EVALUATION OF RAMP CONTROL EFFECTIVENESS IN TWO TWIN CITIES FREEWAYS

By

John Hourdakis¹

Panos G. Michalopoulos²

¹. Department of Civil Engineering
   University of Minnesota
   500 Pillsbury Dr. SE
   Minneapolis, MN 55455
   Phone: (612) 625-8832,
   Fax: (612) 626-7750
   Email: hourd001@tc.umn.edu

². Department of Civil Engineering
   University of Minnesota
   500 Pillsbury Dr. SE
   Minneapolis, MN 55455
   Phone: (612) 625-1509,
   Fax: (612) 626-7750
   Email: micha001@tc.umn.edu

*All correspondence send to second author.

Submitted for presentation and publication
Transportation Research Board 2002 Annual Meeting
January 2002
Washington, D.C.

# WORDS: 7490

July 2001
ABSTRACT

Recent public opposition threatened to abandon ramp control as a traffic management option in the Twin Cities of Minneapolis and St. Paul, which have one of the most extensive ramp control systems in the nation. In response to this Mn/DOT had to produce tangible independent evidence that ramp metering is effective in order to avoid turning off the meters. Simulation is the most widely accepted technique for achieving the stated objectives without turning the metering system off and was therefore used in this study. Two freeway sections were selected for detailed testing and the results along with the methodology are presented here. The results confirm that ramp metering is effective on the ramp/freeway system (not just the freeway) but they also revealed excessive delays on certain ramps that seem to support the concerns raised by the users. Unfortunately, pressure from the local government resulted on a two month all ramp meter shut-off before this study was finalized. Real life issues related to the simulation implementation process (data collection and filtering, calibration, interpreting/summarizing results, etc.) are also presented. Through the course of this work simulation reliability was established by defining a successful calibration/validation methodology and by identifying, in the process, certain operational problems related to the surveillance and control system deployed that were unknown. Finally a general methodology was developed for evaluation that can easily be adapted to any user specified control strategy or used to improve an already existing one without field disruptions.
1. INTRODUCTION

Recent deployments in freeway ATMS systems include consideration of ramp control as part of the overall traffic management plan. Since each freeway has its own characteristics, the decision is not trivial especially when combined with recent public concerns related to ramp metering effectiveness. In addition, selecting the most effective control strategy and calibrating its parameters prior to implementation is problematic. A combination of factors such as these suggests the need for a systematic methodology for design and justification of ramp metering during the planning stages and beyond. More often than not, the ramp control strategies deployed are substantially modified after field installation and calibrated over a period of time by trial and error. Even though such empirical processes can be effective, there is no assurance that they are the best for a particular freeway, while they take time to be fine-tuned and often adversely affect traffic flow resulting in driver frustration.

Such considerations suggest a need to develop a better engineering procedure to determine the effectiveness and need for ramp control and prepare a platform to test any improvements in the strategy. In this paper we present such a methodology, which was developed for evaluating the effectiveness of the ramp metering developed by the Minnesota department of transportation (Mn/DOT) and implemented in the Twin Cities of Minneapolis and St. Paul since 1972. This deployment followed the typical implementation process described earlier and because of its extensive expansion in recent years had side effects that raised considerable public opposition and threatened to eliminate ramp control as an acceptable traffic management practice.

Although the methodology presented in this paper was developed in order to evaluate the Mn/DOT ramp metering, considerable effort was spent in order to generalize it for evaluating any user-defined strategy. The result is an effective and practical set of tools for allowing engineers to systematically decide whether ramp control is justified in a particular freeway as well as how to be properly deployed. Special attention was paid in producing the evaluation results in a form that provides sufficient and easily understandable evidence to address public/administrative concerns. As part of the methodology a simulation laboratory was developed for testing operations and management in freeway corridors.

The methodology was developed following an urgent need by Mn/DOT to produce tangible and well-substantiated evidence that ramp metering is indeed effective, in order to avoid turning off the metering following a legislature decision prompted by public opposition. The challenge was to perform the evaluation without turning the meters off due to the unpredictable effects on traffic flow, diversion and safety. Two freeway sections were selected for detailed testing and the results along with the methodology are presented here. Although the ramps were treated as part of the system, lack of data and resources did not allow expansion to entire corridors at this point. The results confirm that ramp metering is effective on the ramp/freeway system (not just the freeway), but they also revealed excessive delays on certain ramps that can be reduced through the methodology presented here without field disruptions. The project also revealed real life issues related to the simulation implementation process (data collection and filtering, calibration, summarizing and presenting results), which are also presented here along with ways to deal with them.

Unfortunately, pressure from the legislature resulted on a two-month all-meter shut-off before this study was finalized. An independent before-after study, albeit less detailed, reconfirmed the benefits and issues presented here.
2. BACKGROUND

The Mn/DOT ramp control logic, described next, was originally developed and implemented since 1972 in the Twin Cities of Minneapolis and St. Paul. Since then the deployment was expanded to 430 ramps and 338 freeway Km. This is the site of one of the largest deployments of adaptive ramp control worldwide. Even though the control strategy has continuously being improved since its inception, it was recently criticized because of excessive delays in some ramps causing the public, the press, and local elected officials to question its effectiveness. Because of this, Mn/DOT needed an in depth evaluation of the control strategy without having to turn the system off for the reasons mentioned earlier. Traffic simulation is the most logical tool for such a task but this technique has not received widespread acceptance in practice. This is mainly due to lingering problems with early simulators. Such problems include tedious geometric and traffic data entry, output data that is cumbersome and difficult to analyse, and questionable accuracy. Furthermore, simulators are, at best, designed to implement only a particular control strategy.

