

## **Evaluating the Benefits of a System-Wide Adaptive Ramp-Metering Strategy in Portland, Oregon**

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## ABSTRACT

A System-Wide Adaptive Ramp Metering (SWARM) system is being implemented in the Portland metropolitan area, replacing the previous pre-timed ramp-metering system. SWARM has been deployed on six major corridors and operates during the morning and afternoon peak hours. This study entails a “before” and “after” evaluation of the benefit of the new SWARM system as compared to the pre-timed system using the existing data, surveillance and communications infrastructure. In particular, the objective of this study is to quantify the system-wide benefits in terms of savings in delay, emissions and fuel consumption, and safety improvements on and off the freeway due to the implementation of the SWARM system. A pilot study was conducted for two weeks on a 7-mile freeway corridor in an attempt to develop a strategic design for the future regional-level study. This paper discusses the selection process of the study corridor, experimental design, and the results that were obtained from the pilot study.

## INTRODUCTION

Ramp meters were first implemented in the Portland metropolitan area by the Oregon Department of Transportation (ODOT) in January 1981, along a 6-mile stretch of Interstate 5. Portland’s original ramp metering strategy employed a pre-timed algorithm that determined the times that the meters were active as well as each ramp’s metering rate based on historical patterns. As part of the original ramp metering deployment, a surveillance system, including inductive loop detectors and closed circuit television (CCTV) systems, is in place. This original ramp metering strategy was shown to be effective (1), and the ramp-metering system was expanded throughout Portland’s freeway network. The freeway system in Portland currently consists of 138 metered on-ramps. Since May 2005, a system-wide adaptive ramp metering (SWARM) system has been implemented in stages in the Portland metropolitan area and is currently operational on six major freeway corridors.

The objective of this research is to use the existing data, surveillance and communications infrastructure to evaluate the new SWARM ramp metering system in the Portland metropolitan area as it is being deployed. While the SWARM system is designed to be more effective than the current ramp metering strategy, the true benefits of the new system have not yet been quantified. Using an existing data stream and infrastructure, a true “before” and “after” evaluation of the benefits of the new SWARM system is on-going. The findings from this study will aid in the optimal deployment of current SWARM system and will be transferable to other regions in Oregon as their planned ramp metering systems come on line in the future.

This manuscript describes the experimental design of the pilot study that was conducted on a freeway corridor for two weeks in June 2006 and the results that were obtained. The SWARM was shut-off for one week and turned back on the following week. During the shut-off period, ramp meters operated at the pre-timed rates that were deployed prior to the SWARM implementation. Data were collected from loop detectors as well as video data from the CCTV cameras to measure conditions on both the freeway mainline and on-ramps.

In the following section, the SWARM algorithm and previous studies relevant to this study are described. The next section presents the experimental design of the pilot study including the corridor selection process and the data collection efforts. The results from the corridor-level evaluations and the analysis of freeway queue dynamics are described following that. Future work and concluding remarks are provided in the final section.

## BACKGROUND

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 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, as is the case in Portland, Oregon.

Traffic responsive ramp-metering algorithms were developed in an effort to cope with daily fluctuations and non-recurrent freeway conditions. In these algorithms, metering rates and activation/deactivation times at individual ramps are determined proactively in response to real-time freeway conditions along corridors. Many traffic-responsive ramp-metering algorithms have been developed, and some of them have been evaluated for their benefits via field-testing (e.g. 2-4) or simulations (e.g. 5). Various traffic-responsive ramp-metering strategies and their test results are described in numerous publications (e.g. 5, 6).

The system-wide adaptive ramp metering (SWARM) system was developed by the National Engineering Technology (NET) Corporation 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.

In the SWARM strategy (7), a freeway network is divided into contiguous freeway systems, whereby each freeway system is bounded by the locations of two bottlenecks (identified by loop detectors) and contains multiple on-ramps and off-ramps in between. For each system, there are two “competing” modes of SWARM operations—global and local modes. Two metering rates are computed from the global and local modes, and the more restrictive rate is deployed in the field.

The global mode operates on an entire system based on forecasted densities at the system’s bottleneck location. The densities around the bottleneck are forecasted by performing a linear regression on a set of data collected from the immediate past and applying a Kalman filtering process to capture non-linearity. A tunable parameter,  $T_{crit}$  is the forecasting time-span into the future (labeled in Figure 1), which is usually several minutes. The *excess density* (also labeled in Figure 1) is then the difference between the forecasted density and a pre-determined threshold density that represents the saturation level at the bottleneck. This *excess density* is converted to the (current) *required density* to avoid congestion in  $T_{crit}$ ; i.e.,

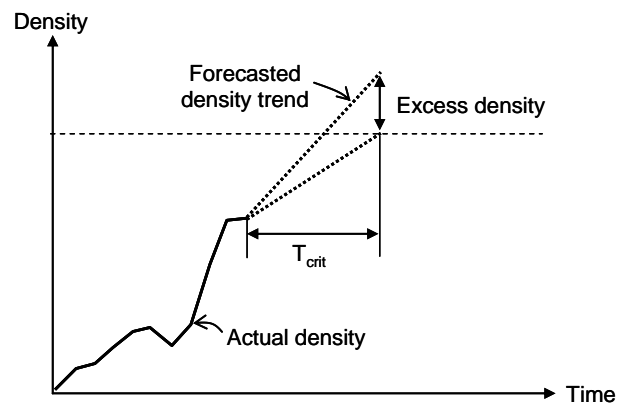
$$\text{Required density} = \text{current density} - (\text{excess density} / T_{crit})$$

