UNIVERSITY OF MINNESOTA

This is to certify that I have examined this copy of a master's project by

HONG HUO

and have found that it is complete and satisfactory in all respects,
and that any and all revisions required by the final
examining committee have been made.

Prof. David M. Levinson

____

Name of Faculty Adviser

____

Signature of Faculty Adviser

____

Date

GRADUATE SCHOOL

EVALUATION OF VARIABLE MESSAGE SIGNS
USING EMPIRICAL LOOP DETECTOR DATA

A PROJECT
SUBMITTED TO THE FACULTY OF THE GRADUATE SCHOOL AT
THE UNIVERSITY OF MINNESOTA
BY

HONG HUO

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE

AUGUST 2002

Evaluation of Variable Message Signs Using Empirical Loop Detector Data

1. Introduction

Variable message signs (VMS) (also called Changeable Message Signs (CMS) or Electronic Message Signs (EMS)), are devices installed along the freeway to display messages of special events. They warn of congestion, incidents, roadwork zones or speed limits on specific highway segments. These signs are usually installed at potentially high accident risk locations (New York DOT, 2001). The major goal of VMS is to improve the condition of traffic flow on roads and consequently improve traffic safety. When an incident is detected by loop detectors, and confirmed by a variety of traffic monitoring and surveillance systems, VMS are used to warn of duration and location of the incidents, inform drivers of the traffic conditions ahead and suggest alternative routes. These messages can help drivers to choose which route to take. A complete message on a panel generally includes a problem statement indicating incident, roadwork, stalled vehicle etc; a location statement indicating where the incident is located; an effect statement indicating lane closure, delay, etc. and an action statement giving suggestion what to do (New York DOT, 2001). It is expected that by providing real-time information on special events on the oncoming road, VMS can improve vehicles' route selection, reduce travel time, mitigate the severity and duration of incidents and improve traffic conditions and performance on traffic networks.

In Minnesota, the first VMS were deployed in the 1960s. The current VMS system consists of over 68 VMS, mainly on freeway or trunk highways. The VMS messages stipulated by the Minnesota Department of Transportation provide the following information:

(1) crashes including vehicle spin-out or rollover;

(2) stalls affecting normal flow in a lane or on shoulders;

(3) non-recurring congestion, residual effect of cleared crash;

(4) entire road closure;

(5) downstream exit ramp closure;

(6) debris on roadway;

(7) vehicle fire;

(8) short-term maintenance or construction lasting less than 3 days;

(9) pavement failure alert.

The information comes from a variety of traffic monitoring and surveillance systems. It is expected that by providing real-time information about special events on the oncoming road, VMS can improve vehicles' route selection, reduce travel time, mitigate the severity and duration of incident and improve the performance of the transportation networks.

This study assesses the effectiveness and estimates the benefits of VMS systems using empirical data from inductive loop detectors. This study includes the following tasks: First, Assess the effectiveness of VMS messages by estimating drivers' response to the traffic information provided by VMS; and second, define and measure the effectiveness of VMS systems in system-wide improvement of traffic conditions.

This study employs empirical traffic data and incident data collected in the Twin Cities of Minneapolis and St. Paul, Minnesota to estimate the effectiveness of existing VMS systems and provide better knowledge for considering the need for new installations.

Few of the existing studies utilize empirical traffic data. They either use surveys or conduct traffic simulations, which are expensive and may not conform well to reality. This study uses empirical traffic flow and occupancy data on both mainline and ramps, collected every 30 seconds to estimate the effectiveness of VMS. The variation of diversion rate before and after warning messages is statistically tested. A discrete choice model is built to predict what proportion of the vehicles diverts to the alternative routes given the characteristics of different messages. So in this study, the effectiveness of VMS is evaluated in two ways: (1) Using a discrete choice model to estimate the response of drivers to messages provided by VMS; (2) Statistical analysis on the variation of diversion rate with and without VMS.

A before and after study allows us to quantitatively evaluate the network wide benefit of VMS systems. We define and evaluate measures of effectiveness (MOEs) before and after installation of VMS for selected corridors. The change in traffic conditions and system performance before and after installation of VMS can be measured by these MOEs. This study will estimate the travel time saving, safety improvement, as well as other benefits, if any.

2. Literature Review

The existing studies for evaluating effects of VMS mainly focus on two objectives: (1) Effect of VMS on route choice guidance; (2) Effect on improving road network performance.

To test the effectiveness of VMS for route guidance, some researchers tried to estimate a route choice model for predicting how drivers respond to the information provided by VMS and whether the drivers will divert to avoid an incident on road. However, the diversion behavior cannot be explained solely by external environmental factors. It also depends on the specific person in the specific situation. If we lack information about drivers' characteristics or the relevance of the message, we are unable to obtain a route choice model to predict which specific route the driver will take after receiving information from VMS.

For this reason, many researchers used surveys or simulations to gather these data. The surveys used revealed preference or stated preference questionnaires of hypothetical situations. (Khattak 1991; Khattak, Schofer and Koppelman 1993; Wardman, Bonsall and Shires 1998; Abdel-Aty 2000; Hao, Taniguchi, Sugie, Kuwahara and Morita 1999). These studies provided valuable information on travel behavior in response to warning messages displayed on VMS. It was found that drivers are more willing to divert if there are fewer traffic stops on the alternate routes and if they are familiar with the alternate routes. In addition, young, male and unmarried drivers were more likely to divert.