2.1 Control Strategy Description

The Minnesota integrated ramp control strategy [1] begins by dividing the freeway into zones. A zone is defined as a unidirectional freeway section, typically three to six miles in length. The beginning or upstream end of a zone is usually a free-flow area, not subject to high incident rates. The downstream end of a zone is a bottleneck, where the demand to capacity ratio is highest on that freeway section. Lane drop locations, high volume entrance ramps, and high volume weaving sections are typical bottleneck locations.

The zone control algorithm is built on the basic concept of balancing the volume of traffic entering the zone with that leaving the zone. All volumes of entering and exiting traffic are measured in real time every 30 seconds. When these total volumes are balanced, the density of traffic in the zone should remain within a narrow range. When the density of traffic in the zone is low, there is "space available" within the zone for additional entering traffic. The metering zone conservation equation can be expressed as:

\[ A + U + M + F = X + B + S \]  

\[ A = \text{Upstream mainline volume (veh/5 min); a measured variable} \]
\[ U = \Sigma \text{(Unmetered entrance ramp volumes) (veh/5 min); a measured variable} \]
\[ M = \Sigma \text{(Metered local access ramp volumes) (veh/5 min); a control variable} \]
\[ F = \Sigma \text{(Metered freeway to freeway access ramp volumes) (veh/5 min); a control variable} \]
\[ X = \Sigma \text{(Exit ramp volumes) (veh/5 min); a measured variable} \]
\[ B = \text{Downstream bottleneck capacity volume (veh/5 min); a constant} \]
\[ S = \text{Space available within the zone (veh); a computed volume based on occupancy of mainline detectors} \]

Stated as the sum of metered ramp volumes, Eq. 1 becomes:

\[ M + F = X + B + S - A - U \]  

Any measured variation in \( X + B + S - A - U \) is equaled by a controlled variation in \( M + F \).
Each individual variable in Eq. 2 has a target value (denoted by $t$). The zone conservation equation written in the target volume form is:

$$M_t + F_t = X_t + B_t + S_t - A_t - U_t.$$  

(3)

Each metered ramp is assigned six metering rates. On local access ramps, these rates over a five-minute time period would correspond to 1.5, 1.3, 1.1, 0.9, 0.7, and 0.5 times the target volume. On freeway-to-freeway ramps, rates over a five-minute period are 1.25, 1.15, 1.05, 0.95, 0.85, and 0.75 times the target volume. The selection of which rate to use is then determined by a comparison of the measured variables ($X + B + S - A - U$) to a series of thresholds.

The AM peak has a turn on period (6 AM to 7 AM) during which ramp meters will turn on individually or in groups when calling for a restrictive rate 5 or rate 6. Once ramp metering has begun, the rate used will be variable between rate 1 and rate 6. The mandatory metering period (7 AM to 8 AM) is used for all AM zones. During the third or turn off time period (8 AM to 9:30 AM), a ramp meter will turn off when the arrival rate of vehicles falls and the ramp empties. The PM peak is also in three parts. The turn on period is 2 PM to 3:30 PM. The mandatory metering is 3:30 to 5:30 PM. The turn off period is 5:30 PM to 7:00 PM.

2.2 Simulation Software

The methodology described in this paper is developed around the AIMSUN (Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks) [2,3] microscopic simulator. The process that lead to the selection of this particular simulator started around 1994 [4] with the evaluation of six well known simulators at that time (FREFLO, FRESIM, INTEGRATION, FREQ11, KRONOS, AIMSUN). During the tests, the suspected reasons preventing widespread use of simulation were confirmed. Specifically, all of the simulation models tested, suffered to varying degrees, from a lack of automation for minimizing the data entry effort. In addition, none of the simulators had, at the time of testing, all of the features needed for emulating state of the art ATMS applications. Such features include user specified adaptive control schemes, origin-destination tracking, map-based geometry interfaces, automated demand data access, and capability to model all common geometric layouts. Based on this evaluation the decision was to select one with the most potential of the six and adapt it to US conditions. The particular simulator was selected because it already included most of the features needed and its developers offered substantial support in its use as well as needed improvements.

The AIMSUN microscopic simulator was developed as part of various projects funded through European ITS Programs. Following its initial development, the simulator matured significantly and was used in numerous large scale projects in Europe (Barcelona, London, Amsterdam, Stockholm, and others), Australia / New Zealand (Auckland, Brisbane), South America (Santiago) and North America (Montreal, Minneapolis). The AIMSUN model has been tested and validated in such real life projects, as well as by outside evaluators including the Robert Bosch GmbH [5,6] group. The latter employed a set of field data; most of the microsimulators developed in Europe and North America were invited to participate. Among the 7 simulators tested, AIMSUN ranked among the first two in accuracy and is currently considered to be among the top three worldwide especially in terms of modeling sophistication.

