Title

Traffic Management System Performance Using Regression Analysis

Authors
Levinson, Davida
Chen, Wei

Publication Date
2006-03-01

CALIFORNIA PATH PROGRAM
INSTITUTE OF TRANSPORTATION STUDIES
UNIVERSITY OF CALIFORNIA, BERKELEY

Traffic Management System Performance Using Regression Analysis

David Levinson, Wei Chen
University of Minnesota

California PATH Working Paper
UCB-ITS-PWP-2006-3

This work was performed as part of the California PATH Program of the University of California, in cooperation with the State of California Business, Transportation, and Housing Agency, Department of Transportation, and the United States Department Transportation, Federal Highway Administration.

Report for Task Order 4132

March 2006

ISSN 1055-1417

Traffic Management System Performance Using Regression Analysis

A case study of Mn/DOT's Traffic Management Systems

David Levinson[1] Wei Chen[2]

Department of Civil Engineering
University of Minnesota
500 Pillsbury Drive SE
Minneapolis, MN 55455
levin031@umn.edu
V: 612-625-6354
F: 612-626-7750

1. Associate Professor, 2. Research Assistant

Abstract

This study can be viewed as a preliminary exploration of using regression analysis to evaluate long-run traffic management system performance. Four main traffic management systems in the Twin Cities metro area --- Ramp Metering System, Variable Message Signs (VMS), Highway Helper Program, and High Occupancy Vehicle (HOV) System were evaluated based on multiple regression models. Link speed and incident rate were employed as the response variable separately. Consequently, regression analysis can be a simple and effective research method for testing the macroscopic association between traffic management and traffic system performance; however, additional research is still necessary to obtain an overall evaluation of each of the traffic management systems. Furthermore, improvements could be made through model improvement, adding relevant predictor variables, and decreasing data-limitations.

Key Words: Regression analysis; Traffic management system; Traffic system performance; Before-and-after study; Response variables; Predictor variables; Multiple regression model; Speed; Incident Rate; Ramp Metering System; Variable Message Signs (VMS); Highway Helper Program; High Occupancy Vehicle (HOV) System.

1. INTRODUCTION

The Minnesota Department of Transportation (Mn/DOT) Traffic Management Center (TMC) started in 1972 to centrally control the freeway system in the Twin Cities metro area. The TMC aims to provide motorists with a faster, safer trip on metro area freeways by optimizing the use of available freeway capacity, efficiently managing incidents and special events, providing traveler information, and providing incentives for ride sharing. The TMC realizes its goal through traffic management systems (TMS), including Ramp Metering System, Variable Message Signs (VMS), Highway Helper Program, High Occupancy Vehicle (HOV) System, Loop Detector System, Closed Circuit TV (CCTV) cameras, and Traveler Information Program.

While the TMC has a long history of operation, the effectiveness of some of the traffic management systems have been recently questioned---do they really help realize the objectives of the TMC, or rather, do they make traffic conditions even worse? This study intends to evaluate the system-wide performance of four main traffic management systems in the Twin Cities metro area --- Ramp Metering System, Variable Message Signs, Highway Helper Program, and High Occupancy Vehicle (HOV) System using regression analysis. The traditional before-and-after study and the regression analysis method were compared, the outline of the regression analysis was presented and its limitations were stated. In the two case studies, link speed and incident rate were employed as the response variable separately. Freeway loop detector data and incident record by TMC freeway cameras were used for this study.

2. Main Traffic Management Systems

This study evaluated the system-wide performance of four main traffic management systems in the Twin Cities metro area --- Ramp Metering System, Variable Message Signs, Highway Helper Program, and High Occupancy Vehicle (HOV) System. The objective, history, scope and operation strategy of each system are summarized as follows [11, 12]:

I. Ramp Metering System

Objective: Ramp meters in the Twin Cities are intended to reduce delay and congestion, reduce accident rates, and smooth flow at on-ramp junctions by helping merge traffic onto freeways and manage the flow of traffic through bottlenecks.

History: The Minnesota Department of Transportation (Mn/DOT) first tested ramp meters in 1969. There were approximately 427 ramp meters located

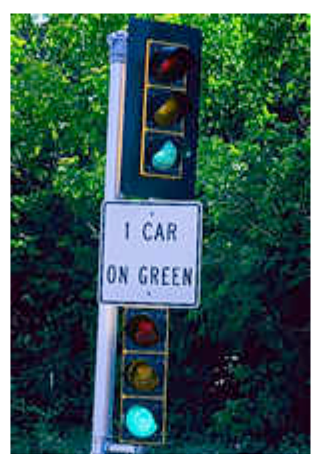


Figure 1 : Ramp meter

throughout the metro area freeway system with 416 of them centrally controlled (on-line), and 11 isolated (stand-alone/pre-timed) meters by July 2000. The number of ramp meters in each year is shown in graph 1.

Scope: Currently, ramp meters manage access to approximately 210 miles of freeways in the Twin Cities metro area. It covers all the freeways within the I-494/I-694 beltline and most of the freeways on and outside the I-494/I-694 beltline.

Operation strategy: Ramp Metering System operates during peak traffic periods or when traffic or weather conditions warrant their use. The original metering strategies (before October 16, 2000) were up to four hours in the morning and up to five hours in the afternoon. Start and end times were determined by corridor traffic conditions.