Using evidence from mail survey results, the French DOT estimated that 50 percent of vehicles would divert given the choice between congested and free flowing links. Nonetheless, we believe this number is higher than the actual number of vehicles that would respond to a VMS. A number of researchers explored drivers' responses to traffic information provided by VMS. Khattak (1993) suggested that diversion behavior was influenced by the *accuracy and detail of information,* including travel times and alternate choices, and *knowledge of nature of the event,* and actions to clear it in case of incidents. Yang (1993) also found that the route choice behavior was affected by the characteristics of the alternative routes. According to the investigation of effects of VMS on link flow, based on loop detector data, they found that VMS could affect vehicle diversion significantly, especially during congested times; VMS had more influence on drivers during morning peak hours than during evening peak hours; the longer the queue length posted in VMS, the more drivers diverted. Peeta (1991) found that the *location of an incident and its duration* also affected route choice. In Virginia, surveys of drivers found *that drivers' characteristics such as* age, education, income, and sex *have no significant influence on their attitude towards VMS messages* (United States Department of Transportation, 2002). In Dallas, 71-85% of surveyed drivers used the recommended route. The factors having influence on diversion include traffic conditions on the alternate routes, familiarity with the alternate route, confidence in the information (United States Department of Transportation, 2002).

All these studies provided valuable information about the effectiveness of VMS. However, the drawbacks of surveys are their cost and the question is whether individuals actually behave in accordance with their stated choices. Therefore, some route choice simulators have been developed to gather information on drivers' characteristics and response, such as VLADIMIR (Bonsall and Merrall 1995), and FASTCARS (Adler, Recker and McNally 1993). Bonsall (1995) concluded by a route choice simulator that the *clarity of the message, the distance of the VMS from the incident,* and *the inclusion of delay time* on message influenced the diversion behavior.

Although a route choice model may provide valuable information on the effectiveness of VMS, there are still some doubts about such a simple model. One is the hypothetical assumption owing to the difficulty of obtaining data on driver behavior. The other is the simplification of models. For this reason, some research evaluated congestion effects after VMS has been widely implemented. But evaluating the impacts of VMS on network performance is difficult because of the complexity of the network systems and various developments or seasonal impacts.(Kraan, Zijpp, Tutert, Vonk, and Megen 1999).

3. Drivers' response to VMS messages

(1) Data collection and description:

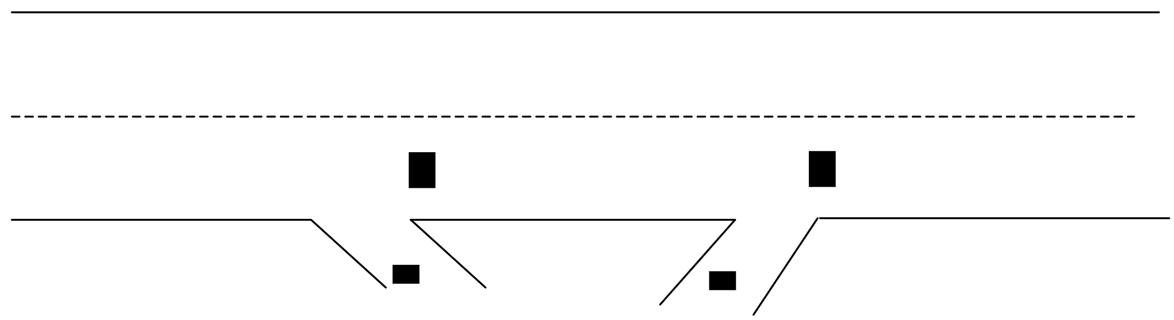
The VMS located at the crossroad of Little Canada Road on I-35E southbound is selected to study drivers' response to VMS. The collected data related to this study site include:

a. Messages displayed on VMS during September 2000;

Detailed messages displayed on panels of 45 VMS in Minnesota during September 2000 were collected. The database includes the content and the start time of messages. We chose the 44 messages at the study location to study the drivers' response to these different messages.

b. Traffic volume and occupancy data from loop detectors on freeways;

The binary data about traffic flow and occupancy were recorded by the loop detectors on freeway in 30 seconds time intervals. This dataset was provided by Transportation Management Center (TMC) and includes traffic data from 1994 until now. We extracted the binary data for September 2000 and translated these to the vehicle counts and occupancy in five minutes time intervals. The flow over a 5 minutes time slice, on both ramps and the mainline, is regarded as one observation, and we choose randomly 2363 observations in workdays under both incident and non-incident situations and during both peak and non-peak hours, in September, 2000.



