Empirical Evaluation of Freeway Corridor Performance Before and After System-Wide Adaptive Ramp Metering System Implementation

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Abstract. A System-Wide Adaptive Ramp Metering (SWARM) system has been implemented in the Portland, Oregon metropolitan area, replacing the previous pre-timed ramp-metering system that had been in operation since 1981. SWARM has been deployed on six major corridors and operates during the morning and afternoon peak hours. This paper reports on the results of a “before” and “after” evaluation of the performance of two freeway corridors as part of ongoing efforts to measure the benefits of the new SWARM system as compared to the pre-timed system. The study benefitted from using the existing regional data, surveillance and communications infrastructure in addition to a regional data archive system. The evaluation revealed that the operation of the SWARM system, as currently configured in the Portland metropolitan region, produced mixed results when comparing the selected performance metrics to pre-timed operation. The development of the capability to log actual ramp metering parameters as part of an ongoing ramp metering performance reporting system is recommended.
INTRODUCTION

Ramp metering is one of the most common freeway management techniques and has been implemented in many cities around the world. At their most basic level, ramp meters are traffic signals located at on-ramps to control the flow of vehicles from the ramp onto the freeway. Based on a pre-defined or variable signal cycle, vehicles are allowed to enter the freeway at a rate of one or two vehicles per green (depending on the geometric configuration). As one of the few freeway corridor management tools available, ramp meters are usually implemented to achieve two main goals: 1) limit the amount of traffic entering a freeway in an attempt to prevent freeway flows from reaching capacity, and 2) break up the platoons of vehicles discharged from an upstream arterial traffic signal. Effective ramp metering has the potential to improve traffic flow, traffic safety and air quality; reduce congestion and fuel consumption; and manage demand by discouraging short trips (1).

Optimal ramp metering strategies are often debated but all involve tradeoffs between imposing delay on those vehicles already on the freeway and those attempting to enter. The amount of delay that can be imposed on vehicles at on-ramps is often constrained by physical limitations for queue storage. Early ramp metering systems in the United States were installed as pre-timed (or fixed-rate) systems, whereby the activation and deactivation times of the ramp meters and the metering rates throughout the day were pre-determined based on the analysis of historical data. This kind of metering strategy was designed to cope with “typical” traffic conditions and was not able to incorporate real-time variations in freeway conditions. Consequently, the effectiveness of the fixed-time system deteriorated substantially with large variations in freeway conditions or when non-recurrent conditions (e.g. incidents) occurred on freeways. With the enhancement of sensing and communication technology, this strategy has been replaced by more sophisticated algorithms that account for real-time traffic conditions.

One of these algorithms — System-Wide Adaptive Ramp Metering (SWARM) — has recently been deployed by the Oregon Department of Transportation in the Portland, Oregon metropolitan area, replacing an existing pre-timed strategy. The objective of this research was to compare selected freeway and ramp performance metrics for the pre-timed and SWARM operation. To facilitate this comparison, the ramp meters were operated for two consecutive weeks under each operation.

The primary purpose of this paper is to summarize the key results of this independent and ex post facto comparison of the metering strategies. The secondary purpose of this paper is to highlight the use of archived data to evaluate ramp metering. In this analysis, data were obtained from the regional ITS data archive, Portland Oregon Regional Transportation Archive Listing (PORTAL—see http://portal.its.pdx.edu), which logs data from the freeway surveillance and communications infrastructure) and supplemental sources. As will be described in more detail in the paper, with a few minor changes to the traffic management software to log ramp meter on/off times, and intended metering rates, a more comprehensive, ongoing, continuous evaluation framework could be implemented.

BACKGROUND

Ramp meters were first implemented in the Portland, Oregon metropolitan area by the Oregon Department of Transportation (ODOT) in January 1981, along a 6-mile stretch of Interstate 5. As part of the original ramp metering deployment, a surveillance system, including inductive loop detectors and closed circuit television (CCTV) camera systems was installed. This original ramp metering strategy was expanded to encompass all of the Portland freeway network which is shown in Figure 1 (1). Portland’s original ramp metering strategy used a pre-timed approach that determined the days and times that the meters were active as well as each ramp’s metering rate based on limited analysis of historical patterns.