The corresponding volume reduction at each detector station is computed as

$$\text{Volume reduction} = (\text{local density} - \text{required density}) * (\text{No. of lanes}) * (\text{distance to next station})$$

The *volume reduction* (or *excess* if local density is smaller than the required density) is distributed to upstream on-ramps within the system according to the distribution (or weighting) factors pre-determined based on demand, queue storage, etc. of each on-ramp.

The local mode operates with respect to (real-time) local traffic conditions near each ramp. The local metering system can be any existing local traffic-responsive algorithm.



**FIGURE 1** Forecasting theory of SWARM global mode.

SWARM has a built-in capability to clean the defective data in case of loop detector failures, which improves the robustness of the algorithm. With this feature and accurate prediction models, SWARM is able to accurately detect and avoid potential congestion in advance. However, if the prediction models are poor or if supporting loop detector data are not accurate, it can generate limited benefits (5).

SWARM was implemented in parts of southern California and is expected to be deployed on the majority of California’s freeway network (8). The SWARM system implemented in Orange County could not be evaluated for a number of reasons. MacCarley et al. (9) noted that Caltrans did not receive proper training or documentation related to SWARM operations. Moreover, the algorithm itself did not seem to operate properly when tested in the field for six weeks.

The implementation and evaluation of SWARM was more successful in Los Angeles and Ventura Counties, California. There are over 1,200 ramp-meters in that network. Before the implementation of the SWARM system, Caltrans District 7 operated pre-timed and local traffic-responsive ramp metering throughout their freeway network in Los Angeles and Ventura Counties. The benefits of the new SWARM algorithm as compared to the previous ramp-metering operations were evaluated during the morning peak periods on a freeway corridor (westbound Route 210) that contains 20 controlled on-ramps (detailed descriptions of the evaluation methods and results are included in 10). Caltrans tested three operational strategies: global mode only, local mode only, and a combined strategy. Each strategy was evaluated for several days between September, 2001 and January, 2002.

Caltrans found that the combined strategy generated the most benefits in terms of traffic conditions on the mainline freeway. In particular, it increased the mainline speed by 11% during the morning rush, decreased the travel time by 14%, and reduced the freeway delay by 17%. Furthermore, on-ramp queue lengths at the 9 busiest on-ramps increased by over 40%.

## EXPERIMENTAL DESIGN

The freeway system in the Portland metropolitan region (see Figure 2(a)) consists of several Interstate and U.S. Highways and State Routes, serving local commuters, through traffic, as well as freight trucks from/to the Portland International Airport and the Ports of Portland. A number of freeways exhibit recurrent congestion during the morning and afternoon peak periods, and the on-ramps on these major freeways are metered during the peak hours (e.g. 6-10 AM and 1-7 PM). There are seven major freeway corridors, where the Oregon Department of Transportation (ODOT) manages traffic congestion via ramp metering. The SWARM system has been implemented on six of these corridors in stages since May 2005.



FIGURE 2(a) Freeway network in the Portland metropolitan area.

### Freeway Corridor Selection Criteria

The aim of the pilot study described here was to conduct a shut-off experiment of the SWARM operation for a short duration, and come up with a strategic design for a future regional-level evaluation. To this end, the following criteria were developed to select a corridor that can most likely achieve our current objective.

1. **Level of congestion:** Duration and spatial extent of congestion should be reasonably large (i.e., no localized queues). This allows for an assessment of the SWARM performance while the global control interacts with the local controls at multiple on-ramps.
2. **Spatial extent of queues:** Queue(s) should be isolated within a corridor; i.e., the location of a recurrent bottleneck (the head of a queue) and the tail of the resulting queue should reside within the same corridor. This ensures a comprehensive evaluation on a single freeway corridor without having to evaluate other intersecting freeways simultaneously. This facilitates more manageable allocation of resources and data collection efforts.
3. **Loop detector spacing:** The spacing between loop detectors should be reasonably small so that the data from loop detectors reflect actual conditions prevailing on the freeways as closely as possible.
4. **Data quality:** The pilot study involves shutting off the SWARM system for a short duration. During this period, it is imperative not to experience communication failures for extended periods between the loop detectors and the Traffic Management Operation's Center (TMOC). In addition, the accuracy of evaluation results will depend on the accuracy of loop detector data received. The recent history of data quality at all corridors was taken into consideration.
5. **Construction schedule:** Construction on several corridors is ongoing or scheduled for the near future. The construction schedules were taken into consideration in selecting a corridor and scheduling the pilot study.
6. **Stability of the SWARM system:** The SWARM system implemented in the field should be stable; i.e., all ramp meters should be working properly, and the actual metering rates deployed should match the theoretical rates determined from the SWARM algorithm.
7. **Corridor length and the number of on-ramps:** The length of freeway and the number of on-ramps were considered to make sure that the pilot study can be conducted in a manageable way in terms of time and resources. In general, a 5-10 mile corridor was considered to be manageable for the pilot study.

