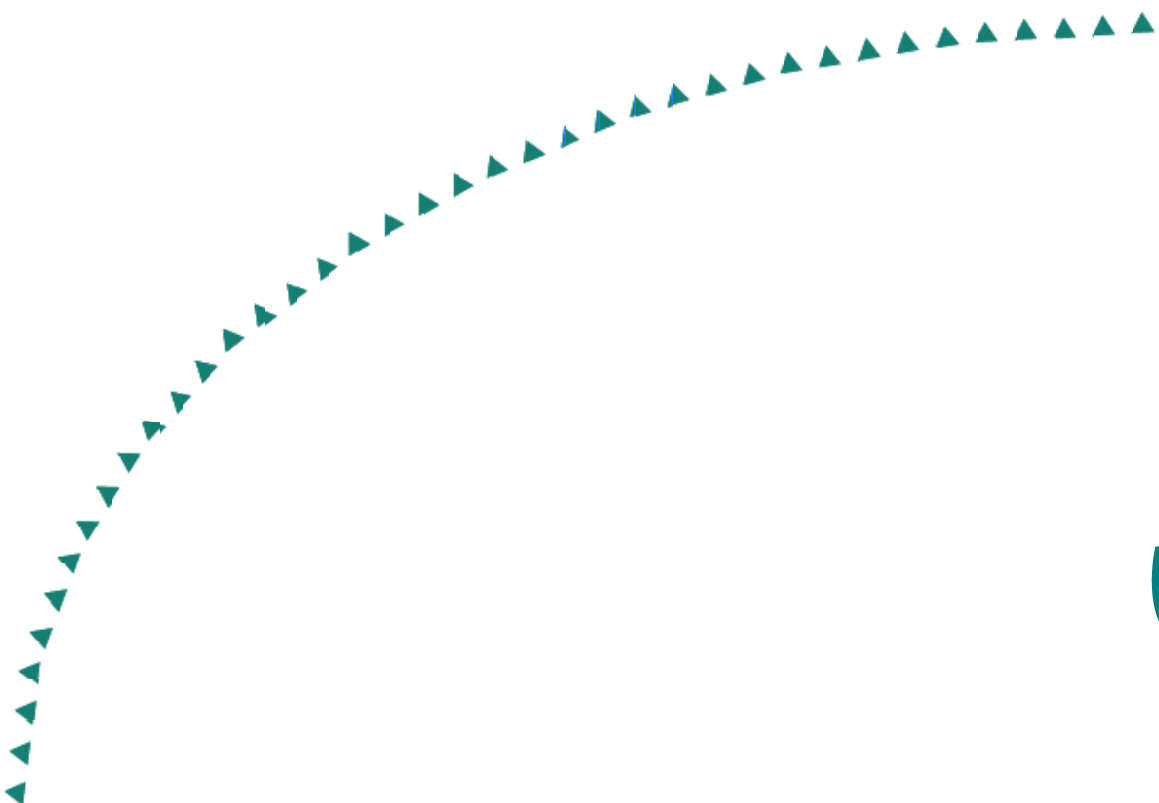# The Employment of the Traffic Management Laboratory (TRAMLAB) for Evaluating Ramp Control Strategies in the Twin Cities

SUMMARY

MINNESOTA DEPARTMENT OF TRANSPORTATION

Summary

Technical Report Documentation Page

1. Report No. MN/RC 2003-06S	2.	3. Recipients Accession No.	
4. Title and Subtitle SUMMARY OF THE EMPLOYMENT OF THE TRAFFIC MANAGEMENT LABORATORY (TRAMLAB) FOR EVALUATING RAMP CONTROL STRATEGIES IN THE TWIN CITIES - SUMMARY		5. Report Date June 2002	
		6.	
7. Author(s) P. Michalopoulos, J. Hourdakis, K. Muralidhar, A Sekhar, and V. K. Subramaniam		8. Performing Organization Report No.	
9. Performing Organization Name and Address University of Minnesota Civil Engineering Department 500 Pillsbury Dr SE, Minneapolis MN 55455		10. Project/Task/Work Unit No.	
		11. Contract (C) or Grant (G) No. (c) 74708 (wo) 164	
12. Sponsoring Organization Name and Address Minnesota Department of Transportation Office of Research Services 395 John Ireland Boulevard Mail Stop 330 St. Paul, Minnesota 55155		13. Type of Report and Period Covered Summary Report 2002	
		14. Sponsoring Agency Code	