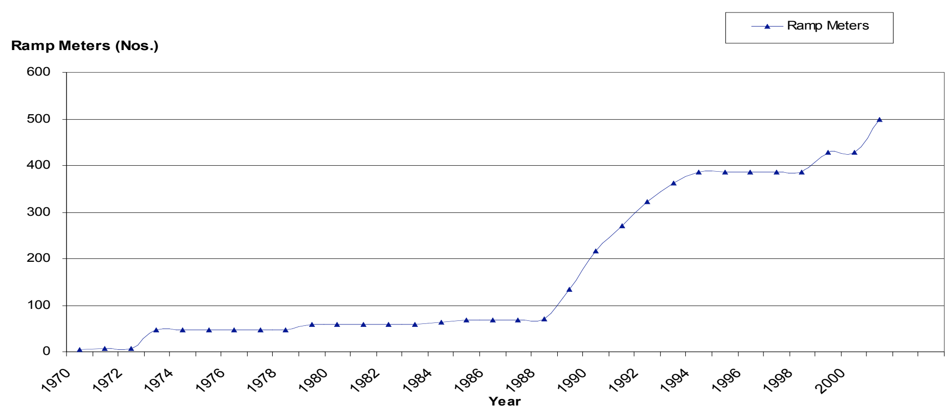


Figure 2 : Number of Ramp Meters in Minnesota

II. Variable Message Signs

Objective: Variable message signs are devices installed along the roadside to display messages of special events warning such as congestion, incident, roadwork zone or speed limit on a specific highway segment. These messages alert travelers to traffic problems ahead and help prevent secondary crashes.

History: There were 62 VMSs in operation including both amber LED and rotary display type signs by January 2001. The start-up dates of VMSs generally coincided with the start-up dates of the on-line metering in that same freeway segment.

Figure 3 : Variable message signs

Scope: About 50 of the 62 VMSs are located within (and on) the I-494/I-694 beltline.

Operation strategy: Instant messages are provided to alert travelers to traffic problems ahead.

III. Highway Helper Program

Objective: Highway helper program intends to minimize congestion through the quick removal of stalled vehicles from the freeway, reduce the number of secondary accidents, assist stranded motorists and aid the State Patrol with incident management. It plays a major role in incident management in the Twin Cities metro area.

History: Highway Helper program was initiated in December 1987, and additional miles were added in September, 1996. Currently there are 8 highway helper routes.

Scope: Highway helper program patrols eight routes (170 miles) in the Twin Cities metro area.

Operation strategy: From 5:00 AM to 7:30 PM Monday through Friday, limited hours on weekends.

IV. High Occupancy Vehicle (HOV) System

Objective: The purpose of the HOV System is to move more people in fewer vehicles and provide a quicker, more reliable trip for those who rideshare or take the bus. A HOV is a vehicle with two or more people in it. Vanpools, car-pools, buses and motorcycles are classified as HOVs.

Scope: There are 18 miles of HOV lanes ---11 miles on I-394 HOV Lanes and 7 miles on I-35W HOV Lanes ---in the metro area. There are two types of HOV lanes--- Concurrent HOV lanes and Barrier-separated HOV lane.

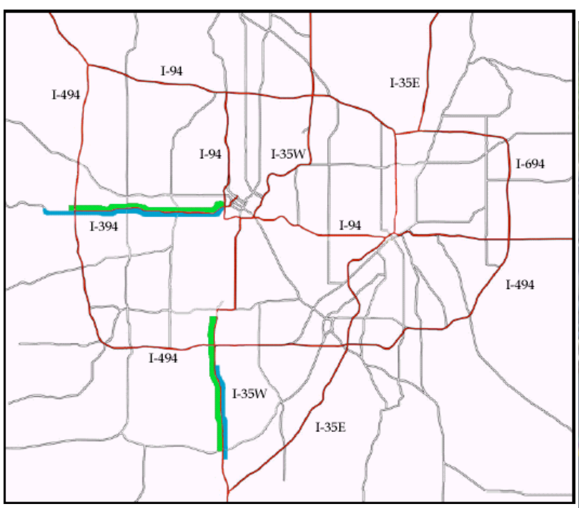


Figure 4 : I-394 HOV Lanes and I-35W HOV Lanes

Figure 5 : HOV Lane on I-394

Table 1: History and Operation strategy:

HOV lane	History	Operation strategy
I-394 (Weekdays and weekends during special events.)	Start up since October 1992	I-394 Eastbound: from 6:00 a.m. to 1:00 p.m. for east of Hwy 100, and from 6:00 a.m. to 9:00 a.m. for west of Hwy 100; General-purpose traffic is never allowed in the barrier-separated lanes.
		I-394 Westbound: from 3:00 p.m. to 6:00 p.m. for west of Hwy 100, and from 2:00 p.m. to midnight for east of Hwy 100; General-purpose traffic is never allowed in the barrier-separated lanes.
I-35W (Weekdays only)	Start up since November 1994	Both directions operate as HOV lanes from 6:00 a.m. to 9:00 a.m. and from 3:00 p.m. to 6:00 p.m. on weekdays; All traffic may use the lanes at other times.