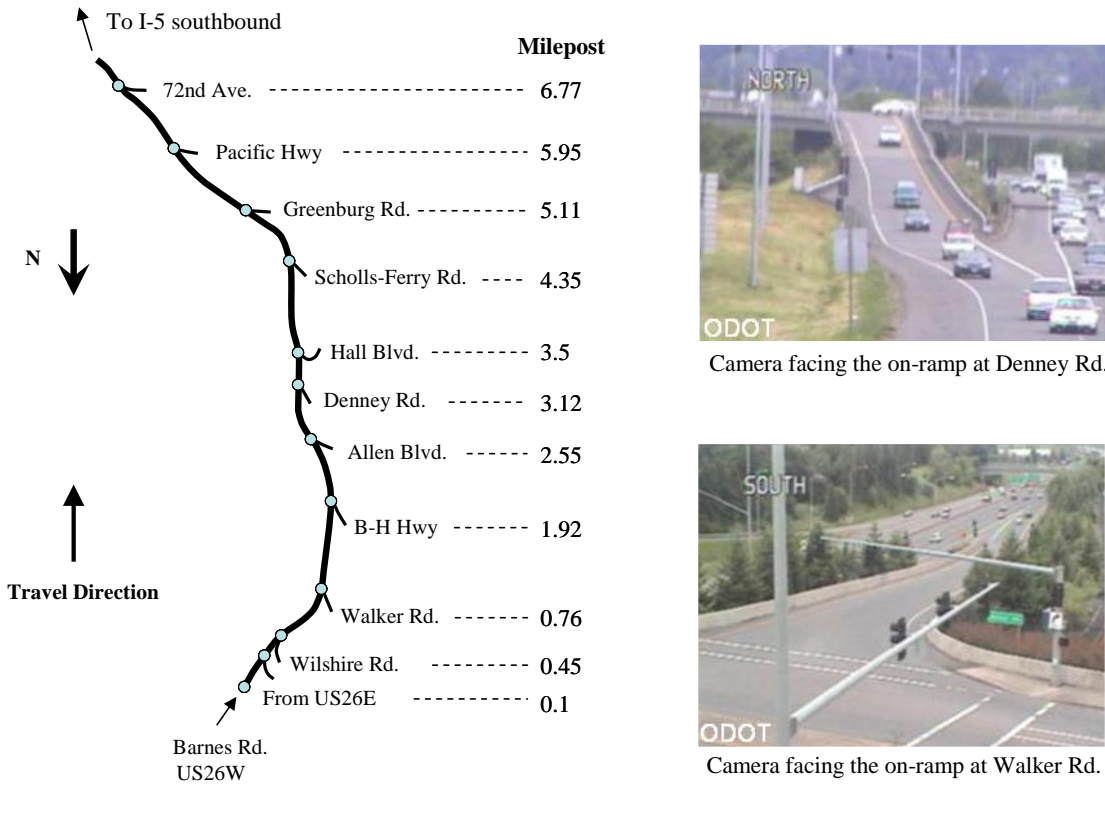
The feasibility of analyzing alternative routes was also considered to measure traffic diversion and its impact on alternative routes. However, this criterion was not incorporated at the final stage of selecting a corridor because 1) identifying all possible alternative routes would be difficult, and 2) it will require extensive data collection efforts even for a small number of routes, which may not be feasible in terms of resources and cost allocation.

The existence of a high-occupancy-vehicle (HOV) lane and transit service was also considered since the change in ramp-metering operation can affect their demand. However, it was believed that the change in demand in the short term would be negligible.

### **Study Corridor: Freeway**

ORE 217 southbound was determined to be most suitable for the pilot study in terms of congestion patterns, coverage of loop detectors, and data quality. ORE 217 southbound is a 7-mile corridor that serves commuters during peak periods between downtown Portland and suburban areas in Beaverton, Tigard, Lake Oswego, etc. It diverges from US26, intersects with Highways 8 (Canyon Rd.), 10 (Beaverton-Hillsdale Hwy), 210 (Scholls-Ferry Rd.), and 99W (Pacific Hwy), and finally merges onto I-5 southbound (see Figure 2(b)).

This freeway corridor contains 12 on-ramps, 10 of which are controlled by ramp meters. The ramp-metering system on this freeway is supported by 36 loop detectors and 9 CCTV cameras. The locations of loop detectors are 0.75 miles apart on average (minimum of 0.31 miles and maximum of 1.23 miles). SWARM was implemented on this corridor in early November 2005.