16. Abstract (Limit: 200 words)

As freeway traffic congestion spreads ramp metering is implemented to address the problem. However, recently there is increasing opposition to freeway ramp control caused by excessive ramp delays. The objective of this research is to employ a recently developed tool called Traffic Management Laboratory (TRAMLAB) for assessing the effectiveness of Mn/DOT's control strategy in three Twin Cities freeway sections totaling approximately 65 miles. The feasibility of a corridor simulation will be followed by the selection and preliminary model development of the combination of an arterial and a freeway in the Twin Cities. As a result of this testing, TRAMLAB will evolve into an effective tool for developing control strategies that could reduce ramp delays without excessively increasing freeway congestion. Finally, a new traffic management concept for early detection of incident prone traffic conditions will be developed and integrated to traffic management through Ramp Metering and Variable Message Signs in order to smooth flow and prevent (to the extend possible) incident occurrence, thereby further reducing delays and improving safety.

Even though this proposal focuses on evaluating ramp metering and implementing a concept recently developed in a current project, we also address the more general issue of research continuity and suggest a strategic partnership with MnDOT.

17. Document Analysis/Descriptors		18.Availability Statement	
Traffic Simulation Traffic Control Corridor Control Ramp Metering	Accident Prevention Machine Vision Detector Freeway	No restrictions. Document available from: National Technical Information Services, Springfield, Virginia 22161	
19. Security Class (this report) Unclassified	20. Security Class (this page) Unclassified	21. No. of Pages 21	22. Price

Employment of the Traffic Management Laboratory (TRAMLAB) for Evaluating Ramp Control Strategies in the Twin Cities

Summary Report

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SUMMARY

1 Background

Since the early 1970's, the Minnesota Department of Transportation (Mn/DOT) has developed, implemented, and continues to expand its freeway traffic management system (FTMS). The overall goal of the FTMS is to optimize traffic flow in metro area freeway corridors by making efficient use of the available transportation facilities. Specifically, the objectives include maximizing the traffic volumes that freeway bottleneck locations can accommodate, minimizing the magnitude and duration of congestion, and minimizing accident rates. Ramp metering is considered to be the most effective single element, by far, in meeting those objectives of the FTMS.

A metered freeway segment with an automated, on-line traffic detection and response system can be expected to carry as much as 30% more vehicles per hour per lane (vphpl) than an un-metered freeway. A few on-line freeway segments in the Twin Cities area have consistently carried as much as 50% more vphpl. Similarly, it is common for congested freeways to be characterized by peak-hour speeds of 25 to 35 mph prior to activation of ramp metering systems. Fully automated ramp metering systems typically operate at 45 to 50 mph, the speed at which optimum capacity is achieved. The number of accidents on Twin Cities area metered freeways was reduced from an average of 9,200 crashes per year in 1988 and 1989 to about 7,900 per year from 1991 to 1996. There are also other benefits such as reduced fuel consumption and pollutant emissions.

In spite of the tangible benefits that accrue due to ramp control, some of the public question the effectiveness of ramp metering through either the media or their elected representatives. This is mainly because of the excessive ramp delays they experience during peak hours. According to perception tracking market research performed for Mn/DOT, there has been a negative trend over the last few years in opinion rating of ramp metering as an effective traffic management tool. Ramp metering has also been questioned by the State Legislature as evidenced by their mandate to shut down the meters for a comparative test in October 2000.