3. Regression Analysis

3.1 About the before-and-after study

'Before and after' studies or 'with and without' studies are perhaps the most generally used methods to evaluate system performance. But this method will meet difficulties when the object of study is a long existing traffic management system. Firstly, it is usually impossible to isolate the effects of traffic management from the effects of external variations [1]. Before and after study is persuasive for evaluation of short-run impact under the condition that there is no significant variation in external circumstances, however, the evolution of traffic management from initialization to full operation usually covers decades. The external circumstances must have experienced great changes and it is impossible to separate from other changes also affecting the system. Secondly, it is quite difficult to separate the effects of one management system from the effects of other systems since almost all of the main freeways are under the combined management of these systems. Thirdly, the traffic management system itself is continuously in variation--- new facilities are gradually added in and some old facilities are gradually removed, accompanying the changes of operation strategies. Even if we can find some freeway segment which has stable before and after phases, the limited analysis won't be representative for the whole system.

A famous example of evaluating traffic management system performance using before and after study is the Twin Cities metro area ramp metering shut-down study [2]. During the eight weeks' ramp metering system shut-down, all other traffic management systems were in full operation. Therefore, the effectiveness of the ramp metering system could be evaluated by comparing the system performance before and during shut-down. But such perfect data cannot often be obtained due to financial consideration or practical concerns. For example, in order to evaluate the HOV system impacts on traffic flow and safety, Mn/DOT planned to open the HOV lanes on I-394 to general-purpose traffic for limited period in 2001 for the before and after data collection. However, this plan was barred by FHWA due to policy considerations.

The performance evaluation of traffic management system can provide important information for planning and for the rationalization of operating budget allocations. We hope to explore a simple and effective approach for this task. Regression analysis is promising. Comparing with before and after study, regression analysis doesn't try to design the stable external circumstances and isolate the effects of the object in study from the effects of combining factors. In fact, it is often quite difficult or even impossible to design or seek the 'stable' external circumstances in a dynamic traffic system. For example, when we evaluate effects of traffic management systems on incident rate, we need to use several years' data to get large enough sample, in this case, it is meaningless to assume unvaried external circumstances [1]. Regression analysis is different from before and after study in that it tries to search out all the potential elements (including traffic management) that effect system performance, record their variation and use these elements as the regression predictor variables to test the association between traffic system performance and traffic management.

3.2 Define the response variable of the regression model

Performance measurement proceeds by identifying and quantifying some feature of the performance of the traffic system (such as travel time or accident rate) and using this to infer the performance of some part of the traffic management system [1]. In regression analysis, the measure of traffic system performance will be employed as the response variable, the traffic management systems will be included in the predictor variables, and their performance will be inferred by their associations with the response variable and by comparison with the coefficients of related predictor variables.
There can be many performance measures of the traffic system [10]. However, a measure can be used as the response variable only if it is significantly associated with the operation objectives of the traffic management systems; furthermore, it should be straightforward to identify the relevant predictor variables.

Speed and incident rate meet these criteria and will be used as the response variables in the following regression analysis. The reason for using speed instead of travel time is that the regression model will include observations from different corridor segments, travel time will present no more information than speed, but it will be influenced by the differences in length of the corridor segments. Actually, some related measures, such as travel time, delays, and travel time reliability, could be derived directly from speed. Some other measures, including environmental impacts and fuel consumption, could also be derived from speed by combining with other factors such as volume, vehicle types, and gasoline quality.

3.3 The framework of an ideal regression model

An ideal regression model is a multiple regression model which employs all the relevant elements affecting system performance as its explanatory variables. The relevant elements can be classified into the following four categories:

1. Infrastructure characteristics, which include capacity, geometric structure, pavement quality and conditions, geographic characteristics and construction activity impact. Capacity has significant effects on speed, but detailed information of capacity is difficult to obtain for each freeway segment. In this case, the number of lanes of the freeway segment could be used as the indication of capacity if the corridors in study are in the same grade-level, e.g., all are interstate freeways. Geometric structure includes the elements of horizontal and vertical curvature, sight distance and the distance between entrance and exit in the same segment**.** Pavement quality can be good, normal, and poor; pavement conditions can be dry, wet, or snow covered [2]. The geographic characteristics of freeways in the Twin Cities metro area can be classified into four groups: the I-494/I-694 beltline freeway, intercity connector, radial freeway within the I-494/I-694 beltline, and radial freeway outside the beltline [2].

2. Traffic characteristics, which include traffic volume, density, vehicle fleet composition, and level of service. Vehicle fleet composition includes passenger car and freight truck, heavy truck fleet has significant impact on freeway capacity and speed.

3. Traffic Management Strategies, which include Ramp Metering System, Variable Message Signs, Highway Helper Program, High Occupancy Vehicle (HOV) System, and some other traffic management strategies such as Traveler Information Program.