In its current form, the simulator employs an improved Gipps [7] model and is capable of dealing with complex urban street networks, freeways, highways, ring roads, arterials and any combination of them. Simulation can be either based on input traffic flows and turning proportions, or based on O-D
matrices and route selection models. In the former case, vehicles are distributed stochastically around the network, whereas in the latter vehicles are assigned to specific routes from the start of their journey to their destination. A variety of Route Choice models are available: fixed, binomial, multinomial logit or any other user defined model. For the shortest path calculation, a cost function library is provided, and the user is also offered the possibility of defining and using his/her own functions. All types of traffic control options can be modeled: traffic signals (isolated, coordinated, real time adaptive), yield/stop and ramp metering. Control plans are phase based, thus providing higher flexibility in the definition of control plans. The simulator has the ability to automatically deal with a set of control plans in the same simulation experiment. For instance, TRANSYT/10 optimized control plans can be loaded into the simulator. Similarly the simulator has been used in SCOOT and SCATS applications. Due to the detailed modeling of each vehicle in the network, AIMSUN can emulate most types of traffic detectors, such as count, occupancy, presence, speed and density. The simulated detection data can be used to feed any external traffic control system. Finally, it is capable of emulating Variable Message Signs and their influence on driver behavior.

A graphical editor for traffic networks accompanies the simulator. The Traffic Editor (TEDI) has been designed with the aim of making the process of network data entry as user-friendly as any of today's modern CAD programs. Its main function is the construction of traffic models with which to feed traffic simulators like AIMSUN. To facilitate this task the editor accepts as a background either a graphical description of the network area or an aerial photograph, so sections and nodes can be built subsequently into the foreground. The geometry of the links is specified at the microscopic level, but the editor's ease of use makes it as fast as specifying one-dimensional links in some macroscopic systems, and nodes can be created automatically. Building complex intersections, including the definition of turning movements, signal groups and control phases becomes a straightforward task, just consisting of clicking on the different intersection objects. The richness of parameters available for characterizing the different types of objects and traffic conditions means that the only limitation to the precision of the model is the quantity and accuracy of the data collected.

3 SIMULATOR ENHANCEMENTS AND STREAMLINING PROCESS

Since the selection of the simulator in 1996, a number of improvements deemed necessary for North American roadway geometries were made. For example, the concept of merging and diverging freeways was introduced and the model behavior in short weaving areas was improved. Specifically, in short weaving sections, the lane-changing model previously employed by the program did not produce satisfactory results. For instance, in heavy congestion, there was a possibility that some vehicles could not switch to the appropriate turning lane on time and consequently miss their exit or turn. This situation could appear either in urban networks where there are short links or in freeways where weaving sections were relatively short. Thus, changes were made to the lane-changing model so as to position exiting/turning vehicles in the proper lane on time regardless of flow levels or section lengths.

One of the major problems in using simulation is the copious and time-consuming task of entering initial and boundary conditions. To minimize this effort software was prepared to store 5-minute volume and occupancy measurements from 3000 detectors, collected by MnDOT’s Traffic Management Center (TMC), in a relational database. This demand tool can produce initial and boundary conditions for any modeled section by accessing the database. In this manner a procedure that used to take days for entering the demand patterns is now accomplished in minutes.
In general, most of the simulators have been designed to include one maybe two known ramp control schemes. This allows the user to compare these specific schemes within a single simulator, but it doesn’t allow comparison with other non-supported schemes. In order to enhance the simulator, a Control Plan Interface (CPI) application was developed, allowing interaction with any external traffic control system. The CPI is an interface that integrates the simulator with an external user defined ramp control logic. It facilitates the exchange of information between the simulator and an external control scheme. This is especially needed for simulating adaptive ramp control strategies, which use real time traffic measurements to determine current metering rates. Such measurements might be volume, occupancy, and speed on the mainline as well as queue-lengths on the ramps. The simulator provides the necessary measurements, which the CPI transfers to the external control logic. In turn, the control logic calculates the new rates and transfers them to the simulator through the CPI.

The simulator is capable of communicating with an external application. The CPI enhances this ability by grouping the necessary information specifically needed for ramp control schemes. In addition, new functions were added to allow easier access to the simulator. This makes the job of the end user easier because he has more tools available to integrate his own control logic with the simulator including manual overrides of the control strategy as in most real-life TMC’s. Specifically, in the CPI the notion of detector stations was added, as most of the current ramp control strategies require measurements over all lanes of the mainline instead of lane by lane. Additionally, the user is now able to define the collection rate of measurements, which can be different from the one specified in the simulator. For example, the simulator may collect lane-by-lane detector data every 30 seconds but the user’s ramp control logic could request and receive 5-minute detector station data.

In the original external interface the user’s logic had to be designed specifically for the network under consideration. With the CPI the user may now access information at run-time about the road geometry, traffic detection and control devices as well as their mode of operation. This allows the user to design or adapt his logic in a more generic way and use it on any freeway. Finally, the implementation allows for customized output to be saved including information specific to the operation, effectiveness and general performance of the control logic. Using the CPI, Mn/DOT’s ramp control logic was interfaced with the simulator and used for evaluating its effectiveness at the selected test sites.

4. SITE SELECTION

Through discussions with Mn/DOT engineers at the TMC, a set of requirements was developed in order to select the appropriate test site(s). These requirements are:

- **Minimum size.** In order to capture a large variety of traffic patterns the minimum freeway section should have at least the length of three zones. The maximum size was determined by the availability of persons needed for the data collection.
- **Upstream and downstream ends uncongested.** The accuracy of the simulation is increased if both main boundary points of the model are uncongested during the simulation. The existence of congestion generated outside the simulated part can result in errors that cannot be captured in the simulation process.
- **Data collection.** The site selected should have most of the mainline detectors operating for successful calibration. In addition, all entrance and exit detectors should be operational, so that the boundary demand conditions are well defined.
Based on the above criteria, two test sites having geometric properties and traffic characteristics that are representative of the Twin Cities freeway network to the maximum extent possible were selected.