With the development of a robust freeway surveillance and communication system, the deployment of a traffic-responsive metering approach became possible. In May 2005, the SWARM system was implemented in stages and is currently operational on all corridors except for I-405. SWARM was developed by the National Engineering Technology (NET) Corporation (2), now known as Delcan, under a contract with the California Department of Transportation (Caltrans). The algorithm was first implemented in Orange County (District 12) and later in Los Angeles and Ventura Counties (District 7) in the late 1990s.

A previous study reported on a literature review, some of the details of the SWARM algorithm, and a limited pilot study evaluation of the OR-217 southbound corridor (3). This paper focuses on the results of a regional study that analyzed freeway performance on two additional corridors. After extensive review of numerous criteria, two freeway corridors were selected for evaluation: I-205 northbound from the Gladstone to Division ramps; and OR-217 northbound from I-5 to US-26. These corridors are shown in Figure 1 with callouts showing ramp entrance and exits, lane geometry, and detector placement. A brief description of the corridors follows.

I-205 NB is a spur freeway that leaves the I-5 corridor south of the Portland metro area near the Wilsonville suburb and returns to I-5 north of Vancouver, Washington (as shown in Figure 1). The corridor is primarily three lanes. There are 9 on-ramps (all of which are controlled by ramp meters) and mainline loop detector stations are 1.1 miles apart, on average. The corridor is typically congested in both the morning and afternoon peak periods. In the
morning peak, there is congestion from the Sunnyside to Johnson Creek to Division stations which clears after the I-84 interchange near milepost 21. In the afternoon peak, congestion usually extends from the Sunnyside station to well downstream of the Division station. Construction of a new light rail facility was underway during the study period but did not directly impact northbound freeway operations (most construction is on a reserved right-of-way in the southbound direction).

The second freeway corridor, OR-217 northbound, is a 7-mile freeway that diverges from I-5 and finally merges onto US-26 (as shown in Figure 1). The freeway contains numerous lane adds and drops but is generally 2 lanes as shown in the corridor schematic. The corridor has 9 on-ramps, all of which are controlled by ramp meters. The average locations of loop detectors are 0.75 miles apart on average. The corridor is generally congested during the afternoon peak period and this congestion persists from the start of the highway near the I-5 and Kruse Way unmetered merge (upstream of the 72nd Ave. merge at MP 6.61) through the lane drops and additions to the Denney Ave off-ramp. The queue that forms often propagates upstream onto I-5 northbound. Downstream of the Denney station, the corridor has limited congestion in the afternoon.

METHOD

Archived traffic sensor data from the Portland Oregon Regional Transportation Archive Listing (PORTAL) was the primary data source used in this evaluation. PORTAL is designed as the official Intelligent Transportation Systems (ITS) data archive for the Portland metropolitan region. PORTAL has been archiving 20-second speed, count, and occupancy data from dual loop detectors positioned in each mainline lane just upstream of on-ramp locations since July 2004 (4). The archive also stores hourly weather (from NOAA), incidents, and messages posted on the region’s dynamic message signs as logged by the advanced traffic management system (ATMS). These data are archived in a PostgreSQL relational database management system (RDBMS) and are accessed through PORTAL’s web-based front end.

Three primary measures of mainline freeway performance used this evaluation were vehicle miles traveled (VMT), vehicle hours traveled (VHT), and delay. These measures are calculated as:

\[
\text{Vehicle Miles Traveled (VMT)} = (\text{Count, veh}) \times (\text{Distance between stations, mi})
\]

(1)

\[
\text{Vehicle Hours Traveled (VHT)} = (\text{Count, veh}) \times (\text{Distance between stations, mi}) / (\text{Speed, mph})
\]

(2)

\[
\text{Delay} = \text{VHT} - (\text{Count, veh}) \times (\text{Distance between stations, mi}) / (\text{Free Flow Speed, mph})
\]

(3)

where the free flow speed was assumed to be 55 mph. These metrics are calculated for each 20-second observation assuming that each detector station is representative of traffic conditions until the next downstream detector.

