fig. B-1a shows the 1-min flows at the radar located at the ramp metering location (11th Ave) and the five downstream radars while Fig. B-1b-c show the corresponding speeds and the occupancies. Fig. B-1d shows the weighted occupancy at each minute calculated per Equation B-1.

Fig. B-1e shows the ramp metering rate for each minute calculated from Table 1 for the weighted occupancy of the previous minute.

$$Weighted\ Occupancy = \frac{\sum \mathbf{1}_2 * 455_2}{\sum \mathbf{1}_2} \tag{B-1}$$

One point of note is that Fig. B-1e **shows the ramp meter turns off and back on several times during the afternoon peak**. On its own, this fluctuation could prove confusing to drivers. It is potentially compounded by the ambiguity of what to do on a green signal. When the meters are operational a green signal means only one car should pass, but when the meters are off a green signal means all cars should pass. **In an effort to reduce volatility in the metering status we consider the impact of instead using 5 min sampling periods**, Fig. B-2 shows Fig. B-1 generated using 5-min data. The procedure for generating Fig. B-2 is the same as that of Fig. B-1 except for using 5-min occupancies to generate the weighted occupancies and metering rates for every 5-min.

It is known that some of the radars on I-71 go down and do not report data and when that occurs the ramp metering algorithm continues to operate but only uses the radar sensors that are operational. To simulate such a scenario, Fig. B-3 shows the speed summary plots generated using full set of radars that were operable during the March data set and the reduced set of radars that were working during the November data set. Fig. B-3a shows the summary plot if all the radars (full dataset) were available on this day along with the 11th Ave radar that is 2nd from the top. On the other hand, Fig. B-3b shows the data on this day for the 11th Ave radar and the five other radars that were available during the reduced data set. To investigate the impact of the absence of radar data on the ramp metering rates, Fig. B-4 plots a figure similar to Fig. B-2 but considering only the three of the five radars downstream that are present in the reduced data set.

Fig. B-5 shows the comparison of the metering rates for the evening peak period using a) 1-min data, b) 5-min data, c) 5-min data with data from the reduced set of radars. Comparing Fig. B-1a-b reveals that the 1-min data produces a lot of flickering in the metering rates than the 5-min data. Additionally, comparing the metering rates for the 5-min data with full and reduced set of radars, we see that the reduced set of radars produces more variation in the ramp metering rates.

While assessing the performance of the current traffic monitoring system, it was found that the archive sometimes had the directions swapped at a given radar sensor, e.g., at the radar located at the 17th Ave in the March data set. To demonstrate the impact of swapping directions, Fig. B-6 plots the 5-min flows, speeds, occupancies, weighted occupancies and the metering rates arrived at considering data from the opposite direction i.e., from SB for the 17th Ave radar (compare to Fig. B-2 where the directional swap was corrected). The metering rates of this configuration is also compared with the three other configurations in Fig. B-5d.