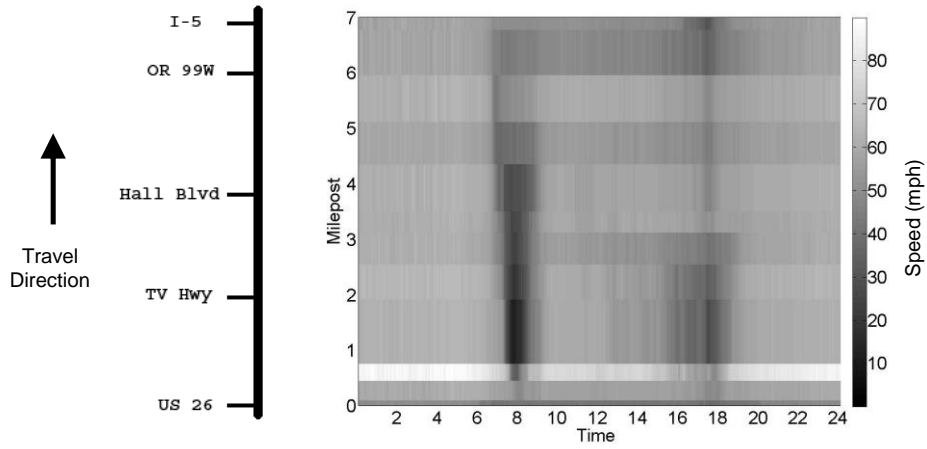
**FIGURE 2(b) Schematic of ORE 217 southbound and sample CCTV camera views.**

Figure 3(a) and 3(b) show two speed contour plots that were constructed from the average readings taken for one month prior to the SWARM implementation and one month after the implementation. The vertical axis in each figure represents distance along the freeway as marked by milepost, and the horizontal axis corresponds to time of day. The grey scale represents average speeds over 5 minutes 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 extent of congestion is illustrated by the dark time-space region corresponding to low average speeds.

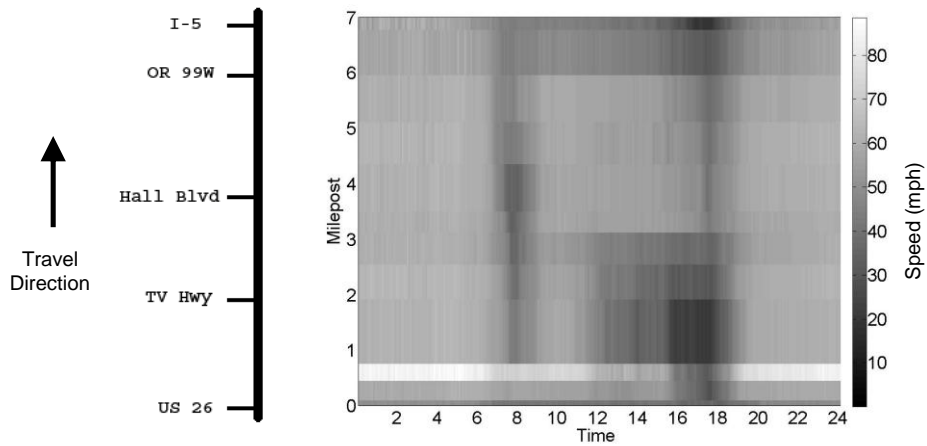
Queues typically form on this corridor during each morning and afternoon rush. In the morning peak period, a recurrent bottleneck is located between Scholls-Ferry Rd. and Greenburg Rd., and the resulting queue propagates over 4–5 miles upstream. The bottleneck activates due to large inflow from the on-ramp at Scholls-Ferry Rd. and remains active for several hours (7 – 9 AM). During this period, traffic speeds can drop as low as 20–30 mph along some portions of the freeway (e.g. near Beaverton-Hillsdale Highway).

During the afternoon peak, a queue forms between Denney Rd. and Allen Blvd. and propagates several miles upstream (often to Barnes Rd.). However, a queue from this active bottleneck is often overridden by another queue that forms on I-5 southbound and spills over to ORE 217 southbound. The duration of congestion is typically longer in the afternoon, and the condition can become severe (especially when the queue from I-5 southbound reaches this corridor), such that traffic speeds can fall below 20 mph for extended periods.

Based on the observed congestion patterns, data collection and analysis were focused on the morning peak periods, where a system-wide evaluation is possible within the corridor.



**FIGURE 3(a) Speed contour for ORE 217 southbound: pre-timed: weekdays in October, 2005.**



**FIGURE 3(b) Speed contour for ORE 217 southbound: SWARM: weekdays in December, 2005.**

**Study Corridor: On-ramps**

On this corridor, there are 12 on-ramps serving traffic from the local areas and from other highways (Highways 10, 8, 210, and 99W). For each of these on-ramps, we measured volumes during the peak hours and the queue storage space (in feet) in order to assess whether on-ramp traffic is adequately accommodated without causing additional delays to local traffic during the rush. In particular, the average hourly volume during each peak was computed based on the total peak-hour volume. The queue storage space was provided by the Oregon Department of Transportation (ODOT). The number of lanes on the ramp was taken into consideration in estimating the storage space.

The bar chart in Figure 4 corresponds to average hourly volumes during the morning rush (6 - 9 AM), and the storage spaces are shown as a line chart. The average hourly volumes were measured from the data taken from April 3 to April 7, 2006, which were the most recent weekdays at the time of analysis. The traffic conditions on

these days were typical for this corridor. (There are 10 on-ramps in this plot, missing the freeway connector from US26E to ORE217 and the on-ramp at Barnes Rd. The data for the freeway-to-freeway connector were not available since the ramp is not controlled. Data at the Barnes Rd. on-ramp are available but were omitted in this analysis since the ramp is located where the freeway begins and is regarded more as part of the mainline.)