2 The Problem

There is a need to develop a scientifically sound procedure to determine the effectiveness and validity of Mn/DOT's ramp control strategy (which includes quantifying the benefits of ramp metering) and prepare a platform to test any changes in the strategy. Mn/DOT's ramp control algorithm, like many others developed in the United States, is empirical and fine-tuned over a period of time but its deviation from optimality is not known. Moreover, any changes to the algorithm have to be tested in "real life" on the road before an effective decision can be made to implement any such changes. This "trial and error" process is time consuming and risky because some of the changes are bound to be counterproductive and lead to further erosion of public opinion.

Traffic flow simulation is an obvious tool to shorten the above process but simulation has yet to become a viable practice for developing freeway traffic control strategies. Some of the problems with simulation include tedious geometric and traffic data entry, output data that is cumbersome and difficult to analyze, and doubts about how well real conditions can be replicated in simulation. Furthermore, simulators are, at best, designed to implement only a particular control strategy. Thus, a flexible and uniform practical tool for selecting the best control strategy and optimizing it or developing and testing new concepts is currently lacking.

3 Project Objectives

The objectives of this project were to:
Develop an automated simulation tool for developing, testing and comparing ramp control strategies.

Emulate Mn/DOT's traffic control strategy by integrating Mn/DOT's strategy with a simulator that has been validated and calibrated
Use the resulting simulation package to test Mn/DOT's control strategy at three test sites on Twin Cities freeways representing different functional designs, various traffic congestion levels
Compare the results with and without ramp control and quantify the advantages and disadvantages of ramp control strategy

4 Minnesota Ramp Control Strategy

The Minnesota control strategy begins by dividing the freeway into zones typically three to six miles in length. 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 it. 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 is expressed accordingly. The variables in the equation are assigned real-time values using data collected from detectors placed on the mainline, entrance and exit ramps.

Each metered ramp is assigned six metering rates. The selection of which rate to use is determined by a comparison of the measured variables in the conservation equation to a series of thresholds. Rates are also varied in response to traffic incidents by measuring vehicle occupancy over the mainline detectors. If the metering rate selected by comparison to occupancy thresholds is more restrictive than one that would be selected by volume control, the occupancy control rate is used until the volume control rate is, once again, the more restrictive.

5 TRAMLAB

This project was part of a larger program which aims to develop the Transportation Management Laboratory (TRAMLAB) as part of the ITS Laboratory at the University of Minnesota. Such an environment will contain state-of-the-art traffic simulation programs and allow the development of viable, intelligent, and automated traffic-flow simulation systems which can function as both operational and research tools. In the course of this program six well-known freeway simulators were evaluated.

After considerable evaluation of the options available, two simulators were selected: one macroscopic (KRONOS) and one microscopic (AIMSUN2) to be joined under the same input interface and database to demonstrate concept and complete a working laboratory. The programs selected performed very well comparatively in the initial tests and were selected because the project had full access to the code and support from their developers. In addition, the programs were field proven in many real-life projects and have been continuously enhanced and tested over the last twelve years. Following model selection, the AIMSUN2 simulator was enhanced to communicate with external user-defined advanced traffic management systems (ATMS) applications and as a demonstration, the current Mn/DOT control strategy was interfaced with the simulator.

The objective of TRAMLAB is to encompass, under one system, all the functions of freeway management including incident detection, incident verification, incident response, traffic monitoring, information dissemination, traffic control, and real-time or off-line simulation. This allows users to test new ideas, test system components, and develop new user interfaces quickly and efficiently. TRAMLAB allows running of several algorithms in parallel with the same data in order to select the best for the particular case.

The first benefit of TRAMLAB was realized by testing the TMC's ramp control strategy and demonstrating its effectiveness on a 15-mile section of I-35W in the Minneapolis area. Following this successful demonstration, the current project, which was the next phase of TRAMLAB, was undertaken. This project attempted to establish the validity of the preliminary tests of Mn/DOT's ramp control strategy by refining and calibrating the traffic simulator to more realistically reflect the traffic characteristics of Twin Cities freeways.