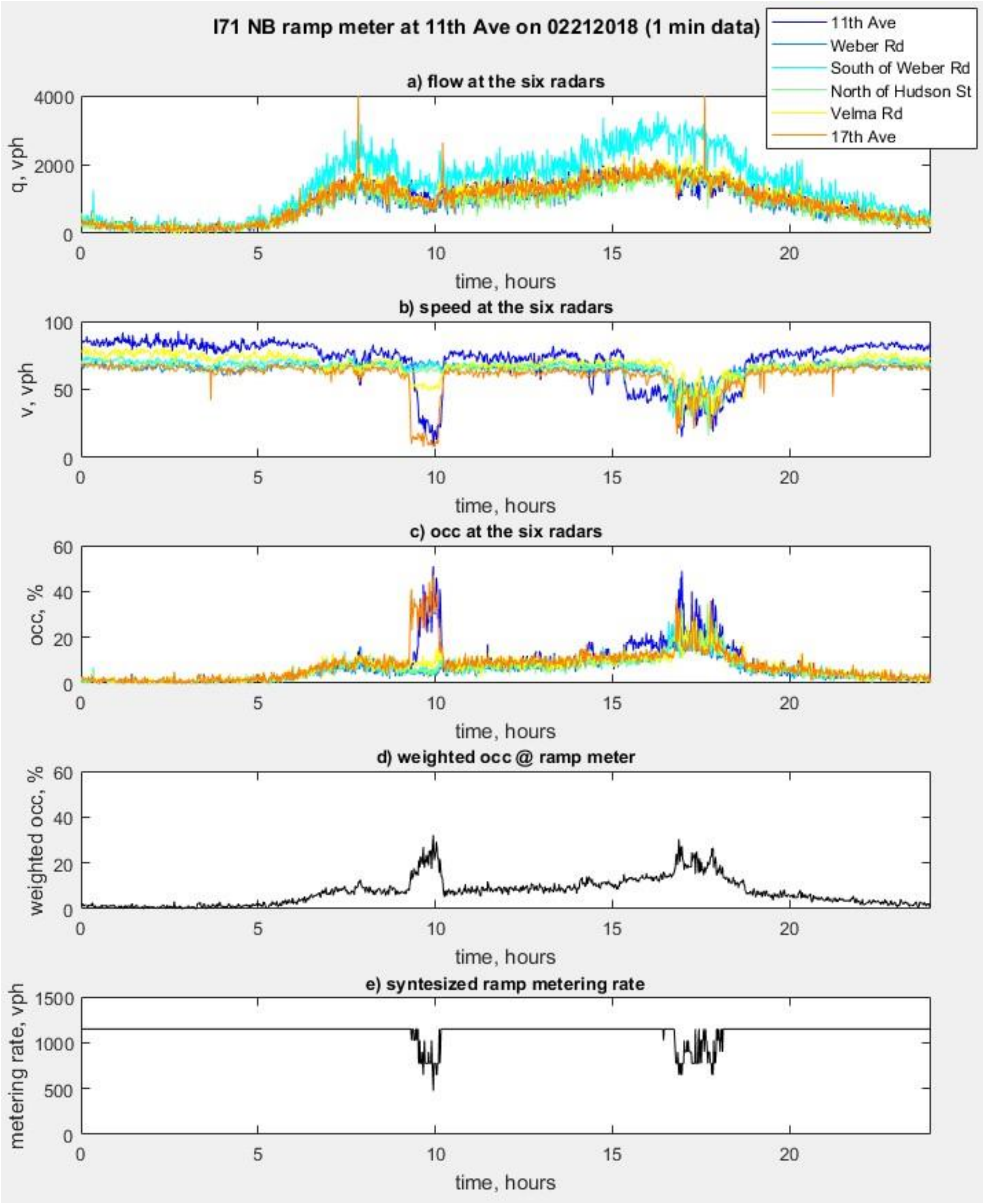

Figure B-1, I-71 NB ramp meter at 11th Ave on 2/21/2018 using 1-min data

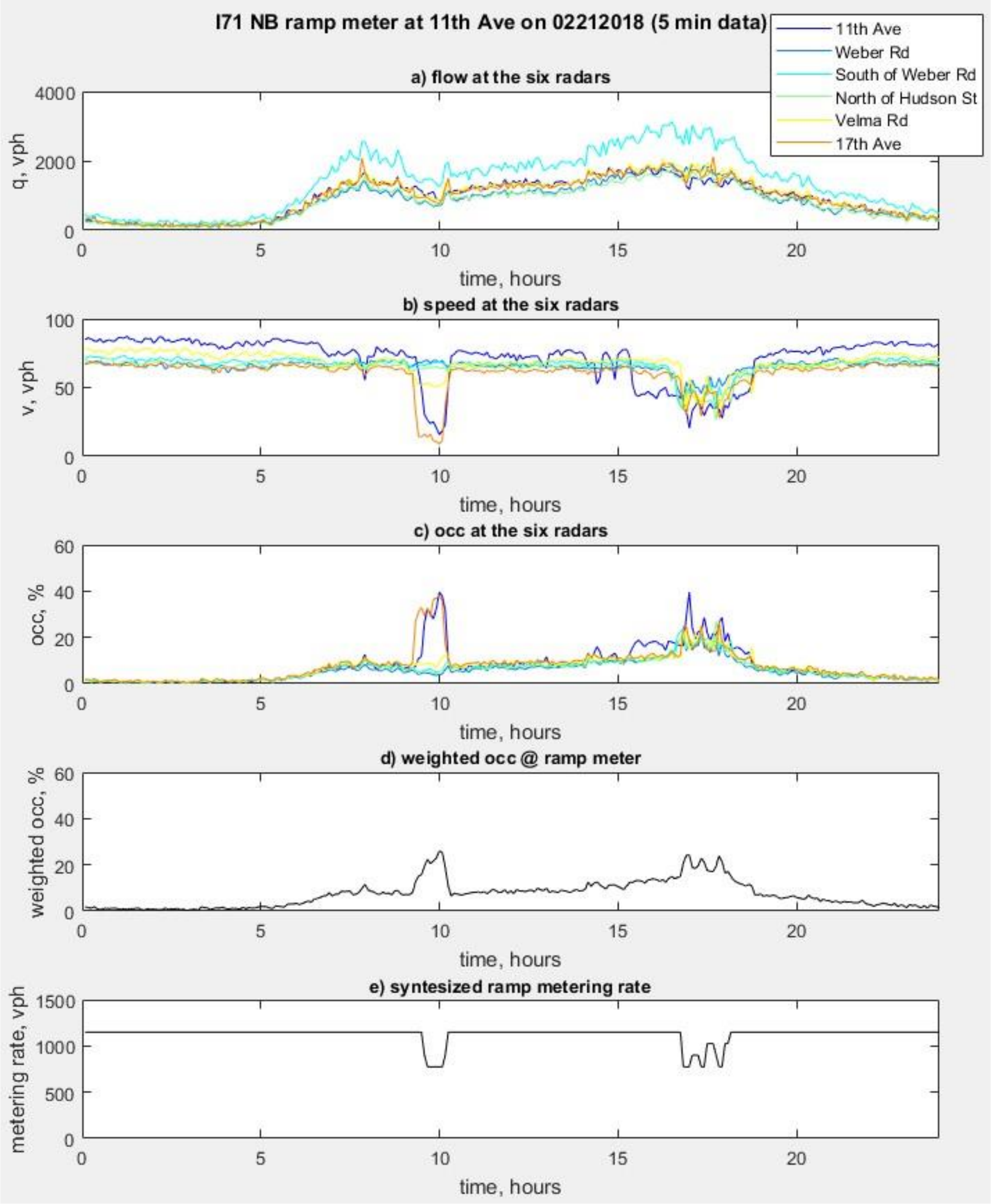

Figure B-2, I-71 NB ramp meter at 11th Ave on 2/21/2018 using 5-min data