The figure shows that the on-ramps at Beaverton-Hillsdale Highway and Scholls-Ferry Rd. carried over 700 vph on average from 6–9 AM. The amount of volumes at these two ramps was nearly twice as large as the amount at the other on-ramps. The figure also illustrates which on-ramps are at risk of queue spill-over to local streets during the peak hours. It appears that the on-ramp at Allen Blvd. is at the highest risk compared to the other on-ramps. (72nd Ave. is located downstream of the recurrent bottleneck and hence, is unlikely to experience a queue spill-over.) Based on these preliminary observations, the on-ramps at Beaverton-Hillsdale Highway, Scholls-Ferry Rd, and Allen Blvd. were given priorities in the video data collection plan so that delays on these on-ramps as well as queue length can be analyzed adequately.

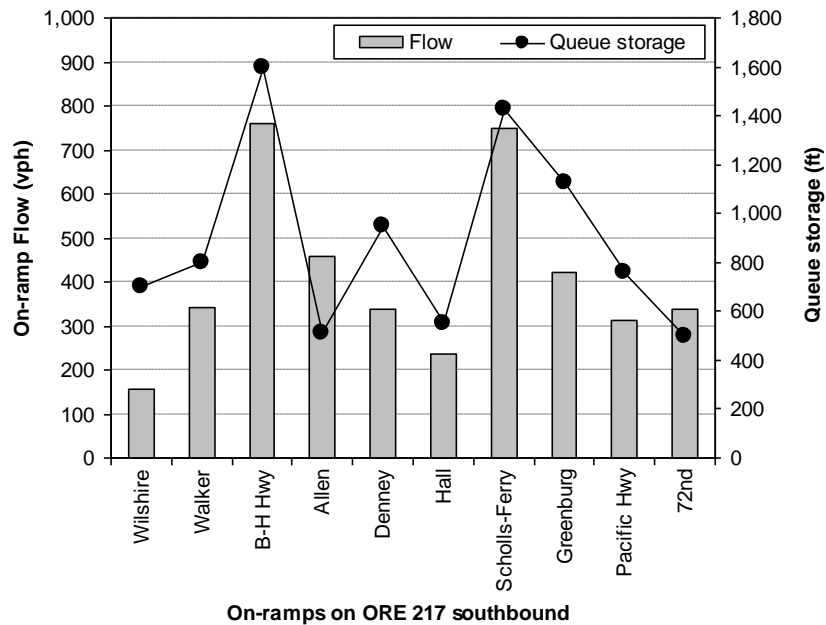


FIGURE 4 Average hourly volumes vs. on-ramp queue storage (6 – 9 AM).

### Data Collection Efforts

Data collection for the pilot study was conducted for two weeks in June 2006. The SWARM system was turned off from June 19 to June 23 to obtain necessary *before* data, and the ramp meters operated based on the historical pre-timed rates instead. SWARM was back in operation on June 26, and *after* data were collected during the same week (from June 26 to June 30).

Changes in freeway conditions were measured in terms of flow, speed, travel time, delay, vehicle-miles-traveled (VMT), and vehicle-hours-traveled (VHT). All these measures were obtained directly or estimated from the data acquired from the loop detectors. On ORE 217 southbound, there are 36 loop detectors including the ones at the metered on-ramps. These detectors are maintained by ODOT and produce vehicle count, occupancy, and estimated speed at the sampling interval of 20 seconds. (The detectors at the on-ramps produce vehicle counts only.)

These 20-second data are archived in the Portland Oregon Regional Transportation Archive Listing (PORTAL, <http://portal.its.pdx.edu>) along with other types of data (e.g. weather data). In addition to SWARM's built-in data quality control process, we further tested a sample of loop detector data in March of 2006 for accuracy. The aim was to assess the performance of loop detectors on ORE 217 southbound and make recommendations on which loop detectors need immediate attention for repair, adjustment, etc. Individual 20-second readings from loop detectors were flagged if they failed any of the tests listed below.

- Volume > 17 ( $\approx$  3060 vph)
- Occupancy > 95 %
- Speed > 100 mph
- Speed < 5 mph
- Speed = 0 when Volume > 0
- Speed > 0 when Volume = 0
- Occupancy > 0 when Volume = 0

These tests detect physically invalid readings (e.g. volume = 0 and speed > 0) or readings that correspond to unlikely events (speed > 100 mph in 20 seconds).

We measured the percentage of readings that failed each category of the tests listed. The majority of the loop detectors on ORE 217 southbound (out of 36 loop detectors) showed a low percentage (less than 5%) of failed readings except for 1) the left lane at Walker Rd. where 18% of the speed readings exceeded 100 mph and 2) the left and center lanes at 72nd Ave. where 10% and 7% of the speed readings were less than 5 mph, respectively. Although these speed readings are physically valid, it is highly unlikely that such large percentages of readings would display those extreme values. Defective 20-second readings and missing ones were replaced with the values that were interpolated using the closest neighboring readings in time.