In the previous SWARM evaluation (3) average weekly peak period performance measures were compared. This approach did not allow analysis of ramp metering operation under various traffic conditions. In this paper, the comparison period was expanded from one week to two and analysis days were grouped by similar traffic conditions. Level of service (LOS) from the Highway Capacity Manual (5) were considered as a means to group traffic conditions but instead a hybrid blend of criteria and subjective judgment was used. This approach resulted in each analysis day being categorized as either 1) least, 2) moderately, 3) highly, or 4) very highly congested. This classification was accomplished by constructing plots of the fundamental traffic flow relationships of flow, occupancy, and speed for each station and day. Analysis of the plots for the number of 5-min observations in the congested regime at each detector station, coupled with time-space speed contour plots to determine the spatial extent of congestion, were used to characterize each day. Full details are in (6).

Any ramp metering approach attempts to balance increased ramp delay and mainline performance; thus any change in ramp delay is an important metric. Two measures are needed to quantify ramp delay: 1) ramp demand; and 2) ramp outflow. When ramp meters are not operational, the demand (vehicles entering the ramp) is equal to the ramp outflow. Ramp outflow is contained in the archived data. When the meters are operational, the demand generally exceeds the ramp outflow, resulting in queues and delays for the vehicles on the ramp. Without supplemental data collection, the demand (vehicles entering the ramp) is not known and ramp delay cannot be estimated. In the previous study, video-based analysis was used to estimate ramp demand and travel times (3). This approach was labor-intensive and only two ramps could be studied (travel times were sampled every 5 minutes). To expand the number of ramps and the amount of data collected, ramp demand was to be estimated using existing infrastructure and application of simple queuing theory in this evaluation. Nearly all of the ramps in the study corridors have detectors placed at the ramp entrance that can be used to capture entering volumes. Counts at these detectors, however, are not included in the archived data (the detector only serves to inform the local controller of potential queues). Using a programmable logic controller (PLC), input signals from the entering and departing vehicles were to be collected and aggregated over the peak analysis period. Unfortunately, while this data collection
method worked in a preliminary test and for some ramps and days in the study period, much of the data were too suspect to be used. The PLC devices did log meter activation times for three ramps on each corridor by logging the output control to the “meter on” variable sign. This information is not current available in the archived data and valuable for the analysis.

The final performance metric used was the ability of the existing communication infrastructure to handle the data intensive nature of the adaptive metering system. The SWARM algorithm requires consistent and accurate data from the ATMS system as well as the ability to send new commands (metering rates) to the controllers on a frequent basis. In pre-timed operation, the ATMS system polls each ramp controller to obtain each 20-second data packet. In normal operations, some base level of these communication polls “fail” and is indicated as such in the archived data. To estimate the overall impact of SWARM on corridor communications, the percentage of 20-second readings that were missing or corresponded to communication failures for each station were calculated.

STUDY PARAMETERS

A summary of the key study parameters are shown in Table 1. The evaluation period consisted of two weeks of pre-timed operation and two weeks of SWARM operation (though only weekdays were evaluated). In the pre-timed period, meters were generally active from 6:15–8:30 AM and 2:30–6:30 PM. When SWARM was implemented, the potential metering window was expanded to 6–10 AM and 1–7 PM. These expanded time windows were used as a basis for comparison (referred to as the morning and afternoon peak, respectively). For I-205 NB, the ramp meters operated under SWARM from September 10 to September 21 and under the pre-timed operation from September 24 to October 5. Both morning and afternoon peak periods were studied. On OR-217, meters operated under the SWARM system from November 5 to November 16 and were programmed to run under the pre-timed strategy from November 26 to December 7. Only the afternoon period was included in this evaluation. No adjustment period was incorporated since it was believed that the difference between the two operations is not significant enough for the majority of drivers to notice (and adjust trip behavior). The last operational metering rates used were used in this evaluation.