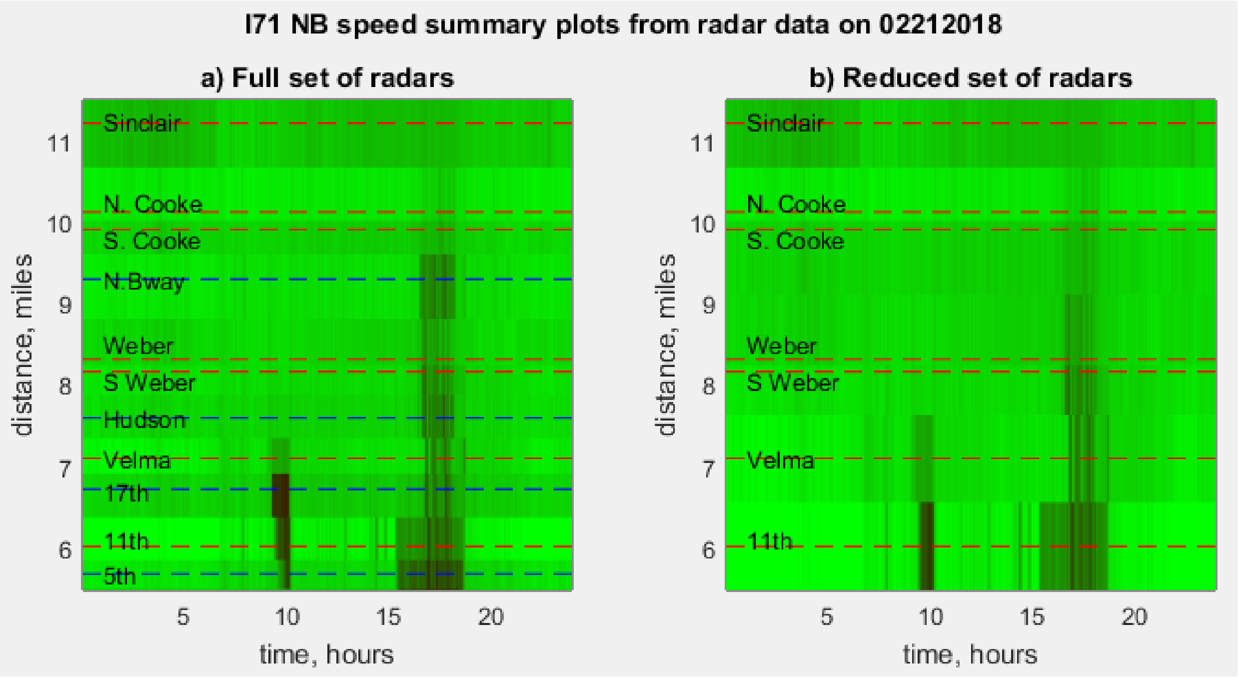

Figure B-3, I-71 NB speed summary plot generated using a) all the radars in the comprehensive (March) dataset and b) with only the radars in the November dataset