For the on-ramps, suitable data collection tools were allocated to measure the metering rates and demand at each on-ramp. The merge loop detectors at the on-ramps provide necessary data to measure the metering rates under two different operations. However, the demands were measured from road tubes and CCTV cameras since the current queue loops at the entrances to the ramps are not currently configured to transmit their data (count, occupancy, and speed) to TMOC.

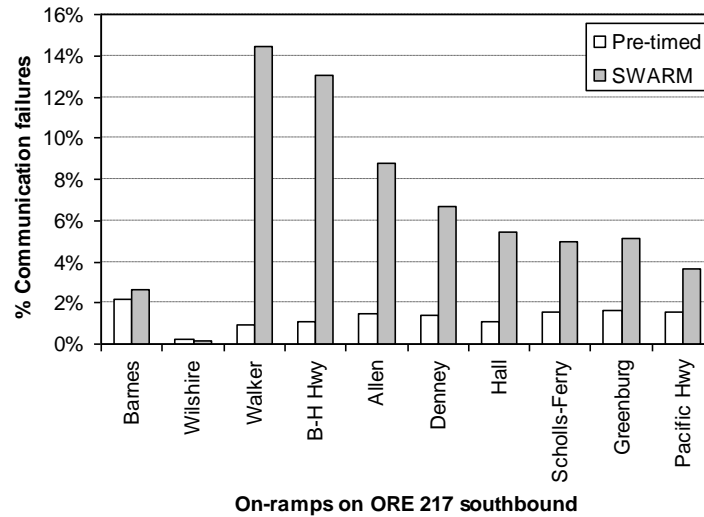
## RESULTS

During the data collection period for the pilot study, there were no adverse weather conditions that could potentially affect the driving behavior. However, there were significant incidents on June 21 and June 30 during the morning peak hours, which resulted in unusual traffic patterns. The data from these two days were excluded in the comparative analysis. Thus, the data from eight days (four days each under the pre-timed and the SWARM operations) were analyzed to make recommendations for the future regional-level study and to report some preliminary findings.

This section presents results of the evaluation of freeway conditions *before* and *after* the SWARM implementation. As a first step, the quality of the loop detector data was investigated to ensure that there was no significant change in quality during the study period. Then, some basic performance measures such as VMT, VHT, and total delay were computed and compared.

One of the major concerns with implementing the SWARM system (or any sophisticated traffic-responsive systems) is communication failures between loop detector stations and the traffic management center, as the performance of SWARM largely depends on the availability of accurate data. In order to compute metering rates in response to the real-time traffic conditions, the SWARM algorithm requires large amount of data from multiple freeway locations and on-ramps. A large amount of (simultaneous) data streams can cause communication failures and loss of data if the communication network is not established to accommodate them.

Figure 5 was constructed by computing the percentage of 20-second readings that corresponded to communication failures during the morning peak hours (6–9 AM) under the pre-timed ramp metering (white bars) and the SWARM operations (shaded bars). The figure shows that the percentages of communication failures were below 2% at most locations with the pre-timed strategy, while the percentages under SWARM were much larger. At some freeway locations, such as near Walker Rd. and B-H Hwy, the communication failures exceeded 10%. (At 72nd Ave. the percentages of communication failures were larger than 60% (64% for pre-timed and 69% for SWARM), indicating that there may be other factors causing the communication failures at the location). The missing data due to communication failures were replaced with interpolated values for further analysis.



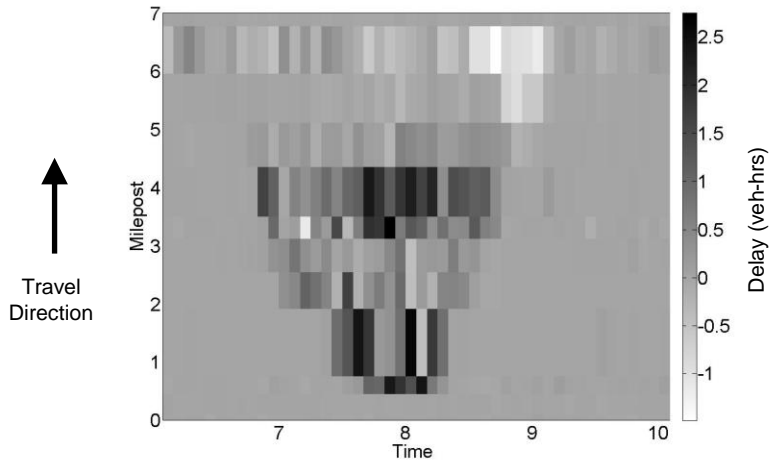
**FIGURE 5** Percent communication failures under SWARM vs. pre-timed.

Table 1 summarizes the basic measures computed from the loop detector data from 6 to 9 AM. This time window was just large enough to capture the morning congestion over the two study weeks. It shows that the VMT increased marginally (0.8%) under the SWARM operation, indicating that the morning demand for this freeway corridor remained nearly independent of the ramp metering control deployed in the field (at least for the short term). However, to our surprise, the VHT and the average travel-time increased by 6.0% and 5.1%, respectively under SWARM, corresponding to a significant increase of 34.7% in total freeway delay.