At the completion of the study period, the archived data were filtered for significant weather, incidents, or data quality issues and these days were excluded from the study. Weather information, incident logs, and communication error reports were taken from the PORTAL archive. For the I-205 corridor, six mornings and five afternoons were excluded from the study due to data quality issues, one morning was excluded due to weather, and two afternoons were excluded due to significant incidents (one of these afternoons also had data issues). For the OR-217 corridor, one pre-timed day and two SWARM days were excluded from the study due to data quality issues and two days were excluded due to weather (one of these afternoons also had data quality problems). These excluded days are shown in Table 1.

<table>
<thead>
<tr>
<th>Corridor</th>
<th>Peak Study Period</th>
<th>Pre-timed Dates</th>
<th>Excluded Days</th>
<th>SWARM Dates</th>
<th>Excluded Days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1–7 PM</td>
<td>9/24–10/5 2007</td>
<td>9/26, 10/3</td>
<td>9/10–9/21 2007</td>
<td>9/12, 9/13, 9/14, 9/18</td>
</tr>
</tbody>
</table>

1 – Data quality, 2 – Weather, 3 – Incident
FIGURE 1 Freeway network in the Portland, Oregon metropolitan area with corridor schematics callouts.
RESULTS

The results of the evaluation are summarized in Table 2. The number of days of pre-timed and SWARM operation available for comparison are shown in the table. For each peak period, the average of each performance metric (VHT, VMT, delay, and communication failures) was calculated and compared. For the communication metrics, days that were excluded from the analysis are not included. For brevity, these metrics are summarized as percent changes from the pre-timed to SWARM operation in Table 2. In addition to these metrics, the standard deviation of delay was also calculated. This metric was used to compare mainline reliability (less variability was assumed to imply more reliable performance). Where there were sufficient numbers of days, the table reports the p-value from a t-test of means on the delay metric (significance was assumed at the 95th percentile). The following subsections describe the results for each corridor.

TABLE 2 Summary of Performance Measures

<table>
<thead>
<tr>
<th>Corridor</th>
<th>Congestion level</th>
<th>Days pre-timed</th>
<th>Percent change</th>
<th>Delay (veh-hours)</th>
<th>P-value</th>
<th>St. Dev delay</th>
<th>Average % Communication Failures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>days swarm</td>
<td>VMT</td>
<td>VHT</td>
<td></td>
<td></td>
<td>Pretimed</td>
</tr>
<tr>
<td>I-205 NB AM</td>
<td>Least Congested</td>
<td>1-1</td>
<td>-1.0%</td>
<td>-1.9%</td>
<td>-5.1%</td>
<td>-</td>
<td>1.3%</td>
</tr>
<tr>
<td></td>
<td>Moderately</td>
<td>6-4</td>
<td>+1.4%</td>
<td>-0.1%</td>
<td>-5.4%</td>
<td>0.765</td>
<td>2.2%</td>
</tr>
<tr>
<td></td>
<td>Highly Congested</td>
<td>1-0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.8%</td>
</tr>
<tr>
<td></td>
<td>Overall</td>
<td>8-5</td>
<td>+0.9%</td>
<td>-3.7%</td>
<td>-18.1%</td>
<td>0.435</td>
<td>1.9%</td>
</tr>
<tr>
<td>I-205 NB PM</td>
<td>Least Congested</td>
<td>1-0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.9%</td>
</tr>
<tr>
<td></td>
<td>Moderately</td>
<td>4-4</td>
<td>+2.2%</td>
<td>+4.7%</td>
<td>+29.7%</td>
<td>0.262</td>
<td>1.4%</td>
</tr>
<tr>
<td></td>
<td>Highly Congested</td>
<td>2-1</td>
<td>-5.5%</td>
<td>-6.6%</td>
<td>-9.8%</td>
<td>-</td>
<td>1.1%</td>
</tr>
<tr>
<td></td>
<td>Very Highly</td>
<td>1-1</td>
<td>+7.2%</td>
<td>-14.0%</td>
<td>-37.5%</td>
<td>-</td>
<td>1.7%</td>
</tr>
<tr>
<td></td>
<td>Congested</td>
<td>8-6</td>
<td>+1.6%</td>
<td>+0.03%</td>
<td>-7.9%</td>
<td>0.896</td>
<td>1.5%</td>
</tr>
<tr>
<td>OR-217 NB PM</td>
<td>Least Congested</td>
<td>3-0</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.5%</td>
</tr>
<tr>
<td></td>
<td>Moderately</td>
<td>3-3</td>
<td>-4.3%</td>
<td>+3.3%</td>
<td>+29.8%</td>
<td>0.001</td>
<td>0.6%</td>
</tr>
<tr>
<td></td>
<td>Highly Congested</td>
<td>1-1</td>
<td>-2.7%</td>
<td>-3.3%</td>
<td>-4.6%</td>
<td>-</td>
<td>0.6%</td>
</tr>
<tr>
<td></td>
<td>Very Highly</td>
<td>1-3</td>
<td>-2.0%</td>
<td>+4.6%</td>
<td>+16.0%</td>
<td>-</td>
<td>0.7%</td>
</tr>
<tr>
<td></td>
<td>Congested</td>
<td>8-7</td>
<td>-3.1%</td>
<td>+10.6%</td>
<td>+55.0%</td>
<td>0.02</td>
<td>0.6%</td>
</tr>
</tbody>
</table>