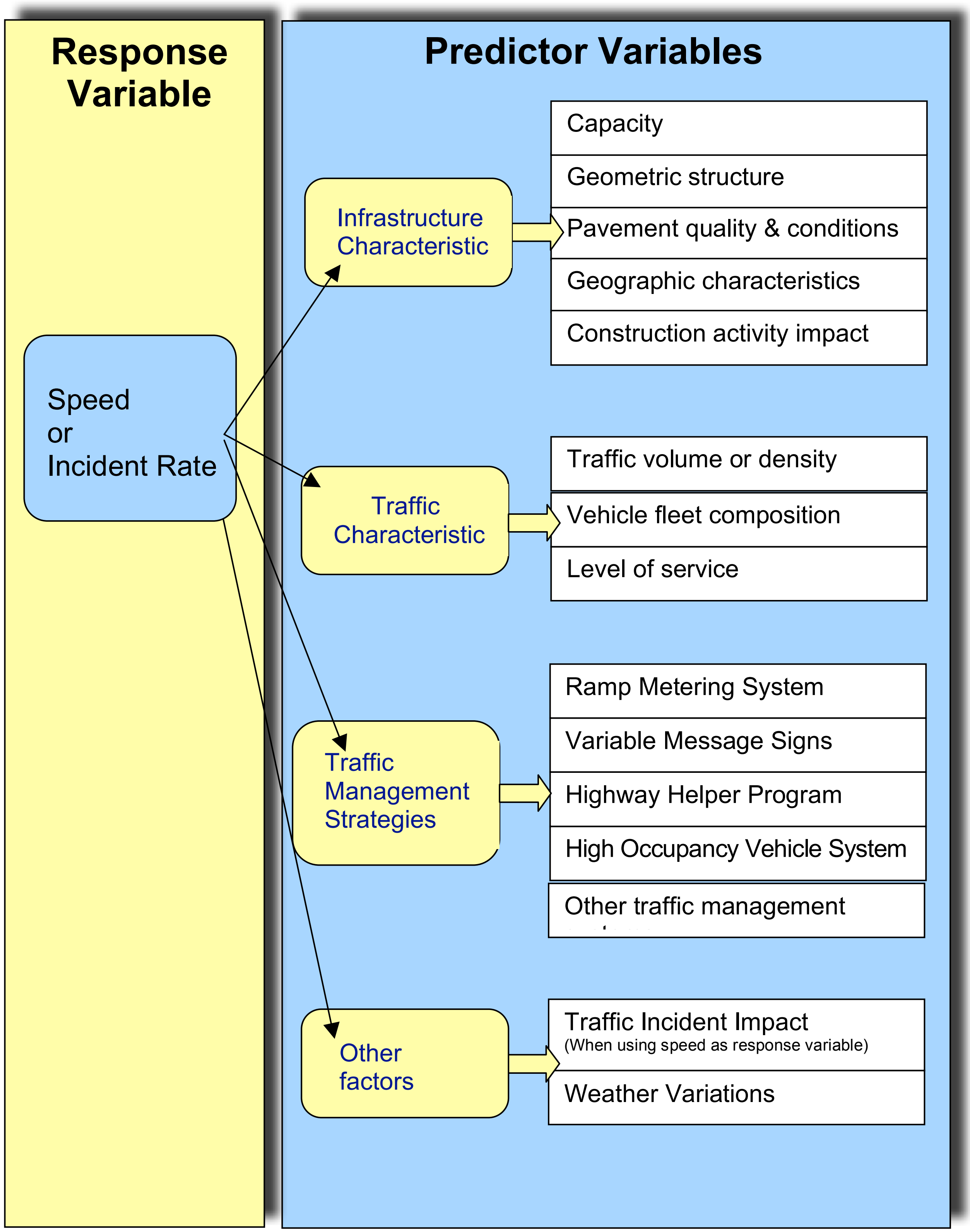
4. Other factors, which include traffic incident impact and weather impact.

Figure 6 shows the framework of the ideal regression model.

3.4 Limitations of Regression analysis

When before and after is impossible or too costly, regression analysis can be a good substitute. But regression analysis can't obtain all the information we need to know about the traffic management system. For example, regression analysis just tells us the association between ramp metering and system mainline speed, it can't tell us whether the travel time saving caused by ramp metering system (if any) on the mainline could offset ramp delay. It also can't tell us whether the person-hours increase on general-purpose lanes (if any) could be offset by the person-hours decrease on HOV lanes. Consequently, regression analysis can be a simple and effective research method for testing the macroscopic association or trend between traffic management and traffic system performance; however, to obtain an overall evaluation of each of the traffic management systems, additional research is still necessary.

Figure 6 : The framework of an ideal regression model



4. Case study I : Using link speed as response variable

4.1 Regression Model

1. Predictor variables:

It should be mentioned firstly that due to the limitation of data, we are not able to test all the potential predictor variables described in the ideal regression model, this is a deficiency of this case study.
For infrastructure characteristics, we used capacity (number of lanes); for traffic characteristics, we used density; for traffic management strategies, we tested Ramp Metering System, Variable Message Signs, Highway Helper Program, and High Occupancy Vehicle (HOV) System; and for other factors, we used traffic incident impact.
We also added 22 corridor dummies, which classified the observations into 22 corridor groups. Each group has its distinctive traffic, infrastructure, and spatial characteristics. The corridor dummy assigned to each observation can be viewed as one 'attribute' just like the 'number of lanes'. As an example, comparing with I-494 NB & SB beltline corridors which carry traffic from suburb to suburb, I-94 intercity connectors cross major commercial zones and they have higher intersection density (or entrance & exit density). Given the same mainline density, I-94 intercity connectors should be slower than I-494 NB & SB beltline freeways due to more entering and exiting disturbance. As another example, I-35W corridors (south of I-494) have higher percentage of heavy commercial traffic than I-35E corridors (north of I-94). Since heavy commercial flows have significant impacts on freeway capacity, holding other conditions fixed, we would expect I-35W corridors to slower than I-35E corridors.
Finally, we don't rule out the possibility that the addition of other predictor variables will change the results.