6 Microscopic Traffic Simulator

AIMSUN2 (Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks), is a simulation package which is able to treat any complex geometry of realistic large-scale urban networks consisting of both freeway and surface streets. AIMSUN2 follows a microscopic simulation approach. This means that the behavior of each vehicle in the network is continuously modeled throughout the simulation period using several driver behavior models such as car following, passing, merging, lane changing, etc. AIMSUN2 is a combined discrete-continuous simulator that accommodates elements of the system whose states change continuously over the simulation time. It can also simulate incidents, conflicting movements, intersection operations, and other complexities encountered in reality. AIMSUN2 can simulate all types of traffic

measurements that traditional or advanced detectors can provide such as vehicle counts, occupancy, presence, speed, queue length, and classification.

6.1 Simulator Enhancements

During the course of this project, several enhancements were developed for the simulator to improve its functionality with respect to the Mn/DOT control strategy and algorithm. These enhancements included a process to simulate operator interaction with the system such as incident management, ramp meter overriding in response to queues spilling on to cross streets, or displaying variable message signs. The operator interaction, of course, is a most critical features of any traffic control schemes involve. In addition, new functions were added to allow easier access to the simulator. This makes the job of the end user easier because more tools are made available to integrate the user's control logic with the simulator. For example, a user is now able to define the collection rate of measurements, which can be different from the one specified in the simulator.

Another enhancement was the development of software providing a relational database to store data collected by the TMC from more than 3000 detectors. This software permits a procedure that used to take days for entering the demand patterns to be accomplished in minutes. Without this tool, the project would have been significantly delayed. During the course of the project, it was found that there were some errors in the detector data used for simulation. If not for this tool, it would have been next to impossible to prepare the input files again. The importance of this tool also has to be viewed in the context that if the data were to be entered manually, it would have lead to inevitable errors and, hence, more time would have been needed to assure that entered data was correct.

7 Research Sites

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 size should be 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 requirements. The site selected must have most of the mainline detectors operating for successful calibration. In addition, all entrance and exit detectors must 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. It 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.

The second test site is I-94 Eastbound beginning at I-394 and ending at the off ramp at 9th St. It falls under the category of central business districts connector because 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. 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. It includes 19 entrance ramps and 14 exit ramps of which 4 are un-metered. It also contains 6 weaving sections and has about 3 lane drop sections. 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.

8 Data Collection Procedure

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.

For performing a realistic simulation definition of the boundary conditions of the freeway and the ramps are essential. This requires counts of the volumes and the 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 turning percentages. 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 provides most of these measurements in 30sec and 5-minute aggregation periods; in this study only 5-minute measurements 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 peek period. In order to capture the entire congestion cycle the experiment was scheduled between 14:00 and 20:00 on three consecutive weekdays (Tuesday, Wednesday, and Thursday).

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.

Although the above-described data are enough to build the simulation model, additional data are needed in order to accurately calibrate it. Towards that end, loop detector volume and occupancy measurements from the freeway mainline were collected 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.

9 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 and a systematic, relatively simple to implement methodology. The calibration of the case study was accomplished in three trial and

error stages. Beginning with a good estimate for all model parameters (from literature), in the first stage mainline detector station1 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 are compared along with the individual ramp rates. Because of the space limitations we can 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. 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, UM, US, and UC.

UM is the "Bias proportion" index and can be interpreted in terms of a measure of systematic error, US 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 UC or "Covariance Proportion" index is a measure of the unsystematic error. The best forecasts, and hence the best simulation model, are those for which UM and US do not differ significantly from zero and UC 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 enough. 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 had been 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 can only present a summary of the test

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[1] Each detector station aggregates counts from all its lane detectors and reports the total volume and average occupancy.

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 r2 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 location of the detectors and subsequently the nature of the measurements was identified. The Mn/DOT 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.