I-205 Northbound, Morning Peak Period

A total of 8 pre-timed peak periods (6-10 AM) were compared to the five SWARM peak periods. Overall, the average VMT increased by only 0.87 percent, indicating that the amount of travel remained fairly constant between the SWARM and pre-timed periods. At the same time, mainline VHT decreased by 3.7% between the two periods which corresponded to an 18.1% improvement in mainline delay under SWARM. This decrease in delay, however, was not statistically significant (p = 0.435). The standard deviation of delay was less under the SWARM operation (overall and for all congestion categories). This indicates that the delay under SWARM was less variable and overall freeway performance was more reliable—a valuable benefit of the SWARM system. The ability of the
communication infrastructure to handle the additional demands was clearly impacted by the deployment of the SWARM algorithm. Under SWARM, average communication failures went from 1.9% to 10.4%.

When the performance measures are considered by congestion level, the results are similar. The results found that on the least congested days VMT decreased 1.0%, VHT decreased 1.9% and the average delay decreased 5.12% under SWARM operations. This difference could not be tested for significance (there is only one day to compare in each category). On moderately congested days VMT increased 1.4%, VHT decreased 0.1% and the average delay decreased 5.41%. This change was not statistically significant \((p=0.765)\). On highly congested only one pre-timed day was classified as highly congested. This day had significantly more delay than any other day in the study period and heavily influenced the overall averages. If this day was excluded from the overall results the mainline delay decreased 5% under SWARM (rather than the 18.1% including this day). The standard deviation of delay

I-205 Northbound, Afternoon Peak Period

In the afternoon, a total of 8 pre-timed days and 6 SWARM days were available for comparison. Overall, the corridor VMT increased by about 1.6% while mainline VHT remained nearly unchanged and average mainline delay decreased by 7.9%. This decrease was not statistically significant \((p=0.896)\). Average communication failures were about the same in the pre-timed period (1.5%) but slightly higher in the afternoon (14%). As an example, the scale of these failures can be seen rather dramatically in Figure 2 which shows the failures for each station and day in the corridor. It is clear that SWARM operation impacted data quality.

The analysis by level of congestion revealed a mixed picture of SWARM’s performance for this period. On moderately congested days (4 days in each), average VMT increased 2.2%, VHT increased 4.7% and the average delay increased 29.7%. This change was not statistically significant \((p=0.262)\). Despite the increase in delay, the standard deviation was 52.5% less under SWARM. On the highly congested and very highly congested days, SWARM operation resulted in a 9.8% and 37.5% decrease in mainline delay, respectively. These contrasting results are explored in more detail in the discussion section.