(Fig.1 Loop detectors)

(2) Diversion Choice Model

In this study, a weighted Probit model is used to estimate the drivers' diversion behavior given the characteristics of messages and incidents. We considered the total flow in each five minutes n_j as a subgroup of trials, among which the numbers of diverted vehicles y_i are recorded as successes. We want to describe the proportion of successes, that is, the diversion rate in each subgroup in terms of selected factors, $P_j = y_i / n_j$. The Probit model is used to model the probability of diversion, of which the link function is defined as the inverse cumulative normal probability function. The model can be written as:

$$\Phi^{-1}(p_j) = \beta_0 + \beta_k x_{jk} + e_j$$

Where p(j) represents the proportion of vehicles that choose to divert in response to the message in subgroup j of total volume of vehicles. x_{jk} are the k^{th} factor considered to influence vehicles' diversion behavior for subgroup j of total volume of vehicles, which are selected as follows:

a. Whether there is a message or not (0-1 dummy variable);
b. The nature of incident: congestion, crash, roadwork, or non-incidents (categorical variable);
c. Peak period (7:00 – 9:00 am) and non-peak period (10:00 – 20:00) (0-1 dummy variable);
d. Whether there are alternative routes ahead. We define this term as 1 if there is other exits ahead, otherwise, as 0. (0-1 dummy variable)
e. Whether the message attracts vehicles to the exit at the studied ramp, discourages vehicles from diverting (repel), or has no influence on this route (categorical variable). (Overall there were 6 repel messages, 35 attract messages, and 3 messages with no specific effect)

In this study, we assume that the diversion rate is stable within each 5-minute interval. Traffic flow on both off-ramps and the mainline in 5-minute intervals are used to calculate the diversion rate on each exit. The dependent variable is the proportion of vehicles exiting at the off-ramp among the total vehicles on both the off-ramp and mainline.

The number of diverted vehicles in each subgroup of total volume of vehicles can be assumed to follow the binomial distribution. The counts of vehicles in each five minutes interval are not constant, consequently the variance of number of diverted vehicles is not constant, but correlated to the total volume. Therefore, we use a weighted least squares method to estimate the model with weights of $n_j \pi_j (1-\pi_j)$. The minimization objective function is:

$$\chi^2 = \sum \frac{(y_j - n_j \pi_j)^2}{n_j \pi_j (1-\pi_j)}$$

where y_j represents the observed numbers of diverted vehicles in each subgroup. $n_j \pi_j$ represents the estimated numbers of diverted vehicles in each subgroup.

The STATA statistical software was used to estimate the model in this study. The Probit choice model is estimated for the proportion of diversions at exits downstream of the VMS at Little Canada Road on I-35E.

The results are shown in Table 1. The first coefficient is an alternative-specific *constant*, which reflects the difference in the utility of alternative *i* (diverting) from that of *j* (not diverting). In the model depicted above, the estimate for β_0 is negative, reflecting a relative preference for staying on the freeway without any information promoting diversion.

The second and the third coefficients correspond to whether an *alternative route* is available ahead. The third term is the interaction of an *alternative route* with whether the *message* is on. The positive sign of the second term indicates that the diversion rate at the first exit is greater than the downstream one if there are no warning messages. The negative sign of the third coefficient means that the probability of diversion is lower at the first exit than the downstream one if there is a message warning of an accident ahead by VMS. This indicates that if drivers divert in response to messages, they prefer to choose the downstream alternative exits instead of the first one.

The next three terms are corresponding to the categorical variable of the nature of incident: congestion, incident, roadwork, or non-incident, which reflect the content of the message. The first three categories indicate that an *incident*, *congestion,* or *roadwork* is provided by VMS. Non-incident was considered as the basis of the other three categories. Basically, these variables reflect the differences in preferences for response to the message or not. These three coefficients are all positive, which means the probability of diversion increases in response to the message of *incident*, *congestion*, or *roadwork* compared with the non-incident situation. The term for *roadwork* is not a significant factor. The reason is the messages collected are limited, of which only three messages indicate roadwork ahead. Moreover, all three messages appeared within half an hour. Another important discovery here is that the coefficient for *incident* is greater than the other two. This indicates that the influence of *incidents* is greater than *congestion*; both are greater than *roadwork*.

The *peak* term indicates whether the message appeared during the peak period. The coefficient is negative and significant, which means the VMS is less effective during the peak period. One possible reason is that the traffic conditions are unstable during the peak hour and the traffic is too heavy for vehicles to divert easily. Moreover, during the peak hour the traffic conditions on most other routes are also not good, so lacking no clear knowledge about the traffic conditions on alternative routes, vehicles will not choose to divert. The influence of incidents was reduced.

The last two terms indicate the message *attracts* vehicles to divert or shows incidents on the alternative roads or *repels* them from diverting. e.g. If the message warns of an incident downstream, the exit *attracts* vehicles to divert. If the message warns of an incident on the alternative route, the message will *repel* vehicles from diverting (exiting). The positive sign of *attract* indicates that vehicles are more likely to divert to alternative routes when a message indicates a downstream incident. The negative coefficient of *repel* means more vehicles will choose to stay on the road instead of diverting when there are incidents on alternative roads.

This Probit choice model provides a reasonable explanation of drivers' response to messages with different characteristics. It is clear that the content of messages has a significant influence on drivers' diversion behavior.

Table 1: Weighted least squares probit estimates for grouped data

Probit	*Coefficient*	*t-ratio (p-value)*
Constant	-1.34	-265.19 (0.000)
Alternateroute	0.461	74.61 (0.000)
*Alternateroute*message*	-0.216	-8.55 (0.000)
Accident	0.158	2.56 (0.011)
Congestion	0.140	2.10 (0.036)
Roadwork	0.004	0.05 (0.963)
Rush-hour	-0.214	-38.66 (0.000)
Attract	0.016	2.06 (0.040)
Repel	-0.084	-2.03 (0.042)
R-squared	0.7292	
Residual SS	47.9584	
Observations	2363	
Degree of freedom	2353	
Model test		F(9, 2353) = 703.83 (0.000)

(3) Statistical Analysis

Statistical analysis is used to test the difference of the diversion rate before and after a message is activated. It is expected that the vehicles will take an alternative route instead of the congested road and the number of exiting vehicles on off-ramps would change immediately after a warning message. That is to say, the diversion rate after a message should significantly increase immediately warning of a special event ahead on the road. On the other hand, the diversion rate should significantly decrease immediately after a message warning of congestion or an incident on other roads.