The first test site selected is a 20 km (12 miles) long section of Trunk Highway 169 in the northbound direction starting from the interchange with I-494 and ending at 63rd Avenue North. This is a circumferential freeway in the sense that it traverses the metro area without passing through the center. Most of the test site consists of two lanes with 10 weaving areas. It has 24 entrance ramps of which one is un-metered. The metered ramps include 4 HOV bypasses and two freeway-to-freeway ramps from TH 62 and I-394. The test site contains 25 exit ramps. The upstream and downstream boundaries are uncongested. Among the two test sites, TH 169 is the least complex in terms of the geometry and generally carries lower traffic volumes. Specifically, during the study an average of 49889 vehicles traversed the site over 6 hours producing a Total Travel of 219700 veh-miles.

The second test site is I-94 Eastbound beginning at I-394 and ending at the off ramp at 9th St. This is a central business district connector as it connects the Minneapolis and St. Paul downtown districts. It is about 18 km (11 miles) long, carries high traffic volumes and often is severely congested during peak hours. Specifically, during the study an average of 103344 vehicles traversed the site over 6 hours producing a Total Travel of 404301 veh-miles, i.e. over double the values of TH-169. The upstream boundary of the test section is an un-congested area just ahead of a tunnel near I-394 and the downstream boundary is mostly un-congested. The site consists of 19 entrance ramps and 14 exit ramps of which 4 are un-metered. It also contains 6 weaving sections, has about 3 lane drop sections, and into the average it has 3 lanes of traffic. One of the unique features of this site is the section where I-94 merges with I-35E near downtown St. Paul. Because of its complex geometry it was one of the most difficult sections to model but it provided an opportunity to study the interaction between the two freeways.

In both cases, what was simulated was the system of the freeway proper and its ramps up to the point of the intersection with the surface streets. This modeling does not take into account diversion caused by the control strategy, as there were no sufficient data to expand the simulation to the entire corridor. In short, the demand patterns had to be assumed the same with and without control; even though this is not entirely realistic it allows comparison of both alternatives with the same demand patterns which is not possible with before and after studies.

5. DATA REQUIREMENTS

5.1 Geometry

The geometric data include design elements such as the number of lanes and their width, grades, curvature, length of the mainline between ramps, entrance ramps length, and detector and ramp meter location. As a starting point for entering the geometry of the test sites, CAD diagrams of the freeway, were obtained from Mn/DOT. The diagrams contain information concerning the detailed horizontal/vertical alignment, lane markings, and the location of the traffic control devices such as detectors and ramp meters. Using this background as a reference, the specific data needed were extracted and entered in the simulator. The speed limits obtained from Mn/DOT were also added.

To determine whether the network was accurately modeled, visual inspections were made by driving several times along the test sites. It was found that though most of the information was accurate in the AutoCAD files, at some locations it was outdated, especially where improvements to the original freeway geometry were made such as addition of lanes and HOV bypasses. There were also some uncertainties about the length of the acceleration and deceleration lanes. Construction plans were used to
extract more details about the freeway geometry. In addition to the on-site inspections, in order to ensure that the current freeway geometry was replicated, aerial videotapes of the sites, produced specifically for this project by the State Patrol through a specially equipped helicopter, were used.

5.2 Traffic Data

For performing a realistic simulation, definition of the boundary conditions of the freeway and the ramps are essential. This requires volume counts and traffic composition at each of the entrance ramps as well as the upstream end of the freeway. The above are also needed at the exit ramps in order to calculate exiting percentages per vehicle class. Even though the simulator does not pose limits on the number of different vehicle classes, following meetings with Mn/DOT engineers, it was decided that the vehicles would be classified into three types: cars, trucks and semi-trailers. Mn/DOT sensors provide most of these measurements in 30sec and 5-minute aggregation periods; in this study 5-minute counts were used. Unfortunately, the loop detectors that are counting the entrance ramp demand are located downstream of the ramp meter. This positioning does not result in measurement of the real demand at the upstream end of the ramp. Because real upstream demands are in fact the boundary conditions, manual counts had to be made using cameras and on-site personnel to supplement the detector counts. The selected freeways develop higher congestion levels during the afternoon peak period. In order to capture the entire congestion cycle the experiment was scheduled between 14:00 and 20:00.

To ensure correct replication of the actual traffic patterns and to be able to verify the correct operation of the ramp-metering algorithm, it was not possible to use data collected over a number of days. For this purpose, loop and manual counts had to be captured simultaneously for the entire freeway sections tested for each of the three days used in the study. The hardest part of this undertaking was to synchronize all the crews in the field with the loop master control and video observers.

An additional constraint on the data that had to be collected was that it should be incident free. This restriction was placed because at the time of data collection, Mn/DOT has an active mechanism to deal with incidents that includes broadcasting about the incidents on traffic radio and displaying the same on variable message signs. It can be safely assumed that this results in diversion for which data collection was impractical due to time and cost considerations. As the number of drivers choosing alternate routes was not available, it was felt that it would be more practical to perform the tests with incident-free data. This complicated and delayed the data collection process, which finally occurred on 3 consecutive weekdays in March 2000 (Tuesday, Wednesday, and Thursday).

Although the aforementioned data are sufficient for performing the simulations, additional data were needed in order to accurately calibrate it. For this purpose, loop detector volume and occupancy measurements from the freeway mainline were also obtained in every freeway section between ramps, along with 5-minute counts of the queue lengths at the ramps. Speed was subsequently derived from volume and occupancy, as it is not measured directly from sensors in Minnesota. This additional data was compared to simulated ones for calibration.