2. Detect multicollinearity

Since we face a multiple regression problem, we should use the correlation matrix to detect the possible multicollinearity. Multicollinearity is likely to exist between density and the TMS dummies. It is assumed that multicollinearity will be diagnosed to be present if the absolute value of the correlation between two predictor variables is larger than 0.6, otherwise no multicollinearity. From the correlation matrixes (Appendix 3) we get to know that each correlation is less than 0.6, therefore, no multicollinearity exists between density and the TMS dummies. What should be noted is the low correlation between ramp metering and mainline density. In practice, people tend to inflate the correlation between ramp metering and mainline density. It is often thought to be true that a segment controlled by ramp metering will have relatively lower density than a segment without metering. But actually obvious linear relationship between ramp metering and mainline density can't be found from our data. The reason should be that density is such a complex measurement which is associated with many factors, and ramp metering is just one of them.

On the other hand, ramp metering affects mainline speed through not only mainline density but also other traffic factors such as drivers' behaviors. When ramp cars try to merge into the mainline, mainline drivers usually have to slow down or even turn aside to let them in. That is, ramp cars will have impacts to mainline drivers' behaviors even if their merging doesn't cause significant increase in mainline density. (To get an intuitive understanding about this just think that even when the middle lane has the same density as the right lane, the middle lane is typically faster than right lane because the right lane has to sustain the impacts of merging(and exiting) cars). Under ramp metering control, ramp cars enter the freeway in a spaced and controlled manner. Even in the case that ramp metering doesn't significantly decrease mainline density, its effects in controlling merging disruption to mainline traffic will lead to mainline speed increase.

3. Model expression

Model 1. Incident-free case

Hourly average speed = $ß_0$ + $ß_D$× Density + $ß_{TMT1}$× Ramp Meter (1,0) + $ß_{TMT2}$× VMS (1,0) + $ß_{TMT3}$× Concurrent HOV (1,0) + $ß_{TMT4}$× Barrier-separated HOV (1,0) + $ß_{L1}$× Two-Lane (1,0) + $ß_{L2}$× Three-Lane (1,0) + $ß_{L3}$× Four-Lane (1,0) + $ß_{C1\sim C22}$× Corridor dummies+ ε

Where,

$ß_D$ indicates the coefficient of hourly average density;

$ß_{TMT1\sim TMT4}$ indicate the coefficients of Ramp Meter Dummy, VMS Dummy, Concurrent HOV Dummy, and Barrier-separated HOV Dummy;

$ß_{L1\sim L3}$ indicate the coefficients of the number of lanes-- two-Lane, three-Lane, and four-Lane;

$ß_{C1\sim C22}$indicate the coefficients of the 22 corridors we selected for this study (refer to 4.3 Corridor selection and study periods).

Model 2. Incident case

Hourly average speed = $ß_0$ + $ß_D$× Density + $ß_{TMT1}$× Ramp Meter (1,0) + $ß_{TMT2}$× VMS (1,0) + $ß_{TMT3}$× Highway Helper Program (1,0) + $ß_{TMT4}$× Concurrent HOV (1,0) + $ß_{TMT5}$× Barrier-separated HOV (1,0) + $ß_{L1}$×Two-Lane (1,0) + $ß_{L2}$× Three-Lane (1,0) + $ß_{L3}$× Four-Lane (1,0) + $ß_{I1\sim I5}$× Incident* + $ß_{C1\sim C22}$× Corridor dummies + ε

Where,

$\beta_{I1\sim I5}$ indicate the coefficients of the five incident groups; Incident* indicates the following five groups:

Incident1 --the incident occurred within the studied segment;

Incident2 --the incident occurred in the first segment upstream the studied segment;

Incident3 --the incident occurred in the second segment upstream the studied segment;

Incident4 --the incident occurred in the first segment downstream the studied segment;

Incident5 --the incident occurred in the second segment downstream the studied segment;

Notes:

1. Highway Helper Program is not included in the incident-free case because when the studied segments are incident-free, Highway Helper Program has no effects to the segments;

2. Ramp Metering Dummy, Highway Helper Dummy, VMS Dummy, Concurrent HOV Dummy, and Barrier-separated HOV Dummy are defined as follows:

Ramp Meter=1 if the segment is under ramp metering control; otherwise, Ramp Meter=0.

VMS=1 if the segment is within the impacting range of VMS; otherwise, VMS=0.

Highway Helper =1 if the segment is within highway helper program patrol area; otherwise, Highway Helper =0.

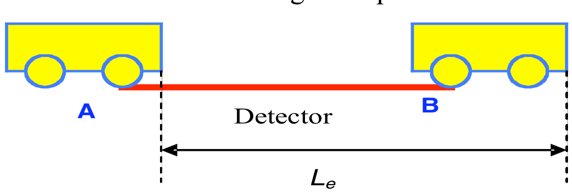
HOV=1 if the corridor has HOV lane(s) in operation; otherwise, HOV=0.