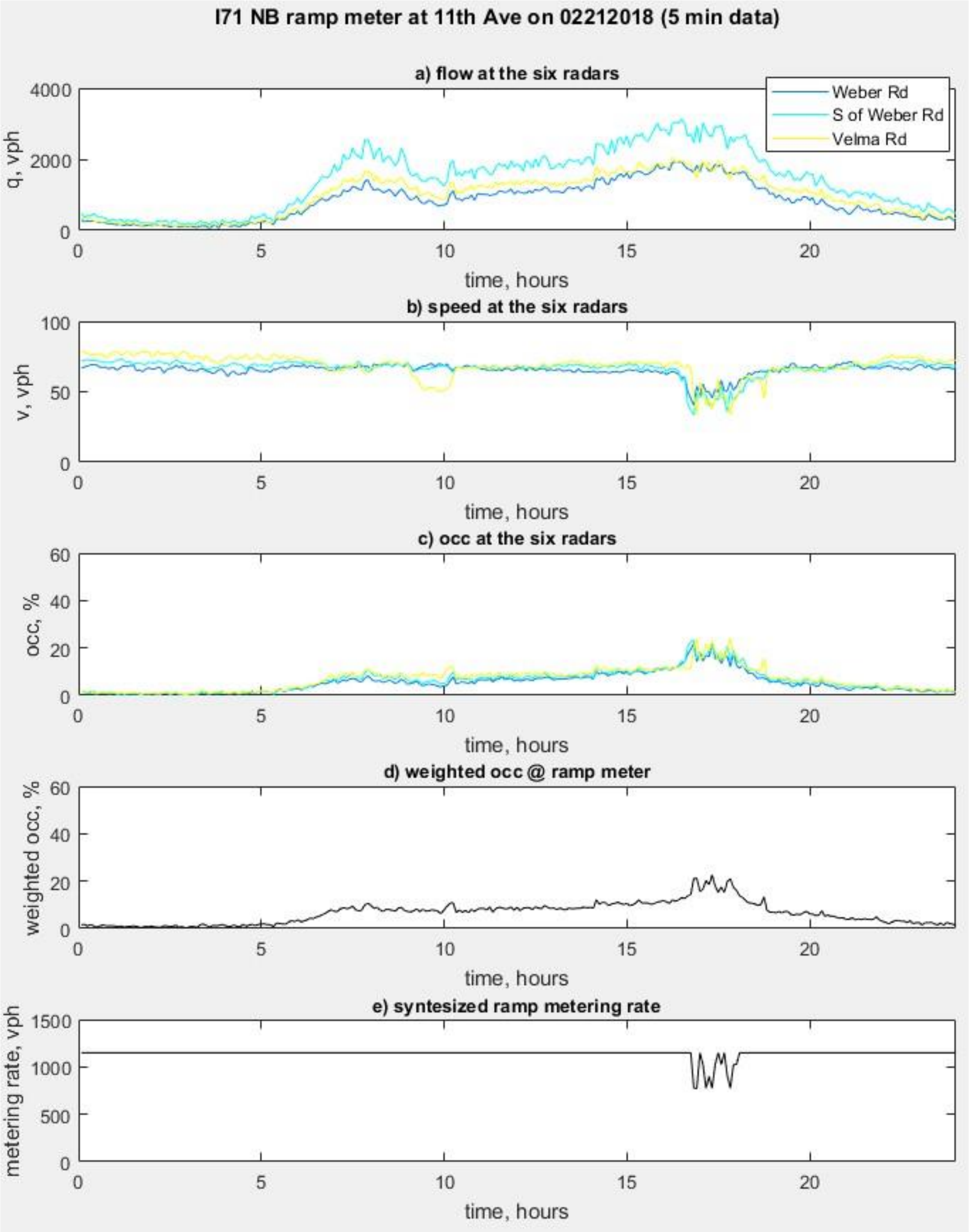

Figure B-4, I-71 NB ramp meter at 11th Ave on 2/21/2018 using 5-min data (using only the data from the three sensors available in the November dataset)