6. CALIBRATION METHODOLOGY

One of the most difficult issues in traffic simulation is model calibration, which is principally caused by the lack of sufficient simultaneous data collection at the boundaries and intermediate mainline stations, and a systematic, relatively simple to implement methodology. The calibration of this study was
accomplished in three trial and error stages. Beginning with a good estimate for all model parameters, in
the first stage mainline detector station\(^1\) volumes from reality were compared with their corresponding
values from simulation. In the second stage the speeds on the mainline are the control variable. In the third
and final stage the actual vs. simulated ramp queue sizes were compared along with the individual ramp
rates. Because of space limitations we only present very limited test results here focusing instead in the
general calibration process.

The initial model parameters used were based on values found in the literature for vehicle
characteristics and the posted speed limits on each of the freeway sections. Based on these model
parameters and on demand information of one day for each site, a “first guess” scenario was formed. This
“first guess” was calibrated during the first phase by comparing real mainline volumes with simulated
ones. After approximately 300 iterations per site, a satisfactory score was achieved based on statistical
tests. The comparison statistics used were the well known Root Mean Square Error, Root Mean Square
Absolute error, Mean error, Mean Absolute Error, Correlation coefficient and the less known Theil’s
Inequality Coefficient or U-statistic \([8,9,10]\). The known comparison statistics have the deficiency to
emphasize large errors. Theil’s U-Statistic is a measure that considers the disproportionate weight of large
errors. The U-statistic can be decomposed in three components called the proportions of inequality, \(U_M, U_S, \text{ and } U_C\).

\(U_M\) is the “Bias proportion” index and can be interpreted in terms of a measure of systematic error,
\(U_S\) is the “variance proportion” index and provides an indication of the forecasted series ability to replicate
the degree of variability of the original series or, in other words, the simulation model’s ability to replicate
the variable of interest of the actual system. Finally \(U_C\) or “Covariance Proportion” index is a measure of
the unsystematic error. The best forecasts, and hence the best simulation model, are those for which \(U_M \text{ and } U_S\) do not differ significantly from zero and \(U_C\) is close to unity.

The second stage aimed at calibrating the model so that the speed (calculated from
volume/occupancy from the real data) on every mainline detector station achieves a good match between
simulation and real measurements. By the end of the second phase the model had already achieved a high
level of accuracy. This phase required approximately 100 iterations. The same statistics were used as in
the first stage.

In the third phase, where entrance ramp queues were compared, we discovered that in the case
were adaptive control logic is involved, the high level of accuracy reported in the second stage was not
adequate. Based on the qualitative comparison of the queue lengths and also of the exit ramp volumes an
even stricter fine-tuning of the model was achieved after approximately 100 iterations per site. By the end
of the calibration cycle, mainline volume, speed, and entrance ramp queue lengths achieved an almost
perfect match.

At the end of the three calibration stages and when good model accuracy was achieved (based on
counts, speed and queue sizes), the model was validated based on the remaining two days of the
experiment. Because of space limitations we only present a summary of the test results for the TH-169
site. For all three days the overall statistical scores from the final simulation of this site are presented in
Table 1; these scores represent 5-min volume comparisons in all mainline detector stations. As it can be
readily observed, through this systematic calibration and validation methodology, very high accuracy was
achieved. For instance the \(r^2\) coefficients are exceptionally high ranging from 0.96 to 0.98.

It should be noted that during the calibration/validation process, a number of irregularities in the
input data were observed. Specifically, in two locations the placement of the entrance ramp loop detector
was not the one reported in the plans. Because of this sensor misplacement, the real data did not match
with the simulation data prompting an investigation. After some analysis and visits to the field the true

\(^1\) Each detector station aggregates counts from all its lane detectors and reports the total volume and average occupancy.
location of the detectors and subsequently the nature of the measurements was identified. The MnDOT engineers who were up to that point oblivious of the problem have acknowledged these two detector misplacements, which were only discovered during the simulation runs.

7. OUTPUT PROCESSING

In the simulator, sections and joints comprise the model. Section is a straight link of variable length with one entrance and one exit. Sections are connected together with joints to form the network. The simulator has the capability of generating statistics and measurements at different levels of aggregation in space and time. Detailed vehicle data such as entry and exit times, speed, number of stops and total stopped time is collected when a vehicle enters and leaves a section. From this information, the following traffic measurements are calculated per section:

- Mean Flow
- Density
- Mean Speed
- Travel Time
- Delay Time
- Stop Time
- Number of Stops
- Mean Queue Length
- Maximum Queue Length
- Total Travel
- Fuel Consumed
- Pollutants Emitted

In this study, the time slice was selected to be five minutes for every section. Since microscopic simulation is a stochastic process, to be statistically correct the average output from 30 simulation runs was used in the study. The averaged output was then used to compute the above MOEs for each section, the freeway mainline, all the entrance ramps, and for the entire system (freeway and ramps).