4.2 Measure speed and density using loop detector data

1. Measuring speed in one hour's interval

Loop detectors provide freeway volume and occupancy information in 30-second intervals. The data-extracting program Data_Extraction TMC, which is developed by MN/DOT TMC, was used for extracting and formatting freeway loop detectors data. Volume Q_i and occupancy K_i in 5-minute intervals were extracted using this program.

The method of measuring link speed based on volume Q_i and occupancy K_i is explained as follows:



The detector starts to be read as 'occupied' once the front wheels of a vehicle reach point A; and the 'occupied' status ends when the back wheel of the vehicle reaches point B. During this 'occupied' period, the vehicle actually passes a distance of l_e, which is usually called the effective vehicle length. The average effective vehicle length is taken as 22 ft in this study. In a 5-minute interval, Q_i vehicles pass the detector, therefore, the total distance driven by these Q_i vehicles should be $Q_i \times l_e/5280$ (mile). Furthermore, the detector is occupied for K_i (%) percent of 5 minutes' time, that means the total time actually used for traveling in a 5-minute interval should be $300\times K_i/100$ (sec). Therefore we can obtain the space mean speed $\bar{u}_s$ during a 5-minute interval as follows [5]:

$$\bar{u}_s = \frac{total\ distance}{total\ time} = \frac{3600\times 100\times Q_i \times l_e}{5280\times 300\times K_i}\ (mile/hr) \qquad (1)$$

Where:

$\bar{u}_s$ Space mean speed of one detector in 5-minute intervals (mile/hr);

l_e Effective vehicle length (ft);

Q_i and K_i Volume and occupancy of one detector in 5-minute intervals

$\bar{u}_s$ is the space mean speed for one lane in 5-minute intervals. Freeway segments have 2 to 5 lanes. Space mean speed for one segment is estimated using the weighted mean speed (weighted by volume) of all lanes. The space mean speed for a three-lane segment is as follows:

$$\bar{u}_{s,Q} = \frac{Q_1\bar{u}_{s,Q_1} + Q_2\bar{u}_{s,Q_2} + Q_3\bar{u}_{s,Q_3}}{Q_1 + Q_2 + Q_3} \qquad (2)$$

Space mean speed for one segment in one hour's interval is the arithmetic mean of the twelve 5-minute speeds of this segment in one hour.

It should be noted that when the loop detectors read to be '0' for occupancy, the calculated speed will have invalid number and the observation will be removed. Loop detectors read '0' for occupancy in two conditions: 1. Loop detectors malfunction; 2. It happens to have no vehicles passing by during the counting period. Under condition 1, the occupancy will continue to be 0 for several hours or even days; under condition 2, the occupancy will be 0 for at least 5 minutes (because the volume and occupancy data were extracted in 5-minute intervals in this study.). When condition 2 happens, the observations with relatively low average hourly speeds are removed. This might lead to some bias in the regression result. But since the four hours in study (7:00AM—8:00AM, 8:00AM—9:00AM, 4:00PM—5:00PM and 5:00PM—6:00PM) are all peak hours, condition 2 happens with quite low probability, and its influence on the final result will be slight.

2. Measuring density in one hour's interval

The equation 1 can be rewritten as follows:

$$\bar{u}_s = \frac{100\times Q\times l_e}{5280\times 300\times occupancy} = \frac{\frac{Q}{300}\times\frac{l_e}{5280}}{\frac{occupancy}{100}} = \frac{q\times\frac{l_e}{5280}}{\frac{occupancy}{100}}(mile/s) \qquad (3)$$

then, density can be calculated as follows:

$$k = \frac{q}{\bar{u}_s} = \frac{q}{\frac{q \times \frac{l_e}{5280}}{\frac{occupancy}{100}}} = \frac{\frac{occupancy}{100}}{\frac{l_e}{5280}} (veh / mile) \tag{4}$$

Effective vehicle length l_e is assumed to be 22 feet, and the density k will be equal to:

$$k = \frac{\frac{occupancy}{100}}{\frac{22}{5280}} = \frac{5280}{100 \times 22} \times occupancy = 2.4 \times occupancy (veh / mile) \tag{5}$$

The density k estimated using equation 5 is the average density for one lane in 5-minute intervals. The average density of one segment is the arithmetic mean of the densities of all lanes. Furthermore, the average density of one segment in one hour's interval is the arithmetic mean of the twelve 5-minute densities of this segment in one hour. The unit of segment density is vehicles per mile, per lane.

4.3 Corridor selection and study periods

1. Corridor selection

Totally 22 corridors were selected for this study based on the following two rules:

I. The selected corridors should form a geographically representative sample of the entire system. Based on the geographic characteristics, the freeway corridors within the Twin Cities metro area can be classified into the following four types: the I-494/I-694 beltline freeway, intercity connector, radial freeway within the I-494/I-694 beltline, and radial freeway outside the beltline [2]. The 22 selected corridors covered these four types (refer to Appendix 1 and 2).

II. The selected corridors should include segments with and without ramp meters, with and without VMS, with and without highway helper program, and with and without HOV lanes (refer to Table 2).

2. Study periods

Study periods range from 1998 to 2000, which includes the periods before ramp meter start-up, ramp meter in full operation, and ramp meter eight weeks' shut-down in 2000; before VMS start-up and VMS in full operation; highway helper program in full operation; and HOV system in full operation.