We use t-test to test the null hypothesis that the means of diversion rate in two populations --- all the vehicles in 10 minutes before and after the message are equal. Samples selected for testing the population means are the vehicles in 10 minutes before and after 44 messages on the VMS located at the crossroad of Little Canada Road on I-35E southbound during September 2000.

The null hypothesis is:

$$H_0: \mu_{-10} = \mu_{+10}$$

Using t-test:

$$t = \frac{\bar{x}_{-10} - \bar{x}_{+10} - (\mu_{-10} - \mu_{+10})}{\sqrt{\frac{s_{-10}^2}{n_{-10}} + \frac{s_{+10}^2}{n_{+10}}}}$$

Where

$\bar{x}_{-10}$: The sample mean of diversion rate in ten minutes before the message;

$\bar{x}_{+10}$: The sample mean of diversion rate in ten minutes before the message;

μ_{-10} : The population mean of diversion rate in ten minutes before the message;

μ_{+10} : The population mean of diversion rate in ten minutes after the message;

s_{-10} : The sample standard deviation in ten minutes before the message;

s_{+10} : The sample standard deviation in ten minutes after the message;

Since the two population means of diversion rate are assumed to be equal, the t-statistic is:

$$t = \frac{\bar{x}_{-10} - \bar{x}_{+10}}{\sqrt{\frac{s_{-10}^2}{n_{-10}} + \frac{s_{+10}^2}{n_{+10}}}}$$

The large t-statistic indicates that there is significant difference between two means. We have to reject the null hypothesis. The diversion rate in 20 minutes, 30 minutes, 40 minutes after message is also compared with that before messages in the same way. The diversion rate here is integrated in 5 minutes intervals. Messages can have two different influences on different exits, one is to attract diversion, the other is to repel diversion. So the data were grouped into two groups according to the effect of the message. The study site is the VMS of Little Canada Road on I-35E southbound.

When the message indicates an incident on alternate route (a *repel* message), the drivers' response within different period before or after the message is summarized as follows:

Table 2: Diversion rate before and after the repel messages

Period	*Mean*	*Sd*	*Number*
Before message	0.168	0.039	23
10min after message	0.139	0.037	13
20min after message	0.139	0.045	8
30min after message	0.155	0.040	8
40min after message	0.156	0.044	8
Total	0.152	0.041	60

When the message induces diversion (we called it an *attract* message), the drivers' response within before and after the message is summarized as follows:

Table 3: Diversion rate before and after the attract messages

Period	*Mean*	*Sd*	*Number*
Before message	0.119	0.059	191
10min after message	0.144	0.066	137
20min after message	0.128	0.059	84
30min after message	0.122	0.057	80
40min after message	0.119	0.057	76
Total	0.127	0.061	568

We perform a t-test on the equality of means for periods before and after messages. From these tests, the large value of t-statistic indicates that diversion rate within 10 minutes after the message is significantly different than that before the message. Results of these tests are shown in Table 4 and 5:

Table 4: Statistical test result for the repel messages

	Difference of mean	t-statistics	Two-tailed significance
$Mean_0 = Mean_{0-10}$	0.029	2.182	0.0361
$Mean_0 = Mean_{10-20}$	0.029	1.718	0.0964
$Mean_0 = Mean_{20-30}$	0.013	0.809	0.4254
$Mean_0 = Mean_{30-40}$	0.012	0.707	0.4852

Table 5: Statistical test result for the attract messages

	Difference of mean	t-statistics	Two-tailed significance
$Mean_0=Mean_{0-10}$	0.025	-3.643	0.0003
$Mean_0=Mean_{10-20}$	0.009	-1.143	0.2547
$Mean_0=Mean_{20-30}$	0.003	-0.382	0.7030
$Mean_0=Mean_{30-40}$	0.000	0.0014	0.9989

4. Estimation of MOE to assess the benefit of VMS

A before and after study is employed to evaluate the improvement of performance on the network. The benefits of VMS are comprised of: 1) travel time saving; 2) reduction of total delay; 3) safety improvement; 4) environmental improvement; and 5) providing information to travelers who choose not to divert. In this study, we consider the first three measures to estimate the benefit of VMS systems.

(1) Data collection and description

Three newly installed Variable Message Signs in July 1999 were selected for the before and after study: the first one is located at the crossroads of Lone Oak Rd on I-35E northbound; the second one is at the crossroads of TH77 on I-35E northbound as well; and the third one is located at the crossroad of I-35E on TH77 northbound. The data collected include:

a. Traffic volume and occupancy from loop detectors on freeways:

The traffic data in November 1998, 1999 and 2000 were collected from the loop detectors deployed on freeway I-35E and TH77 and the access ramps. These traffic counts and occupancy data were used to calculate the travel time and delay on the freeway.

b. Detailed incident log from 1991 till 2001:

An incident database was obtained from TMC, which recorded the detailed incident information from 1991 to 2001. This database includes the type of incident, direction and exact location of each incident, start time and clearance time of incidents, the lane closed and the number of vehicles involved.

c. Installation time of VMS systems

There is no record of exact installation time of VMS systems. It is estimated that the VMS is installed around the installation time of ramp meters close to it. So in this study it is difficult to identify the influence of VMS or Ramp Meters if we only consider two situations before and after installation of VMS. The third situation in which the ramp meters are shut down should also be considered.