OR-217 Northbound Afternoon Peak Period

Overall, in the afternoon period VMT decreased 3.1% while mainline VHT increased by 10.6% in the SWARM period, compared to the pre-timed period. The average mainline delay increased by 54.95%; this increase was statistically significant \((p=0.02)\). Communication failures were generally lower on the OR-217 corridor. In the pre-timed period failures averaged 0.6% of all readings. Under SWARM the communication failure rate increased to 3.9%.

The results by congestion level revealed that SWARM operations resulted in more mainline delay for all but the highly congested days. On moderately congested days average VMT decreased 4.5%, average VHT increased 3.3% and the average delay increased 29.7%. This increase in delay was comparable to the increase in the I-205 PM for this congestion level (29.73%) and was statistically significant \((p=0.001)\). For highly congested days (only one day to compare) average VMT decreased 2.7%, average VHT decreased 3.3% and the average delay decreased 4.6% under SWARM compared to pre-timed operation. This difference could not be tested for significance. Finally, on very highly congested average VMT decreased 2.0%, VHT increased 3.3% and the average delay increased 16.0% over pre-timed. This difference could not be tested for significance.
FIGURE 2 Average Percent Communication Failures by Day and Station, I-205 northbound.

DISCUSSION

The PORTAL archived data is a rich source of information that can be mined both historically (as in this evaluation) and in an ongoing manner to characterize and monitor ramp meter system performance. In this section, a number of plots are presented which were used to diagnose the performance results presented in the previous section. These same plotting techniques could be used to measure changes in performance resulting from modifications to operational parameters, communication, or infrastructure that are made in the future and there are plans to automate these diagnostic plots in PORTAL.

Much of the performance information can be visually summarized by constructing speed contour plots from the 20-second archived data. Additional information can be presented by overlaying the activation and deactivation times of metering. A sample of this plot type is presented in Figure 3 for the I-205 corridor on September 17, 2007. The vertical axis in the figure represents distance along the freeway as marked by milepost, and the horizontal axis corresponds to time-of-day. Travel direction is from bottom-to-top. The color scale represents average speeds over 20-second period as estimated from loop detector readings, and the ranges of speeds and the corresponding colors are provided on the right side of each figure. The blue lines represent the duration of metering under SWARM at three ramps (Sunnyside, Johnson Creek, and Powell). The purple dots represent the pre-timed metering on/off times that would have been implemented.
From a traffic management perspective, this visualization is very useful. First, communication failures are clearly evident. In the data, failures are represented as “zero” speed readings. The large blocks of red at the Clackamas and Lawnfield stations from 6:00-11:00 are not representative of congestion but rather communication failures. In addition, the “chatter” of red at the Sunnybrook station indicate intermittent data outages (and clearly corresponds to the SWARM operating window). The same chatter at the Powell station appears to have triggered intermittent operation of metering under SWARM from the 13:00 to 16:00 time period. Lastly, it is easy to see in these plots the adaptive nature of the SWARM as the metering times are clearly different from the pre-timed operation on this particular day.

**FIGURE 3 Speed Contour for I-205 northbound, September 17, 2007 with meter activation times.**

While a plot such as Figure 3 is useful for a quick system diagnostic, more detailed analysis is required to investigate the varying performance found in the results. One useful plot to construct is a contour plot of the changes in vehicle hours of delay. As an example of this diagnostic technique, the change in average corridor delay for moderately congested days on the I-205 afternoon corridor is used. Under SWARM operation, these “moderately congested” days saw a substantial increase (29.7%) in delay for the afternoon peak period.

Figure 4 was constructed to show the changes in moderately congested average delay under SWARM in time-space plane. The x-axis and y-axis are the same as Figure 3. In the plot, the color scale represents the change in average delay over 5 minutes as estimated from loop detector readings. The key is provided on the right side of the figure. Green colors indicate that SWARM operation resulted in less delay while red colors reveal the opposite. The figures communicate the spatial and temporal variability in the comparisons; further plots are used to delve into the trends.