It is noted that no 'before' data are included for highway helper program and HOV system. The reason is that the start-up dates of I–394 HOV lanes and I-35W HOV lanes are in 1992 and 1994 respectively, but no loop detector data are available before 1994. As to the highway helper program, the initial patrol routes started in December 1987, and additional routes were added from September, 1996, the 'before' data could be obtained for the additional routes. However, although loop detector data were available from 1994, they were insufficient before 1996. Furthermore, three years already form a long study period. The longer the period, the more variations and fluctuations experienced in the network, which will significantly affect the regression result. Consequently, we didn't include the before data of the additional routes of highway helper program in the database. The study periods and corridor selection are summarized in Table 2:

Table 2 : Corridor selection and study periods

	Ramp Meter	VMS	Highway Helper program	HOV lanes
Corridor Selection	➢ Corridors with Ramp Meters (RM=1); ➢ Corridors without Ramp Meters (RM=0);	➢ Corridors with VMS (VMS=1); ➢ Corridors without VMS (VMS=0);	➢ Corridors with Highway Helper (Highway Helper=1); ➢ Corridors without Highway Helper (Highway Helper=0);	➢ Corridors with HOV lanes (HOV=1); ➢ Corridors without HOV lanes (HOV=0);
Study periods	➢ Before RM start-up (RM=0); ➢ RM in full operation (RM=1); ➢ RM eight weeks' shut-down in 2000 (RM=0);	➢ Before VMS start-up (VMS=0); ➢ VMS in full operation (VMS=1);	➢ Highway Helper Program in full operation (Highway Helper=1);	➢ HOV lanes in full operation (HOV=1);

In addition, the following criteria are applied for data collection:

1. Samples are gathered on typical workdays (Tuesday, Wednesday, and Thursday). Monday and Friday are avoided;
2. Holidays are avoided;
3. A gap between the "before-after" periods is taken to permit the public to become accustomed to the new improvement before a check on its effect is begun [8]. The length of gaps range from 30 to 80 days in 1999. Due to the limited normal loop detector data, the length of gaps in 1998 range from 10 to 20 days.

4.4 Results and analysis:

The statistical software STATA was used for the study. Results were obtained for four peak hours -- 7:00AM—8:00AM, 8:00AM—9:00AM, 4:00PM—5:00PM, and 5:00PM—6:00PM under both incident-free and incident cases. All the traffic management systems are in operation in these four hours. The regression results are summarized in Table 3. Note: detailed regression results of case study I are in Appendix 6-13.

Table 3 : Summary of regression results

Incident-free	7:00AM—8:00AM	8:00AM—9:00AM	4:00PM—5:00PM	5:00PM—6:00PM
Number of observations	8988	9030	8937	8888
R-squared	0.4639	0.4694	0.5806	0.6026
Adjusted R-squared	0.4623	0.4678	0.5793	0.6014
F value	F(27, 8960) = 287.13	F(27, 9002) = 294.99	F(27, 8909) = 456.73	F(27, 8860) = 497.54
Prob > F	0.0000	0.0000	0.0000	0.0000
Incident	**7:00AM—8:00AM**	**8:00AM—9:00AM**	**4:00PM—5:00PM**	**5:00PM—6:00PM**
Number of observations	365	370	387	426
R-squared	0.7315	0.7557	0.7559	0.6900
Adjusted R-squared	0.7057	0.7333	0.7338	0.6639
F value	F(32, 332) = 28.27	F(31, 338) = 33.72	F(32, 354) = 34.25	F(33, 392) = 26.44
Prob > F	0.0000	0.0000	0.0000	0.0000

The R-squared values suggest that speed is a complex phenomenon of which we only explain about half for the incident- free case and about seventy percent for the incident case. But the analysis is based on three years' systemwide data and the number of observations for incident-free case is that huge, we have to say that the results are really not bad. The regression results of density and the TMSs are summarized in Table 4:

Table 4 : The regression results of density and the TMSs.

Incident-free	7:00AM—8:00AM		8:00AM—9:00AM		4:00PM—5:00PM		5:00PM—6:00PM	
	Coefficient $ß_D$	P-value	Coefficient $ß_D$	P-value	Coefficient $ß_D$	P-value	Coefficient $ß_D$	P-value
Density	-.2520507	0.000 (S)	-.250744	0.000(S)	-.2617367	0.000(S)	-.3012855	0.000(S)
RM	4.828919	0.000(S)	2.32501	0.000(S)	3.931768	0.000(S)	4.802929	0.000(S)
VMS	-2.703652	0.000(S)	-2.976521	0.000(S)	-3.115385	0.000(S)	-3.321087	0.000(S)
Con. HOV	-29.90661	0.000(S)	-14.84777	0.000(S)	-22.04745	0.000(S)	-9.621244	0.000(S)
Bar. HOV	-36.27597	0.000(S)	-17.19873	0.000(S)	-27.93467	0.000(S)	-17.54004	0.000(S)
Incident	**7:00AM—8:00AM**		**8:00AM—9:00AM**		**4:00PM—5:00PM**		**5:00PM—6:00PM**	
	Coefficient $ß_D$	P-value	Coefficient $ß_D$	P-value	Coefficient $ß_D$	P-value	Coefficient $ß_D$	P-value
Density	-.7513397	0.000 (S)	-.5816094	0.000 (S)	-.5026647	0.000 (S)	-.4669298	0.000 (S)
Highway Helper	11.43915	0.015 (S)	9.254188	0.087 (S)	8.453485	0.308 (NS)	-1.599863	0.911 (NS)
RM	2.939419	0.152(NS)	-.3066842	0.894 (NS)	4.101622	0.054 (S)	6.54014	0.010 (S)
VMS	-2.991247	0.029(S)	-3.244612	0.011(S)	-5.936508	0.000 (S)	-3.752483	0.010 (S)

Note: S---Significant; NS---Nonsignificant. The level of significance is 0.1 in this study.