**TABLE 1** Summary of evaluation results of the mainline freeway

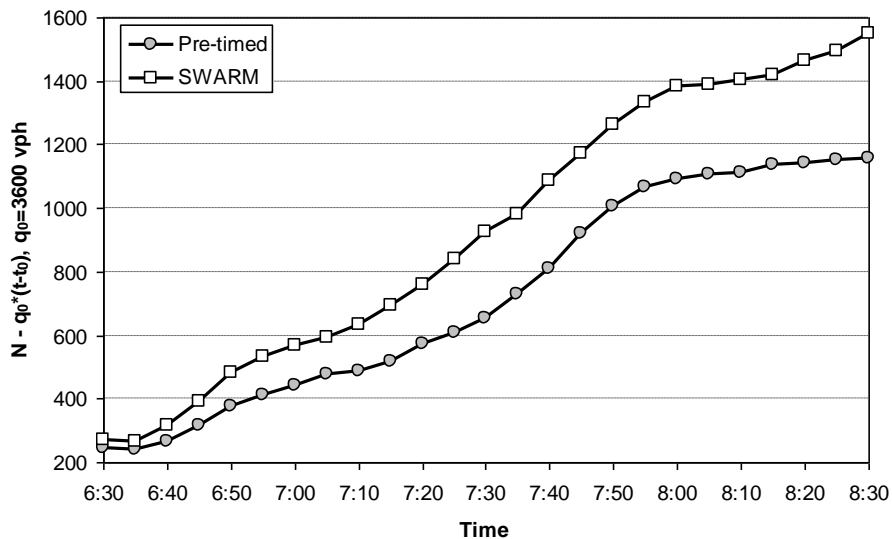
	VMT	VHT	Travel-Time	Delay (vehicle-hours)
Pre-Timed	65,871	1,337	8.8	210
SWARM	66,426	1,416	9.2	283
% Change	0.8%	6.0%	5.1%	34.7%

In an attempt to reason this increase, the temporal and spatial changes in freeway delay were plotted as shown in Figure 6. The darker time-space regions correspond to the increases in delay under SWARM, as indicated by the gray scale on the right side of the figure. The figure illustrates that most increases were observed between 6:30 and 8:30 AM.



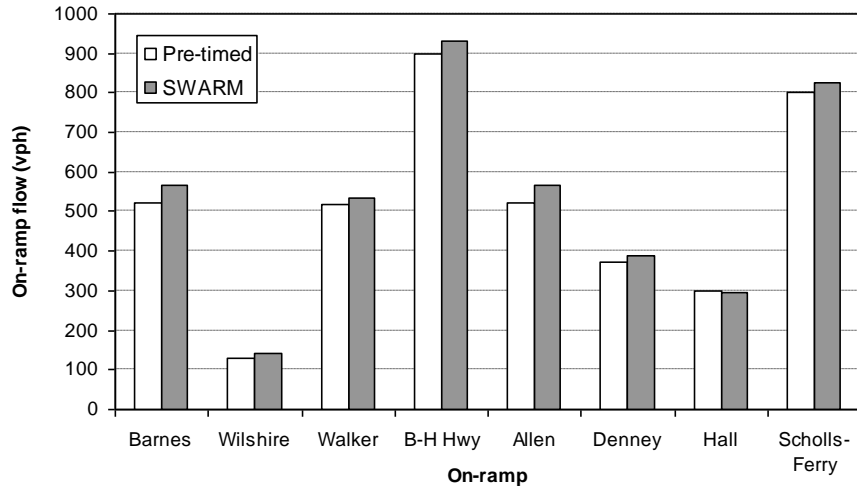
**FIGURE 6** Changes in delay under SWARM in time-space plane.

The increase in freeway delay with the SWARM operation is attributable to either higher metering rates at the on-ramps or diminished flow through the bottleneck (i.e. bottleneck discharge rate). Unfortunately, we could not verify the latter since the bottleneck discharge rate can not be estimated solely from the current configuration of the loop detectors. However, higher metering rates seem to play a role in the increase in the freeway delay as illustrated in Figure 7. The figure shows the cumulative vehicle counts at all on-ramps,  $N$ , plotted on an oblique time axis. In other words, the curves shown in the figure correspond to the quantities,  $N - q_0*(t - t_0)$ , where  $q_0$  is a background flow (3600 vph in this case),  $t$  is time, and  $t_0$  is the start time (6:30 AM in this case). This data processing technique was used to better reveal the changes in traffic states (i.e., flows) over time, as described in detail in numerous references (e.g., 11 and 12). Figure 7 shows that the cumulative curve for SWARM (squares) lies above the one for the pre-timed (shaded circles) strategy, and the vertical separation between the two curves increases over time. This indicates that the SWARM strategy consistently admitted higher flows to the freeway throughout the two hour morning-peak period.