(2) Travel time savings

The chief objective of VMS is to divert traffic flow when an incident happens ahead and to increase the effective capacity of the freeway during incidents by encouraging vehicles to take alternative routes. Therefore, the travel time saving for drivers is one of chief benefits of VMS systems.

Travel time saving can be measured as the difference of travel time before and after installation of VMS on the same segments of freeway in the same situation. The situations under both incident and non-incident situations, peak period and non-peak period are considered respectively. Empirical data from loop detectors are used to calculate travel time on freeway.

The freeway is divided into small segments. Travel time on the freeway can be obtained by summing the travel time on continuous segments. Each segment includes one mainline station of loop detectors. The segments are divided by the midpoint between mainline stations, or by the ramp exit point. The time period is divided into 5 minutes time slices, and travel time is calculated for each time slice on each freeway segment.

From loop detectors, we can get traffic flow and occupancy data. Given each segment length, it is also necessary to get the space mean speed during each segment. It is a challenging problem to accurately calculate space mean speed on each segment. For simplicity, the calculation of speed is based on the following assumptions:

a. Traffic speed and volume data are determined from the loop detectors on the segment, and volume, speed and density in 5 minutes time slices throughout the same segment are assumed to be homogenous.
b. Effective vehicle length is 22 feet.
c. Speed is free flow speed (60 miles/hour) if occupancy is below 10%, and 5 miles/hour if occupancy is above 80%. (This is to avoid the extremely high speed and low speed due to the errors of loop detectors).

Under these assumptions, travel speed in miles per hour on a specific segment can be calculated as:

$$speed = \frac{5.909\, flow}{occ}$$

The travel time on the segments of TH77 northbound from the location of the VMS to I-394 is compared under three situations: Situation 1 is November 1998 before installation of ramp meters and variable message signs; Situation 2 is November 1999 after installation of ramp meters and variable message signs; Situation 3 is during the eight-week period of the ramp meters shutdown from the middle of October till the middle of December 2000, while variable message signs still operated. Note that ramp meters only operated during the peak hours in Situation 2.

Table 6: Comparison of travel time on TH-77

		Incident travel time (Seconds)	Non-incident travel time (Seconds)	Hourly Volume
Situation 1 1998 No VMS and No Ramp Meters	Peak hour	658	281	4498
	Non-peak	281	258	1870
Situation 2 1999 With VMS and Ramp Meters	Peak hour	512	273	4641
	Non-peak	247	238	1899
Situation 3 2000 Ramp Meters Shutdown (VMS alone)	Peak hour	765	431	4928
	Non-peak	320	271	1882

From the above result, we conclude that the there is a 22.2% reduction of travel time with incidents during AM peak hour after installation of both VMS and ramp meters.

Similarly, during non-peak hours, travel time can be reduced by 12.1% with incidents, attributable solely to VMS, as the ramp meters in general were not operating. Under normal conditions without incidents, the travel time decreased by 6.4% after installation of VMS and ramp meters during peak hour and 7.75% during non-peak hour. However after the ramp meter shut down, it is obvious that the travel time increased again, especially during peak hour. Ramp meters are a much more significant factor in reducing peak hour travel time than VMS. In fact, there is little evidence here that VMS can improve peak hour travel time at all, as the 2000 data with VMS is always worse than the 1998 data. However, hourly volume increased year-by-year especially during peak hours. Therefore, the increase on travel time may reflect an increase in traffic levels.

In case 2, the travel time on segment of I-35E from VMS to I-394 is also compared in three situations as in case 1.

Table7: Comparison of travel time on I-35E

		Incident travel time (Seconds)	Non-incident travel time (Seconds)	Hourly Volume
Situation 1 1998 No VMS and No Ramp Meters	Peak hour	514	421	3030
	Non-peak	488	418	1563
Situation 2 1999 With VMS and Ramp Meters	Peak hour	561	425	3246
	Non-peak	452	416	1579
Situation 3 2000 Ramp Meters Shutdown (VMS alone)	Peak hour	680	447	3614
	Non-peak	464	437	1579

From the comparison, we find the travel time increased slightly under incident situations during the AM peak hour; and saved 7.38% during the non-peak hour with incidents after installation of VMS and ramp meters. Under non-incident situations, the travel time didn't decrease during the peak hour. After the ramp meter shut down, it is shown once more that the travel time increases, especially during the peak hour. However, at this location, VMS and ramp meters save freeway travel time with incidents in the peak hour. Also, in this case, hourly volumes increase year-by-year during peak hours. Therefore, the increase on travel time is also partly caused by increase traffic levels.