TABLE 1. Goodness of Fit for TH-169 Mainline Station Volumes (14:00-20:00)

	Root Mean Square Error %	Correlation coefficient	Theil's Inequality Coefficient	Theil's Bias Proportion	Theil's Variance Proportion	Theil's Covariance Proportion
Mar 21st	10.62	0.98	0.00426	0.68070	0.01052	0.30877
Mar 22nd	6.42	0.97	0.00154	0.12352	0.05365	0.82281
Mar 23rd	7.39	0.96	0.00238	0.08826	0.03098	0.88075

10 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 Measures Of Effectiveness (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 so additional ones where defined and calculated from the raw simulation output through of 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, NOx) 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, which 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 this disagreement in measuring delay, total travel time yields a more objective measurement for comparing the alternatives.

11 Freeway Simulation 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 the control case 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 increased with control but the overall system benefits from ramp metering since the aggregate MOE's are improved.

From the overall results it was found that Total System Travel Time (TTT) at both sites was reduced with ramp control strategy, by 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 by 13% to 26%. The increases 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 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 affected (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 it should be realized 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 max individual delay of 5 minutes and max 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.

TABLE 2. MOE's for 3/21/00 on TH-169 NB during 14:00 to 20:00

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

* Negligible since results presented are for entire congestion cycle
** No ramp congestion occurs without control throughout this freeway

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TABLE 3. Evaluation Summary Results for Key MOE's (14:00-20:00)

Freeway MOE's	I-94			TH-169		
	Day 1	Day 2	Day 3	Day 1	Day 2	Day 3
T. Travel Time	-16%	-14%	-13%	-6%	-16%	-7%
Speed	+14%	+12%	+11%	+6%	+14%	+7%
Fuel	-47%	-11%	-2%	-34%	-55%	-34%
CO	-27%	-11%	-7%	-18%	-32%	-20%

TABLE 4 Metered Ramp MOE's, 3/22/2000 TH-169 NB, 14:30 to 18:30

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

* 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

TH-169 MARCH 22 SPEED
WITH CONTROL

TH-169 MARCH 22 SPEED
WITHOUT CONTROL
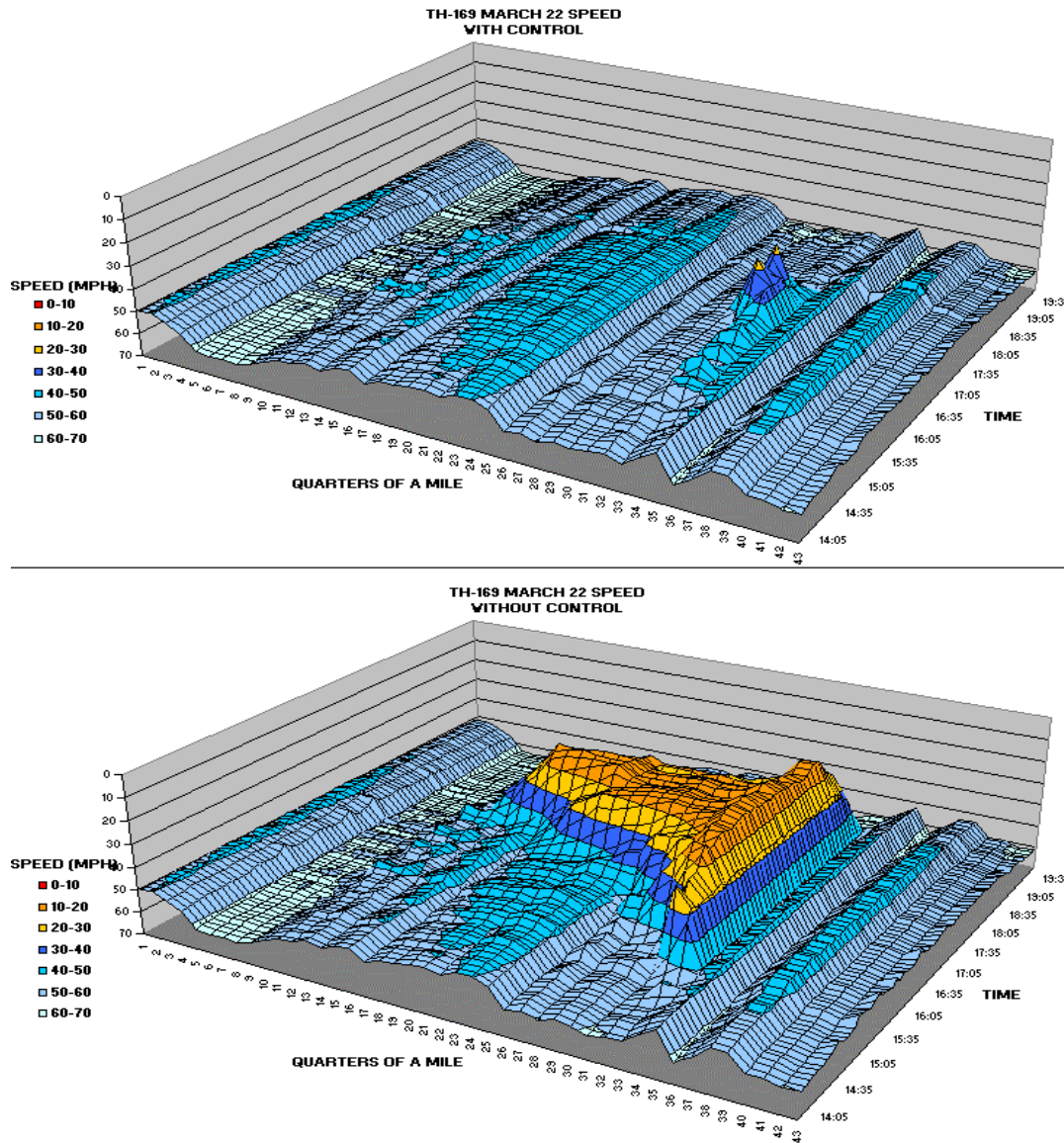
12 Ramp Metering Evaluation Conclusions