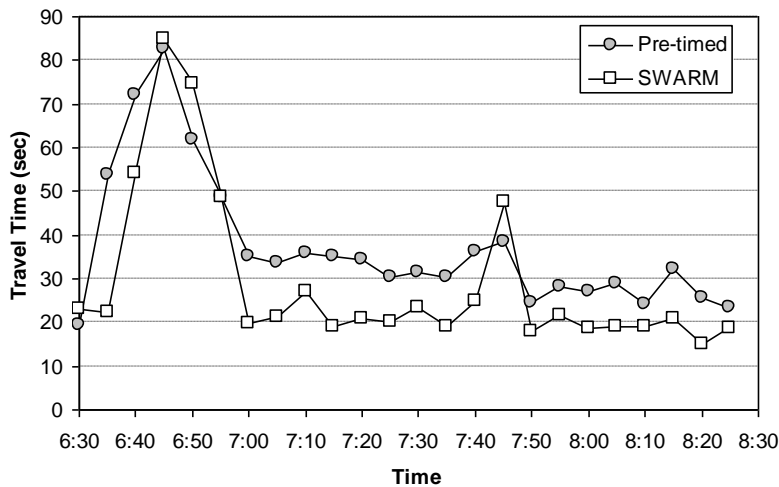


**FIGURE 7** Cumulative on-ramp vehicle counts.

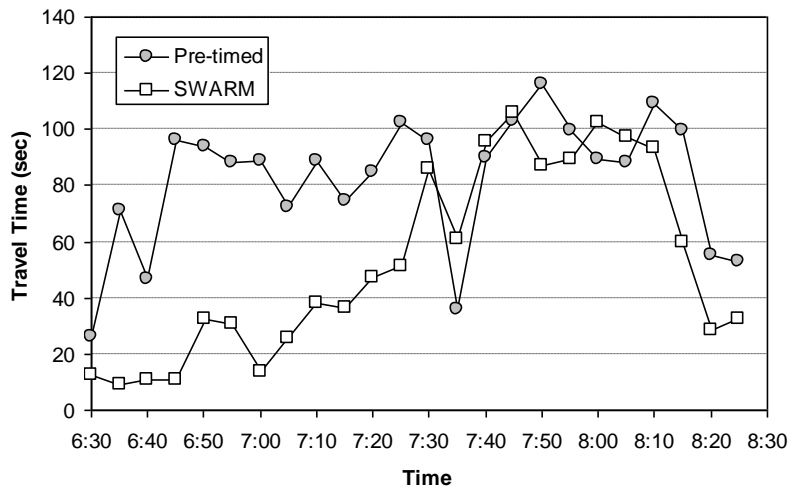
Figure 8 displays the on-ramp flows at the meters between 6:30 and 8:30 AM under the pre-timed (white bars) and the SWARM (shaded bars) operations. It shows that the flows were slightly larger at most on-ramps when SWARM was in operation. The increases in flow (except at Hall Blvd.) were in the range between 3% and 9%. These moderate increases in flow resulted in decreases in travel time on the ramps, as indicated in Figures 9(a) and 9(b). For these figures, vehicle travel times were sampled once every five minutes at Beaverton-Hillsdale Highway and Scholls-Ferry Rd. on-ramps. Both of these figures show that travel times on the on-ramps were lower in general with SWARM. Assuming that each travel time is a good representative of travel times during the preceding five-minute period, the overall decreases in travel time were 23% at the Beaverton-Hillsdale Highway on-ramp and 37% at the Scholls-Ferry Rd. on-ramp (large percent decreases in travel time are not surprising since travel times on these two on-ramps are less than 2 minutes).



**FIGURE 8 On-ramp volumes between 6:30AM and 8:30AM.**



**FIGURE 9(a) Travel time on the Beaverton-Hillsdale Highway on-ramp.**



**FIGURE 9(b) Travel time on the Scholls-Ferry Rd. on-ramp.**

## CONCLUSION

This paper described the experimental design to evaluate the benefit of the SWARM strategy as compared to the pre-timed metering strategies. In designing our study, the freeway corridor for the pilot study was carefully selected based on a number of criteria that were developed, taking into consideration the congestion patterns and the feasibility in terms of resource allocation. For the selected corridor, data quality and on-ramp conditions were further investigated in order to come up with a data collection plan that conformed to our objective given the resources available.

The pilot study was conducted for two weeks, and the changes in freeway conditions were reported. We found that the VMT exhibited a marginal increase under the SWARM operation. However, the total delay on the freeway increased with SWARM, and empirical evidence suggests that this increase resulted from higher metering rates at most of the on-ramps. These higher metering rates under SWARM resulted in lower travel times on several major on-ramps, indicating that the increase in freeway delay was traded with lower on-ramp delays. However, whether the increase in the total freeway delay was solely caused by the higher merging rates remains an open question since the bottleneck discharge rate could not be measured from the data. Moreover, delays could not be quantified at all on-ramps due to the limitations on data collection efforts, and hence, it was not feasible to analyze the system-wide trade-offs between the freeway and on-ramp delays.

The lessons learned from the pilot study are being incorporated in designing the regional-level study, and the results of this research will assist ODOT in fine-tuning the deployment of the SWARM system and in reporting its benefits to decision-makers and the public. These results will be transferable to other regions, states and countries in the future.

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