(3) Reduction of total delay (vehicle-hours saving)

Vehicle-hours reduced per incident are measured to evaluate the benefit of VMS. In this section of the report, input/output analysis is used to calculate the total delay, that is, vehicle-hours in the queue. A queuing diagram explains the formation and clearance of the queue, and the delay time in queue. As illustrated in the diagram, theoretically, when an incident happens, the capacity of road reduces and the queue begins to stack behind the bottleneck when the arrival rate exceeds the reduced capacity. The vertical difference of the two curves is the length of queue at a specific time and the horizontal distance between the two curves is the delayed time in queue. Therefore, the total delay can be calculated as the area between the input and output curve.

The freeway is divided into small segments as in the calculation of travel time. Each segment includes one mainline station of loop detectors. The segments are divided by the midpoint between mainline stations, or by the ramp exit point. If some loop detector in a certain segment is bad, the segment is split between two adjacent segments. The counts of vehicles entering the segment are recorded as input and the counts departing the segment as output. The criterion for determining bad detectors is an occupancy over 80% or zero flow. In the space and time domain, the time period is divided into 1-minute time slices, and traffic flow and speed are calculated for each time slice on each freeway segment.

VMS provides dynamic information about incidents to drivers and increases the rate at which drivers divert at the exits before the incident location. Theoretically, after VMS is turned on, the arrival rate decreases (assuming the VMS is warning of a message ahead on the same road). From Figure 2, we can see a reduction in the duration for queue dissipation. So both the queue duration and the number of vehicles involved in the queue are less than without VMS, which results in a reduction of the total vehicle-hours delay caused by incident. Therefore, the difference of the area between the input and output curve is the reduction of total delay in vehicle-hours.

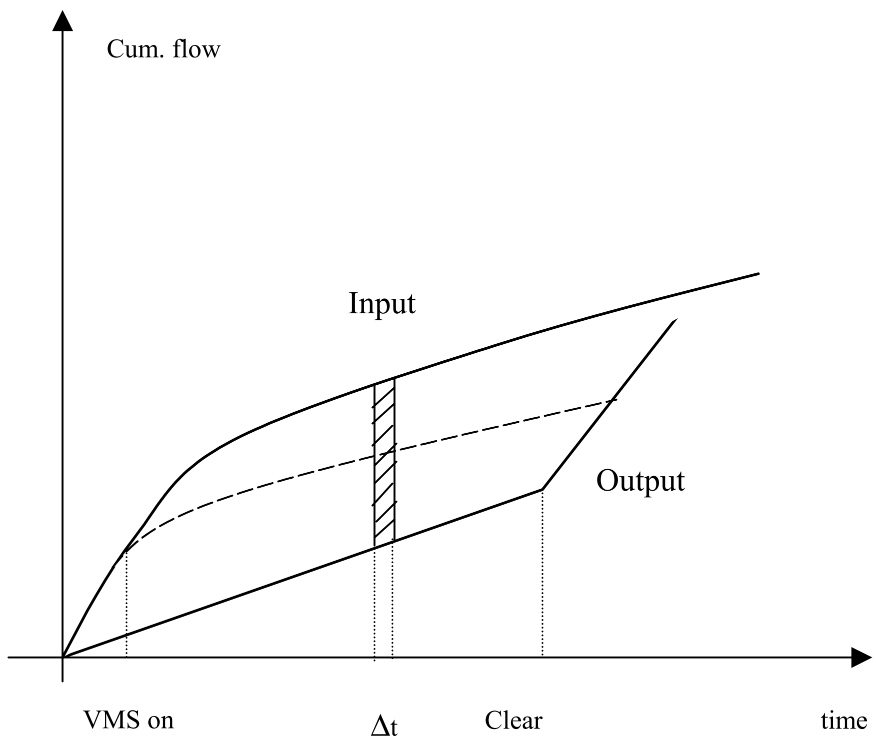


Figure 2 Input and Output diagram

Total delay in vehicle-hours can be calculated as follows:

Total Delay time: $D(t_n) = D(t_{n-1}) + (t_n - t_{n-1})(I_n - O_n)$

Average delay: $\bar{d} = D(t_n) / \sum_{n=1}^{T/\Delta t} (\lambda_n - \mu_n)$

Where

I_n is the cumulative arrivals at time slice n.

O_n is the cumulative departures at time slice n.

λ_n is the arrival rate at time slice n.

μ_n is the departure rate at time slice n.

T is the incident duration.

$\bar{d}$ is the average delay.

It is necessary to know the cumulative arrival rate, cumulative departure rate and duration of incidents for calculating the total delay for each incident. By comparing the difference of average vehicle-hours per incident before and after installation of VMS, the effectiveness of VMS in incident management can be measured.

Assumptions:

a. In the input and output method, the queue doesn't begin to form until the arrival rate exceeds capacity.

b. This method estimates a queue formed at one single point and assume that vehicles are vertically stacked.

The reduction of total delay of vehicle-hours is calculated before and after installation of VMS and ramp meters on I-35E southbound. Vehicle-hours saved due to VMS are calculated as table 8 in November 2000 when ramp meters shut down.

Table 8: Reduction of total delay before and after VMS

Total Delay per incident (Vehicles-minutes)	1998 no VMS and Ramp meters	1999 with VMS and Ramp meters	2000 Ramp meter shut down (VMS alone)
	14500	7635	10895

On the average, VMS and Ramp meters reduced the total delay up to 114 vehicle-hours per incident and 60 vehicle-hours per incident after ramp meters shut down.