Inspection of Figure 4 reveals that the increase in delay was concentrated in two areas: Johnson Creek to Powell between 3:45 PM and 4:30 PM and at Clackamas to Lawnfield before 3:30 PM and after 6:00 PM. It is interesting to note that while the entire time period (1–7 PM) experienced an increase in delay under SWARM, this increase was neither systematic nor corridor-wide; there are many time-space periods that benefited from SWARM operation.

To supplement Figure 4, additional plots were constructed to further explore decreased performance in the area between the Johnson Creek to Powell stations. These plots, shown in Figure 5, contain 5-min time-series plots of mainline flow (vph), ramp flow (vph) and mainline speed (mph) over time at Sunnyside, Johnson Creek, and Foster for two moderately congested days. In order from top to bottom, these lines are orange, blue and red respectively. Vertical dashed lines in the figure indicate the meter on and off times as recorded by the PLCs or the pre-timed ramp meter times (note that SWARM on-off time were not available at Foster). Pre-timed operation
(10/1) is shown in the top row and SWARM operation (9/17) on the bottom row. The following points are annotated on the figure:

1. At Sunnyside, SWARM metering (shown by the dashed vertical line) started later than it would have in the pre-timed strategy. However, SWARM did activate as soon as allowed (13:00) at busiest station (Johnson Creek).
2. The metering rate can be estimated from the ramp flow time series (red bottom line). Inspection of the plots reveals that when metering did start in the SWARM period, it was always higher than the corresponding pre-timed metering rate. This higher metering rate is consistent for the three stations presented here.
3. While it is difficult to attribute the exact cause as related to metering, the mainline speed drops occur much earlier at the Johnson Creek station under SWARM despite the earlier start of metering.
4. As shown in all plots, the mainline volumes peak in the 3–5 PM time period.

Taken together, it appears that the primary reason for decreased mainline performance under SWARM is related to the higher metering rates. On these moderately congested days, the observation is that the higher SWARM metering rates initiated a flow breakdown as mainline volumes began to peak. The higher metering rates observed under SWARM are partially explained by the system configuration. When ODOT implemented SWARM in 2005 and 2006, it anticipated that SWARM would admit fewer vehicles to the freeway as found in SWARM evaluations in Southern California (7,8). ODOT conservatively used a high maximum metering rate in order to gain confidence in the system and to prevent vehicles from backing up onto city arterials.

To explore the contrasting results on the highly and very highly congested days where SWARM operation resulted in lower average corridor similar plots were constructed. In the delay change plot in Figure 6, the time periods with better SWARM performance (bright green) are again concentrated at the Johnson Creek to Powell ramps. Unlike the moderately congested days, the improvement under SWARM appears to be corridor-wide. As before, similar plots for the three stations comparing two very highly congested days are shown in Figure 7. The following points are annotated on the figure:

1. At Sunnyside and Johnson Creek, SWARM activates as early as allowed (13:00). Again, the metering rate is slightly higher than the pre-timed operation. Also, note that the pre-timed meters deactivate while congestion is still present at the Sunnyside ramp, perhaps delaying the queue clearance and increasing the duration of congestion.
2. At Johnson Creek in the pre-timed operation, it is clear on this highly congested day that mainline speed drops well before metering starts.
3. While difficult to draw clear conclusions, comparisons of the mainline speed over time appear to indicate fewer oscillations in the SWARM period particularly for the Sunnyside and Johnson Creek stations (less so at Foster). This implies more stable operations (better reliability).
4. While not confirmed by data collection, it is apparent in the archived data that metering activates at around 1:30PM under SWARM.

Taken together, it appears that the primary reason for improved mainline performance under SWARM is related to the adaptive metering times. SWARM’s earlier activation time on the highly congested and very highly congested days was able offset higher metering rates and decrease mainline delay.
FIGURE 4 Changes in moderately congested average delay under SWARM in time-space plane, I-205NB PM

FIGURE 5 Annotated plots of mainline flow (vph), ramp flow (vph) and mainline speed (mph) over time with meter activations at Sunnyside, Johnson Creek, Foster stations, 9/17/2007 and 10/1/2007.