The final MOE’s used in the evaluation reveal the benefits or shortcomings of ramp metering compared to no-control. In addition, this information must be clearly understood not only by engineers but also by planners, administrators, and the public. The MOE’s described above were not deemed sufficient for this purpose; therefore, additional ones where defined and calculated from the raw simulation output through a relational database build specifically for this purpose. These “extended” MOE’s are:

- Throughput, defined as the total number of vehicles serviced by the ramps and the system.
- Total Travel Time on the mainline, ramps, and the entire freeway.
- Total Travel at the ramps and the system
- Average Speed on the mainline.
- Total Delay on the mainline, ramps, and the system.
- Average Delay per vehicle on the mainline, ramps, and the system.
- Total number of stops on the mainline.
- Average Number of stops per veh on the mainline.
- Total Fuel Consumption (gallons) in the system
- Pollutants (CO, HC, NO_x) produced in the system
The most controversial of the above MOEs is Delay for which there are several definitions in the literature. For the purposes of this study, Delay is defined as the time difference between the measured travel time and the travel time of a vehicle if it were driving with its desired speed; the later is randomly selected by the simulator based on the speed limit in each section and the individual vehicle parameters by assuming a normal probability distribution. Because of the disagreement in measuring delay, total travel time yields a more objective measurement for comparing the alternatives.

8. RESULTS

The “extended” MOEs described in the previous section were summarized for all three days on both freeways in order to compare the effect of ramp control. Two time aggregation intervals were used, the entire simulation period (14:00 to 20:00) and the peak period only (15:00 to 18:00). The results were summarized in 12 tables, which are too extensive to present here. One representative table from the TH-169 test site is included in this paper (Table 2). This table contains the results from the day that presented the least benefit; the base case is with ramp control and the percent increase or decrease on each of the “extended” MOE’s without control is calculated. As expected, ramp travel times and delays are greatly decreased without control but the overall system is benefiting from ramp metering since the MOE’s for the whole system are improving.

From the overall results it was found that Total System Travel Time (TTT) at both sites was reduced with ramp control, from 6% to 16%. For TH-169, the 6% reduction in TTT was observed on March 21st, whereas the 16% decrease in TTT was observed on TH-169 on March 22nd and on I-94 on March 29th. The average freeway mainline speed with ramp control increased from 13% to 26%. The increase in speed on TH-169 ranged from 17% to 26%; on I-94 the increase in speed on the mainline ranged from 13% to 20%. The overall benefits in delay, varied by freeway and day, with I-94 benefiting much more than TH-169 as it carries substantially higher volumes.

On both freeways the total number of stops with ramp control was relatively low. However, without control the total number of stops increased tenfold. Specifically, with control, the average number of stops I the mainline varied from 0.14 to 0.38 per vehicle on TH-169 and I-94 respectively, while without control the same average number of stops varied from 0.22 to 5.45 per vehicle. Since control smoothes flow on the freeway proper considerably, fuel consumption and pollutant emissions are greatly reduced (fewer acceleration-deceleration cycles). Specifically, in TH-169 fuel consumption increased without control from 34% to 55%, while on I-94 (who still exhibits congestion with control) from 2% to 47%. Pollutant emissions followed the same trend. Table 3 summarizes the overall test results for selected MOE’s on both sites. As this table reveals, the variation between sites and even between days on the same site is most evident. This confirms that control performance depends not only on the geometry but also on the daily fluctuation of the demand patterns.

In addition to the 12 summary tables mentioned earlier, six additional ones describing Entrance Ramp MOE’s were created, Table 5 represents an example. As it can be seen in this table although the overall ramp waiting times are tolerable, a few ramps exhibit unacceptably high waiting times. The latter as high as 21 minutes of maximum individual wait time, or 11 minutes maximum average wait time, defined as the time from which a vehicle enters the ramp to the time it is released from the meter. This suggests that the public concerns of ramp metering ineffectiveness are not totally unfounded. On the other hand this suggests that standards should be established to determine what is acceptable in terms of maximum ramp wait. Once this is defined, the methodology can identify problem ramps such as those marked in Table 4 (assuming a maximum individual delay of 5 minutes and maximum queue of 50
vehicles) and the problems corrected prior to field deployment by adjusting and testing the control strategy in the simulator.

Many additional details were examined through the simulation process to explore the effectiveness of ramp control, which cannot be presented here due to space limitations. For instance, the 3-D chart presented in Figure 1 shows the speed changes vs. time in the entire Th-169 freeway. As can be seen most visibly from this speed graph, ramp-metering smoothes out the flow considerably, resulting in substantial reduction of stops, pollution levels, and by implication accidents.

9. CONCLUSIONS

An important lesson learned in this study is that familiarity with the use of a simulator alone is not sufficient. Caution should be exercised with the data collection and filtering which in our case went well beyond identification of malfunctioning detectors and filling the gap of missing data. Similarly, the calibration process involved more elaborate statistical tests and two additional stages of testing beyond matching the volumes on the mainline stations (Speed/occupancy and queue length checking). In addition, the methodology developed is general and suitable for selecting, testing and calibrating the best adaptive ramp control strategy for any freeway or to develop new ones. This subject along with expansion to corridor simulation is left for future research.

Implementation of the methodology in the two test sites lead to some general conclusions that appear to be reasonable and even expected. For instance, freeway delays decreased while ramp delays increase substantially with ramp control but overall system delay decreases. Other expected findings include a substantial variation of the effects of ramp metering by location and the particular demand patterns on the days the experiments were performed. In short, ramp-metering effectiveness depends not only on the freeway geometry but also on the daily demand patterns, which can change unexpectedly. This suggests that even at the same site, ramp-metering decisions may have to vary from day to day depending on the changes of the demand patterns. In order to make such decisions, as well as to determine if ramp metering should be implemented on a particular freeway, it was felt that standards such as maximum allowable ramp delays, maximum queue lengths, and others need to be established.