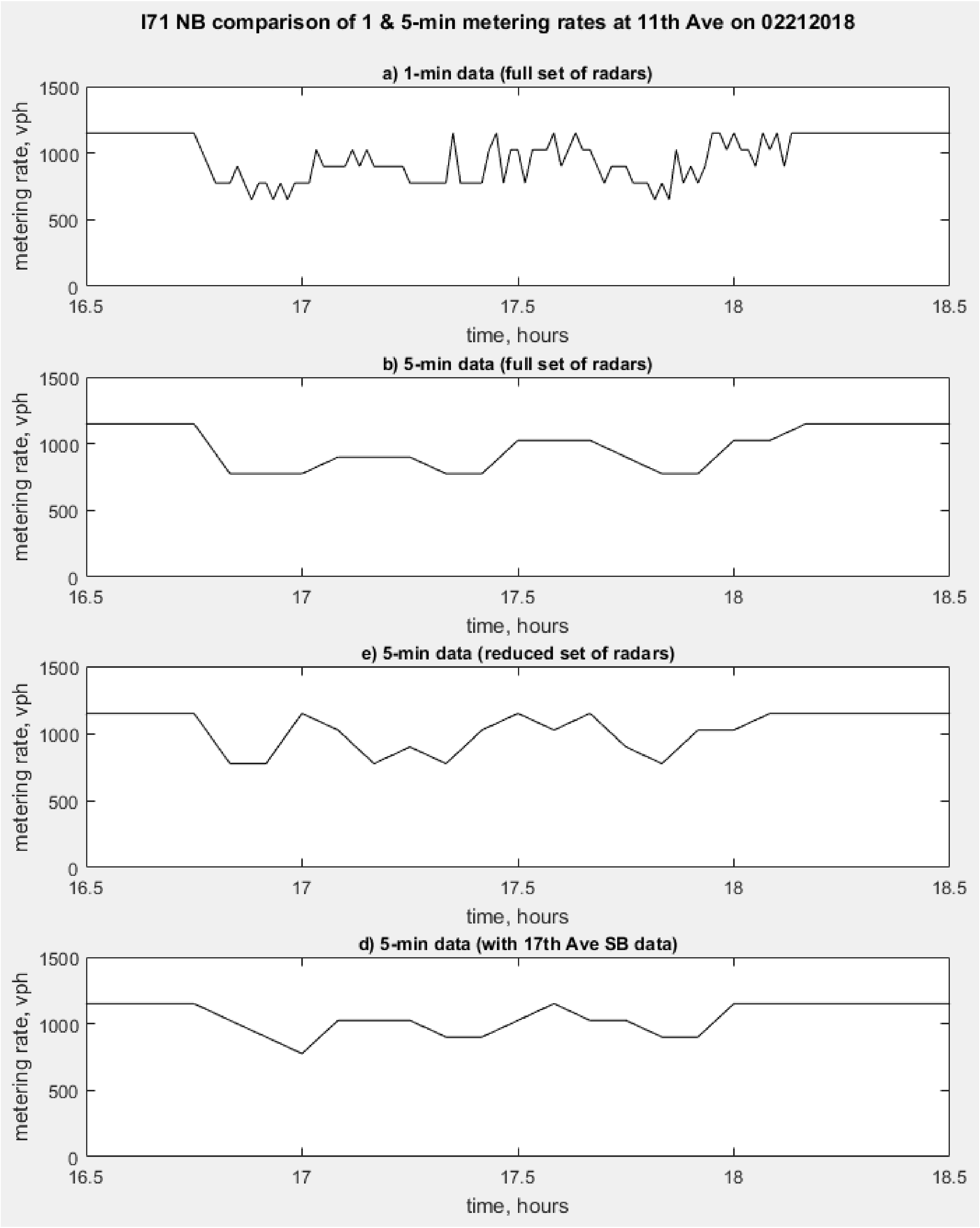

Figure B-5, I-71 NB comparing the ramp metering rates at 11th Ave on 2/21/2018 a) using 1-min data, b) using 5-min data, c) using 5-min data from reduced set of radars and d) 5-min with data from 17th Ave SB instead of NB