(4) Safety Improvement

VMS can help to reduce the duration and severity of congestion, which should reduce occurrences of crashes. The variation of average number of crashes on each segment is considered as the measurement of safety improvement.

The number of all kinds of incidents (crashes, stalled vehicles, rollover, and other incidents) happened in three situations as before on I-35E and TH-77 are compared as follows:

Table 9: The number of incidents on freeway I-35 E

Number of incidents	Situation 1	Situation 2	Situation 3
Crash	25	41	66
Stall	19	12	29
Rollover	2	0	0
Other	2	5	6

Table 10: The number of incidents on TH-77

Number of incidents	Situation 1	Situation 2	Situation 3
Crash	5	5	12
Stall	5	8	9
Spinout	0	1	0
Other	0	0	1

It can be found that incident frequencies increase year by year despite the installation of ramp metering and VMS on I-35E and TH-77. Therefore, data were not sufficient to demonstrate a safety improvement considering only the number of incidents.

5. Conclusion

The effectiveness of VMS on route guidance is assessed by a discrete probit choice model and statistical test using empirical traffic flow and occupancy data from loop detectors on both mainline and ramps, collected every 30 seconds. The difference in diversion rate before and after warning messages is statistically tested. The discrete choice model estimates the proportion of vehicles that diverts to alternative routes given the characteristics of different messages.

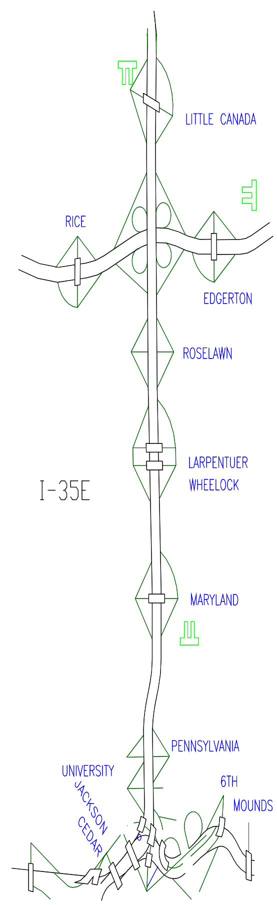
The result of the statistical analysis shows that VMS is an effective tool in route guidance and can increase drivers' diversion rate significantly by providing warning messages about the traffic conditions on the road. The probit choice model provides a reasonable explanation of drivers' response to messages with different characteristics. The nature of the incidents is a factor that influences the diversion behavior. Incidents warned by the message have greater influence than congestion; both have greater influence than roadwork. VMS is more effective in light traffic than heavy traffic. This may be because it is difficult to change lanes, merge or divert in heavy traffic. Alternatively, it may be due to congestion on alternatives during times of heavy traffic. Drivers prefer to start to divert at several exits prior to the incident.

A before-after study is also conducted to quantitatively evaluate the network wide benefit of VMS systems. We defined three measurements of effectiveness: travel time savings, vehicle-hours reduced per incident and safety improvement to evaluate the benefit after installation of VMS systems. From the results, we see that VMS has no obvious effect on reduction of travel time. It is shown that VMS and ramp meters on TH-77 can help to reduce travel time together for vehicles. But during the ramp meter shut-down, the travel time increased again. It indicated that the ramp meters are more effective in reducing travel time. But this also reflects an increase of the traffic level. On I-35E both ramp meters and VMS are less effective in reducing travel time. After ramp meters shut down, the travel time increased again. Tests on I-35W demonstrate that VMS and ramp meters together can reduce the total delay up to 114 vehicle-hours per incident and 60 vehicle-hours per incident after ramp meters shut down. The number of incidents on both TH-77 and I-35E increased despite VMS and ramp meters, thus we provide no evidence to the hope that VMS can help to improve safety.

In future studies, the optimization of VMS locations is suggested. VMS effects vary by location. Therefore, with finite budgets, it is important to choose effective locations to deploy VMS systems. The content displayed on VMS is also an influential factor on the effectiveness of VMS. Further study on how to design the messages more effectively is also suggested.

Appendix1:

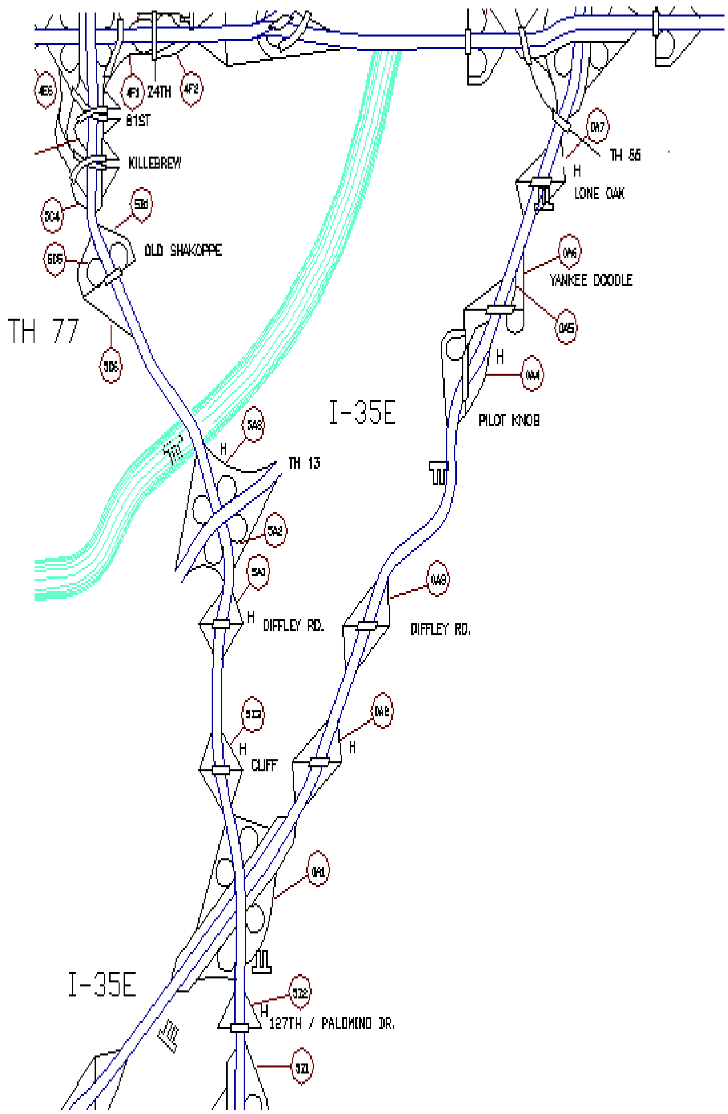
Study site 1: VMS at the road of Little Canada on Freeway 35E south bound



Appendix2:

Study site 2: VMS at the south of Lone Oak Rd on I-35E north bound

Study site3: VMS at the north of Minnesota River on the TH-77 north bound



Referfence:

1. Abdel-Aty Mohamed A. (2000), Using ordered probit modeling to study the effect of ATIS on transit ridership. *Transpn. Res*.-C 9, pp 265-277.
2. Al-Deek H., Garib A. and Radwan A.E. (1995), New Method for Estimating Freeway Incident Congestion, *Transportation Research Record 1494*, pp. 30-39.
3. Adler J., Recker W. and McNally M. G., (1993) A conflict model and Interactive Simulator (FASTCARS) for predicting enroute driver behavior in response to real-time traffic condition information, *Transportation 20*, pp 83-106.
4. Bonsell P. W., MERRALL A.C. (1995), Analysing and Modeling the Influence of Roadside Variable Message Displays on Drivers' Route Choice, *7th WCTR*, Sydney,1995.
5. Chow W.M. (1974), A Study of Traffic Performance Models Under An Incident Condition, *Highway Research Record 567*, HRB, National Research Council, Washington D.C., 1974, pp. 31-36.
6. Hao E., Taniguchi M., Sugie Y., Kuwahara M. and Morita H. (1999), Incorporating an information acquisition process into a route choice model with multiple information sources, *Transpn. Res*.-C 7, pp 109-129, 1999.
7. Khattak A.J., Schofer J. L. and Koppelman F. (1993), Commuters' Enroute Diversion and Return Decisions: Analysis and Implications for Advanced Traveler Information Systems, *Transpn. Res.*-A, Vol. 27A, No.2, pp.101-111.
8. Kraan M., Zijpp B., Tutert B., Vonk T., and Megen D. V. (1999), Evaluating Networkwide Effects of Variable Message Signs in the Netherlands, *Transportation Research Record 1689*, Paper No. 99-1126.
9. Makigami Y., and Woodie W.L. (1970), Freeway Travel Time Evaluation Technique. *Highway Research Record 321*, HRB, National Research Council, Washington D.C., 1970, pp. 33-45.
10. Messer C.J., Dudek C.L., and Friebele J.D. (1973), Method for Predicting Travel Time and Other Operational Measures in Real-time During Freeway Incident conditions. *Highway Research Record 461,* TRB, 1973, pp. 1-16.

11. Morales J.M. (1986), Analysis Procedures for Estimating Freeway Traffic Congestion. *Public Road*, vol. 50, No.2, September 1986, pp. 55-61.
12. Olmstead, Todd (1998), Pitfall To Avoid When Estimating Incident-Induced Delay by Using Deterministic Queuing Models, *Transportation Research Record 1683*, 1998, pp. 38-46.
13. Thill J.C., Rogova G. and Yan J., (2001), Delay Modeling for Corridor-level Benefits Evaluation of VMS deployments, paper presented at *the 2001 Annual Meetings of Transportation Research Board,* 2001.
14. Wardman M., Bonsall P. and Shires J. (1998), Driver Response to Variable Message Signs: A Stated Preference Investigation, *Transpn. Res.-C*, Vol.5, No.6, 1998, pp389-405.
15. Wirasinghe S. C. (1978), Determination of Traffic Delays from Shock-Wave Analysis, *Transportation Research, vol.12*, pp. 343-348.
16. Yim Youngbin and Ygnace J. (1996), Link Flow Evaluation Using Loop Detector Data: Traveler Response to Variable-Message Signs, *Transportation Research Record 1550*, pp. 58-65.
17. New York State Department of Transportation, Long Island Intelligent Transportation Systems, Access time: November, 2001, http://www.dot.state.ny.us/reg/r10/vms.html
18. United States Department of Transportation, ITS Benefits and Unit Costs Database, *Access time*: March, 2002, http://www.benefitcost.its.dot.gov/its/benecost.nsf