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 most suitable 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 to 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.

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. 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.

13 Feasibility of Corridor-wide Ramp control evaluation.

The research and evaluation of the Minnesota Ramp Control strategy as described up to this point was confined to the freeway-ramp system only and therefore did not consider diversion effects. Diversion of traffic onto the arterials could be considerable during the peak periods when there is heavy congestion on the freeways or high traffic demand on the on-ramps and therefore have to be accounted for in the simulation. Due to this limitation, this research team was asked by Mn/DOT to proceed with the next step, i.e., investigate the feasibility of corridor simulation. As a result, a well-instrumented freeway corridor was selected and the feasibility of simulating it was investigated. (In terms of data requirements, data availability and effort involved)

The study objectives were to:
1. Develop a systematic methodology for corridor simulation
2. Determine a methodology for estimating OD matrices for corridor simulation from the data available
3. Determine an effective calibration methodology for corridor simulation
4. Attempt to implement the methodology to the selected corridor

5. Identify problems related to implementing the methodology and devise ways to solve them

The Integrated Corridor Traffic Management (ICTM) corridor (figure 2) was the ITS deployment site for the SCATS control system and as a result is the most heavily instrumented corridor in the Twin Cities. Although in the project proposal two more freeways were named as candidate sites the availability of the advanced instrumentation on the ICTM corridor immediately prompted the research team in choosing that as test site for implementation of corridor simulation. The data needs for corridor simulation were determined and the data availability for the selected corridor was investigated. The most critical step in the entire process was the estimation of traffic demands for the corridor in the form of O/D matrices. This step involves the estimation of Traversal (local) O/D matrices for selected corridor from area-wide O/D information that are available from planning. Estimation of Traversal O/D matrices for the selected corridor turned out to be infeasible with the available data. Consequently two alternative methods were developed to compensate for the lack of data. The feasibility of the