Beyond the obvious general conclusions, the specific results obtained confirm that even though in engineering terms, ramp metering is effective in terms of improving measurable MOEs for the entire system (mainline and ramps) standards for establishing acceptance are lacking.. The results also indicate that the improvements are more substantial on I-94 where the demand patterns and freeway volumes are much higher resulting in severe congestion. In addition, even though no specific accident data could be available for the hypothetical ramp metering shutoff, it can be inferred that due to the considerable reduction in the number of stops and increased smoothness of flow, ramp metering should result in lower accident rates.

Before concluding it is worth noting that due to political considerations ramp metering was in fact turned off in the Twin Cities during October-November 2000. A traditional before-after study was conducted to evaluate ramp-metering effectiveness [11]. The results reported in this study, although limited and less rigorous, suggest similar benefits and trends as the ones presented in this paper; furthermore, they added credibility to simulation as a tool that can reliably and efficiently be used for evaluation of ramp control effectiveness. Specifically, the latter study reported an increase in travel time on I-94 during the no-control days of approximately 22% where in the simulations a 16% increase was observed. Additionally, during the meter shut-off an average of 12-mile/hr decrease in speed was reported with ramp control where the simulations reported a 10-mile/hr decrease.
REFERENCES

1. Lau Rich P. “MnDOT Ramp Metering Algorithm”. Internal Report, Minnesota Department of Transportation, Minneapolis, Minnesota. 1996
LIST OF TABLES

TABLE 1  Goodness of Fit for TH-169 Mainline Station Volumes (14:00-20:00)
TABLE 2  MOE’s for 3/21/00 on TH-169 NB during 14:00 to 20:00
TABLE 3  Evaluation Summary Results for Key MOE’s (14:00-20:00)
TABLE 4  Metered Ramp MOE’s, 3/22/2000 TH-169 NB, (14:30 to 18:30)

LIST OF FIGURES

FIGURE 1  Mainline Speed on TH-169 With and Without Control
### TABLE 1. Goodness of Fit for TH-169 Mainline Station Volumes (14:00-20:00)

<table>
<thead>
<tr>
<th></th>
<th>Root Mean Square Error %</th>
<th>Correlation coefficient</th>
<th>Theil’s Inequality Coefficient</th>
<th>Theil’s Bias Proportion</th>
<th>Theil’s Variance Proportion</th>
<th>Theil’s Covariance Proportion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mar 21st</td>
<td>10.62</td>
<td>0.98</td>
<td>0.00426</td>
<td>0.68070</td>
<td>0.01052</td>
<td>0.30877</td>
</tr>
<tr>
<td>Mar 22nd</td>
<td>6.42</td>
<td>0.97</td>
<td>0.00154</td>
<td>0.12352</td>
<td>0.05365</td>
<td>0.82281</td>
</tr>
<tr>
<td>Mar 23rd</td>
<td>7.39</td>
<td>0.96</td>
<td>0.00238</td>
<td>0.08826</td>
<td>0.03098</td>
<td>0.88075</td>
</tr>
</tbody>
</table>
TABLE 2 MOE’s for 3/21/00 on TH-169 NB during 14:00 to 20:00

<table>
<thead>
<tr>
<th>MOE</th>
<th>Aggregation Level</th>
<th>With Control</th>
<th>Without Control</th>
<th>Percentage Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Travel Time</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(veh-hours)</td>
<td>Mainline</td>
<td>3804</td>
<td>4603</td>
<td>+21%</td>
</tr>
<tr>
<td></td>
<td>Ramps</td>
<td>599</td>
<td>81</td>
<td>-86%</td>
</tr>
<tr>
<td></td>
<td>Entire Site</td>
<td>4403</td>
<td>4685</td>
<td>+6%</td>
</tr>
<tr>
<td><strong>Total Travel</strong></td>
<td>Entire Site</td>
<td>219715</td>
<td>219754</td>
<td>Negligible*</td>
</tr>
<tr>
<td>(veh-miles)</td>
<td>Ramps</td>
<td>5792</td>
<td>5792</td>
<td>Negligible*</td>
</tr>
<tr>
<td><strong>Speed (mph)</strong></td>
<td>Mainline</td>
<td>56.2</td>
<td>46.5</td>
<td>+18%</td>
</tr>
<tr>
<td><strong>Total Delay</strong></td>
<td>Mainline</td>
<td>303</td>
<td>1099</td>
<td>+263%</td>
</tr>
<tr>
<td>(veh-hours)</td>
<td>Ramps</td>
<td>503</td>
<td>0</td>
<td>NA**</td>
</tr>
<tr>
<td><strong>Average Delay/veh</strong></td>
<td>Entire Site</td>
<td>806</td>
<td>1099</td>
<td>+36%</td>
</tr>
<tr>
<td>(min)</td>
<td>Mainline</td>
<td>0.365</td>
<td>1.322</td>
<td>+262%</td>
</tr>
<tr>
<td></td>
<td>Ramps</td>
<td>0.772</td>
<td>0</td>
<td>NA**</td>
</tr>
<tr>
<td></td>
<td>Entire Site</td>
<td>0.970</td>
<td>1.322</td>
<td>+36%</td>
</tr>
<tr>
<td><strong>Total no. of stops</strong></td>
<td>Mainline</td>
<td>7256</td>
<td>153177</td>
<td>+2011%</td>
</tr>
<tr>
<td><strong>No. of stops per veh</strong></td>
<td>Mainline</td>
<td>0.145</td>
<td>3.071</td>
<td>+2017%</td>
</tr>
<tr>
<td>(veh entered)</td>
<td>Entire Site</td>
<td>49884</td>
<td>49884</td>
<td>0</td>
</tr>
<tr>
<td><strong>Fuel Consumed (gal.)</strong></td>
<td>Ramps</td>
<td>39102</td>
<td>39102</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Entire Site</td>
<td>13736</td>
<td>18371</td>
<td>+34%</td>
</tr>
<tr>
<td><strong>CO (kg)</strong></td>
<td></td>
<td>3493</td>
<td>4128</td>
<td>+18%</td>
</tr>
<tr>
<td><strong>POLLUTANTS: HC (KG)</strong></td>
<td></td>
<td>231</td>
<td>262</td>
<td>+14%</td>
</tr>
<tr>
<td></td>
<td>Entire Site</td>
<td>67</td>
<td>84</td>
<td>+25%</td>
</tr>
<tr>
<td><strong>NOX (KG)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Negligible since results presented are for entire congestion cycle
** No ramp congestion occurs without control throughout this freeway
<table>
<thead>
<tr>
<th>Freeway MOE’s</th>
<th>I-94</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>T. TravelTime</td>
<td>Day 1</td>
<td>Day 2</td>
<td>Day 3</td>
<td>Day 1</td>
<td>Day 2</td>
<td>Day 3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-16%</td>
<td>-14%</td>
<td>-13%</td>
<td>-6%</td>
<td>-16%</td>
<td>-7%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Speed</td>
<td>+14%</td>
<td>+12%</td>
<td>+11%</td>
<td>+6%</td>
<td>+14%</td>
<td>+7%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fuel</td>
<td>-47%</td>
<td>-11%</td>
<td>-2%</td>
<td>-34%</td>
<td>-55%</td>
<td>-34%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO</td>
<td>-27%</td>
<td>-11%</td>
<td>-7%</td>
<td>-18%</td>
<td>-32%</td>
<td>-20%</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## TABLE 4 Metered Ramp MOE’s, 3/22/2000 TH-169 NB, 14:30 to 18:30