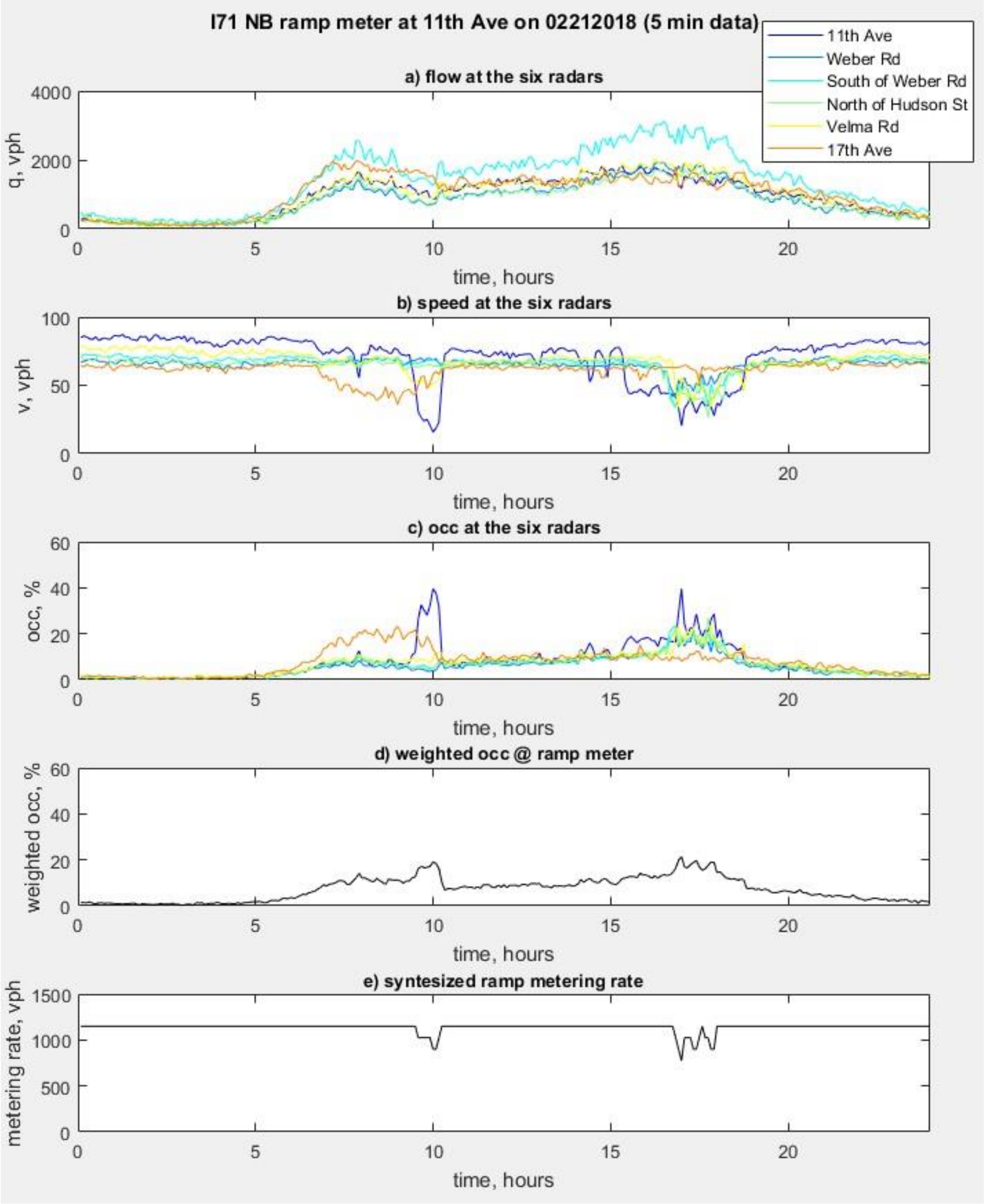

Figure B-6, I-71 NB ramp meter at 11th Ave on 2/21/2018 using 5-min data (with data from 17th Ave SB instead of NB)