implementation of these methods on the selected corridor was explored. The results of the O/D estimation methods are presented along with the issues encountered in their test implementation. The calibration of the entire corridor simulation model could not be performed due lack of link-volume data on the surface streets. However this data was available for the freeways and consequently the freeways in the ICTM corridor were calibrated. The results of the freeway calibration are also presented.
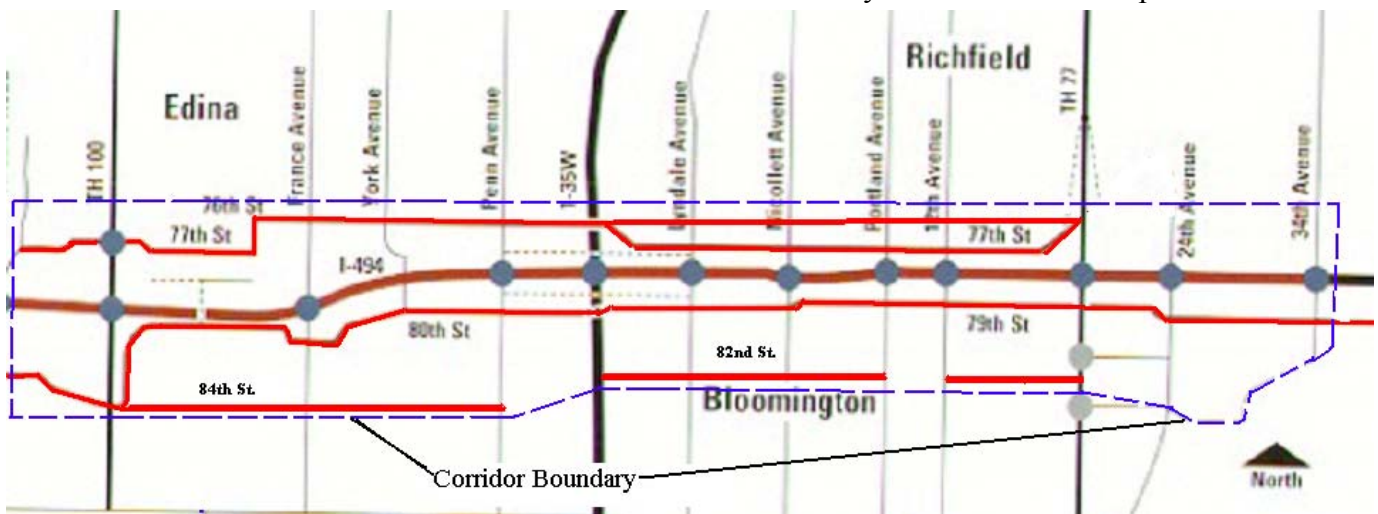

Figure 2. Map of ICTM Corridor

14 Detection of Incident Prone Conditions

The population of urban areas has continued to grow unabated even as we make the transition from the 20th century to the 21st. This increase in population coupled with ever-increasing automobile usage has had a debilitating effect on transportation infrastructure all over the world. A typical household in the United States of America owns an average of 1.85 automobiles. Fifty five percent of peak period travel is carried out under congested conditions. Since 1970, the number of cars on the road has increased by 147%, the number of automobiles per household by 53%, the number of daily vehicle trips by 102%, the number of daily miles traveled by 110% and

the number of peak period incidents by 72%. However, highway capacity has only increased by 6%. Traffic congestion costs the roadway users in the United States an estimated $100 billion in lost productivity, wastes approximately 2 billion hours and consumes 1 billion more gallons of gasoline annually. These numbers help in further ratifying the ill effects of increasing levels of congestion. The most immediate upshots of increasing volumes on the roadways are increased travel times, increased delays, productivity losses, increased levels of pollution, increased fuel consumption and most importantly, increased number of associated accidents and fatalities.

It is a well-documented fact that more accidents occur in congested traffic conditions than in free flow traffic conditions. Congestion leads to accidents and accidents lead to further congestion. Thus, it is possible to visualize the relationship between accidents and congestion as a vicious, never ending cycle.

While recurrent congestion can almost always be expected to occur at specific locations during rush hour, non-recurrent congestion, is characterized by the disturbances caused to traffic flow as a result of any random event or incident (collisions, vehicle breakdowns, road repair and other such unexpected events). Non-recurrent congestion accounts for 50% to 75% of the total urban congestion.