<table>
<thead>
<tr>
<th>Ramps</th>
<th>Average Ramp Wait (minutes)</th>
<th>Max Ramp Wait (minutes)</th>
<th>Total Ramp Delay (veh-hr)</th>
<th>Average Queue (veh)</th>
<th>Maximum Queue (veh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Valley View Rd</td>
<td>0.23</td>
<td>1.47</td>
<td>7.9</td>
<td>3</td>
<td>42</td>
</tr>
<tr>
<td>T.H.62 EB</td>
<td>0.26</td>
<td>1.68</td>
<td>9.6</td>
<td>3</td>
<td>36</td>
</tr>
<tr>
<td>T.H.62 WB</td>
<td>0.42</td>
<td>1.55</td>
<td>14.4</td>
<td>6</td>
<td>32</td>
</tr>
<tr>
<td>Bren Rd</td>
<td>0.82</td>
<td>3.17</td>
<td>19.4</td>
<td>7</td>
<td>39</td>
</tr>
<tr>
<td>Lincoln Dr</td>
<td>4.56</td>
<td>10.77**</td>
<td>48.4</td>
<td>17</td>
<td>41</td>
</tr>
<tr>
<td>Excelsior Blvd</td>
<td>2.52</td>
<td>9.95</td>
<td>46.0</td>
<td>16</td>
<td>68***</td>
</tr>
<tr>
<td>T.H.7</td>
<td>1.46</td>
<td>6.87</td>
<td>29.9</td>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>36th St</td>
<td>0.94</td>
<td>3.98</td>
<td>10.5</td>
<td>3</td>
<td>20</td>
</tr>
<tr>
<td>Minnetonka Blvd</td>
<td>2.94</td>
<td>8.44</td>
<td>30.4</td>
<td>14</td>
<td>42</td>
</tr>
<tr>
<td>Cedar Lake Rd</td>
<td>0.63</td>
<td>2.73</td>
<td>5.3</td>
<td>4</td>
<td>16</td>
</tr>
<tr>
<td>I-394 EB</td>
<td>0.04</td>
<td>0.05</td>
<td>1.0</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>I-394 WB</td>
<td>2.49</td>
<td>4.84</td>
<td>76.0</td>
<td>27</td>
<td>58</td>
</tr>
<tr>
<td>Betty Crocker Dr</td>
<td>3.08</td>
<td>6.3</td>
<td>28.9</td>
<td>12</td>
<td>32</td>
</tr>
<tr>
<td>T.H.55 EB</td>
<td>3.85</td>
<td>11.12**</td>
<td>37.6</td>
<td>18</td>
<td>57</td>
</tr>
<tr>
<td>T.H.55 WB</td>
<td>11.61*</td>
<td>21.54**</td>
<td>126.5</td>
<td>44</td>
<td>82***</td>
</tr>
<tr>
<td>Plymouth Ave</td>
<td>1.94</td>
<td>4.54</td>
<td>24.6</td>
<td>9</td>
<td>25</td>
</tr>
<tr>
<td>Medicine Lake Rd</td>
<td>4.36</td>
<td>9.63</td>
<td>58.3</td>
<td>20</td>
<td>46</td>
</tr>
</tbody>
</table>

* Wait larger than 5 minutes.
** Max Wait larger that 10 minutes.
*** Max queue larger than 50 vehicles.
FIGURE 1 Mainline Speed on TH-169 With and Without Control