(1) Metering at Sunnyside activated later under SWARM than pre-timed but earlier at Johnson Creek

(2) Slightly higher metering rates under SWARM than pre-timed.

(3) Earlier speed drop in mainline speed.

(4) Peak mainline flow at approximately 3-5 PM (15-17).
FIGURE 6 Changes in highly and very highly congested delay days under SWARM in time-space plane, I-205NB PM.

FIGURE 7 Plots of mainline flow (vph), ramp flow (vph) and mainline speed (mph) over time with meter activations, Sunnyside, Johnson Creek, Foster, 9/28/2007 and 9/21/2007.
CONCLUSIONS

This evaluation revealed that the operation of the SWARM system, as currently configured in the Portland, Oregon metropolitan region, produced mixed results. For the I-205 corridor, the results were generally positive. In the morning peak period, SWARM operation resulted in decreased mainline delay and decreased variability in the delay. For the afternoon peak period, improvements were also found with the exception of moderately congested days which saw an increase in mainline delay. On the OR-217, however, significant increases were found in overall average delay. Reliability also decreased under SWARM for this corridor.

The contrasting results for SWARM performance between the two freeway corridors can partially be explained by the general differences between the two facilities. OR-217 is a relatively short freeway (7 miles) bounded on both ends by freeway-to-freeway interchanges. The ramp spacing is generally short (0.75 mile average) and freeway contains numerous auxiliary lane drops and adds. In the afternoon, the unmetered merge with Kruse Way and I-5 NB traffic results in recurrent congestion. The I-205 corridor is unbounded, has greater ramp spacing (1.07 mile average), and maintains three through lanes. Only 1 auxiliary lane add/drop is present. Peak per mainline lane flows are generally higher on OR-217 than I-205. At the 99W WB, Greenburg, and Scholls detector stations the average flow per lane in the afternoon analysis period was 1,470, 1,660, and 1,720 vph, respectively. At the Sunnyside, Johnson Creek, and Foster stations the average flow per lane was 1,320, 1370, and 1440, respectively.

While not presented in this paper for brevity, it was confirmed from the empirical evidence that in all cases evaluated that the SWARM algorithm as configured by ODOT allowed more vehicles to enter the freeway mainline. The higher per lane flows combined with less desirable geometry on OR-217 may explain why higher metering rates on OR-217 produced significant increase in mainline delay. To improve system operations, tunable SWARM parameters that distribute the volume reduction (or excess if local density is smaller than the required density) to upstream on-ramps based on demand, queue storage of each on-ramp should be reevaluated.

These conclusions, however, must be tempered because of lack of ramp demand data. If an assumption is made that ramp demand changes correspond with the measured freeway VMT changes, it is likely that ramp delay decreased under SWARM operation (i.e. more vehicles were allowed on the freeway which would equate to lower delay for vehicles on the ramps). This would be consistent with the previous study but is unverified (3).

Another important finding of this evaluation was that implementation of the SWARM algorithm resulted in significantly more data communication failures. While this outcome is specific to the ODOT communication infrastructure and hardware it was not anticipated. These communication failures have the potential to impact other traveler information programs that depend on the freeway surveillance data as well as the SWARM algorithm. Following the completion of this study ODOT has investigated and implemented measures to improve communications.

Finally, one of the intentions of this research project was to encourage ongoing evaluation and continuous improvement of the ramp metering system, and in general the overall freeway management system. It is clear from the analysis that meter activations times and rates are necessary to evaluate system performance. Incorporating additional logging capabilities into the SWARM system would make it easier to evaluate system operations on an on-going automated basis. In addition, the freeway surveillance system should be modified to incorporate vehicle counts from the ramp queue loop detectors. While not successful in this study, the simple queuing approach should work if data are appropriately collected. For an on-going evaluation of the ramp meter system, these data are critical.

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