Accidents are the major cause of non-recurrent congestion. Around 65% to 80% of non-recurrent congestion occurs due to collisions and accidents and the remaining occurs due to such events as stalled vehicles, material spills etc. If traffic conditions likely to result in accidents could be detected, then the occurrence of accidents should be reduced thereby resulting in reduced congestion and it's side effects.

Advanced Traffic Management Systems (ATMS) use advanced technologies to assist the operators at Traffic Management Centers (TMCs) in better managing the freeway networks. Incident detection, verification and clearance form integral parts of an ATMS. Much research has been devoted to incident detection rather than detection of accident prone conditions because of the claim that since accidents are random events, detection of these conditions will not be particularly easy or even possible. Although, incident detection does help an operator in identifying locations where incidents have taken place and thus ensuring quick clearing of debris and lane blockage, it cannot prevent the occurrence of incidents (accidents) in the first place.

The objective of the task is to explore the feasibility of identifying those traffic conditions that are likely to cause accidents and to begin to develop a methodology to detect these conditions. The research relies on individual vehicle (microscopic) data (vehicle speeds, lengths etc) and visual observation of traffic (live video surveillance) from a Machine Vision Sensor placed on Interstate 394 East Bound in the Twin Cities just near the exit to Penn Avenue. After an extensive literature review and discussion with TMC operators, a list of visual undesirable flow conditions was determined. A library of video recordings and raw traffic data was created containing events matching the ones in the previously created list of undesirable conditions. This information was then used to develop algorithms for detecting undesirable flow conditions. This development can be viewed as the first step towards the identification and detection of accident prone conditions which is the subject of newly funded research.

The data collected was split into two sets – the first data set was used to develop and calibrate the algorithms and the second data set was used to test them. From all the measurements considered, minimum space headway estimated from time headway and speeds, quality of flow index and traffic pressure were found to significantly contribute in detecting undesirable flow conditions. Individual algorithms were developed to determine optimum threshold values for these measurements, which if violated causes the algorithms to raise alarms. Algorithms were then developed combining the above-mentioned traffic measurements. These algorithms were subsequently tested on the second data set to determine whether they produced consistent results.

Analysis of the results obtained by implementing the algorithms on the second data set shows that the algorithms can be implemented on different data sets without any recalibration. The results also show that combining the individual measurements in a single algorithm produce better results i.e. better detection rates with only marginal increase in false alarm rates. Based on this, a neural network algorithm was developed to combine the individual measurements. The performance of the neural network was found to be much better than that of the individual algorithms and the heuristic integrated algorithm.

The neural network produced 80.75% and a false alarm rate of 28.11%. This suggests that the algorithms developed are successful, albeit, they should be further improved for practical implementation with regards to detecting the undesirable traffic flow conditions specified. From the results achieved, it is hoped that actual accident prone conditions can also be detected by extending the methodologies developed. Detection of actual accident prone conditions is in fact being currently pursued in another project in which several Machine Vision Sensors are being installed in high accident risk locations. The cameras are being placed higher so that wide area detection of traffic can be possible. This will ensure improved estimation of measurements such as quality of flow. The methodology developed in the current project will be a starting point for developing algorithms to detect actual accident prone conditions.

15 Technology Transfer

This project covered an extensive ground of research and tool development for freeway traffic simulation in general and specifically for ramp metering evaluation. The ultimate goal is for the results of this project to help Mn/DOT engineers in current and future problems. Towards that end at the end of the project a training course was organized in order to transfer the knowledge and technology produced to Mn/DOT and FHWA engineers. During the training the participants learned how to use the simulator and the various tools developed by the university team as well as being taught the fine points of simulation model construction, calibration and output analysis. The participants used a real life problem as their exercise and received a collection of documents and software to assist them in their future tasks.
Based on the evaluations received after the completion of the training course, the participants found the material and the lectures very helpful and congratulated the university team for a job well done.