Density is an important referent which helps us understand the extent of effects of the traffic management systems on speed, for example, in the incident-free case, comparing the coefficient of ramp meter dummy (7:00AM—8:00AM) with the coefficient of density (7:00AM—8:00AM) gives us an idea that the effect of one ramp meter on mainline speed is approximately equal to decreasing 60 vehicles per mile on a three-lane freeway segment. The estimate for $ß_D$ is negative and significant for both incident-free and incident cases, indicating a negative relationship between speed and density, e.g., when $ß_D$ is estimated to be -0.25 (7:00AM—8:00AM, incident-free), the density increases by one unit (veh/mile, lane) will lead to the link speed decrease by 0.25 mile/hr, assuming that the other terms are held fixed.

The following analyzes the regression results of the TMSs for both incident-free and incident cases.

I. Ramp Metering System:

For incident-free case, the estimates for ramp meter dummy are positive and significant in all the four hours, indicating that the operation of ramp metering system increases mainline speed. This result accords with previous studies. The 2001 Twin Cities metro area Ramp Meter Study (by Cambridge Systematics)[2] showed that on average, in the absence of metering, freeway speeds decreased by approximately 7 miles per hour in the peak period and by 18 miles per hour during the peak hour. This result is based on the eight weeks' ramp metering system shut-down data, while our study is based on three years' data (including previous to ramp meter start-up period, ramp meter in full operation period, and ramp meter eight weeks' shut-down period), so the long run trend was estimated.

The regression result can be explained as below: if we have two corridor segments with all characteristics the same, except that one has ramp metering and the other doesn't, we would expect the corridor segment with ramp metering to be 4.8 mile/hr (7:00AM—8:00AM) faster than the corridor segment without ramp metering.

It should be noted that the value of the ramp metering dummy coefficient is a 'conservative' estimate, that is, this value should be less than the full effects of ramp metering on mainline speed. As we discussed in 4.1.2, ramp metering affects mainline speed through both mainline density and drivers' behaviors. The part of ramp metering's effects on controlling mainline density was not explained by the ramp metering dummy. The actually effects of ramp metering should be even bigger.

For incident case, 2 of the 4 estimates of ramp meter dummy are insignificant, which indicates that holding the other terms fixed, corridor segments with ramp metering are not necessarily faster (or slower) than corridor segments without ramp metering; in other words, the effects of the ramp metering in increasing mainline speed won't always offset the incident influences.

II. Variable message signs:

It should be mentioned firstly that different from Ramp Metering system and HOV system, which both have relatively fixed operational hours, VMS is active only when 'special events' happen. But it is impossible for us to obtain the detailed starting time and duration of these VMS messages. Therefore, we had to define the VMS dummy as '1' if the studied corridor segment is within the impacting range of VMS. The impacting range of VMS is defined as the segments that can 'see' the VMS messages and the 2 to 3 segments downstream the VMS. Therefore, what we estimate here is actually the association between speed and VMS impacting range.

For both incident-free case and incident case, the estimates for VMS dummy are negative and significant in all the four hours. The negative association between speed and VMS impacting range can be explained as follows:

1. VMSs have impacts on drivers' behaviors. VMSs are devices installed along the roadside to display messages of special events warning such as congestion, incident, roadwork zone or speed limit to alert travelers of traffic problems ahead. The messages displayed by VMSs have impacts on drivers' behaviors. Drivers typically slow down to view the message and to plan alternative routes, and some of them may divert to other roadways.
2. The distribution characteristics of VMSs contribute to the negative association. Most of the VMSs in the Twin Cities metro area are located at the freeway segments with high AADT. These segments are typically more congested and have lower mainline speed. The negative relationship between speed and variable message signs is partly due to the distribution characteristics of the VMSs.

Then, should we stop using VMS since VMS impacting range is associated with lower mainline speed? Probably not. Because the speed decrease at one corridor (VMS impacting range) may prevent terrible congestion at some other corridors. Further study should be done to give a more comprehensive evaluation of VMS.

III. Highway Helper program:

Highway Helper Program is not included in the incident-free case because when the studied segments are incident-free, Highway Helper Program is not active.

In the incident case, two of the four estimates are positive and significant (7:00AM-8:00AM and 8:00AM-9:00AM), and two are insignificant (4:00PM-5:00PM and 5:00PM-6:00PM). The positive and significant association between speed and highway helper program indicates that in incident case, the corridor segments within highway helper patrol areas will be faster than the corridor segments out of the areas; while the insignificant relationship can be due to two reasons:

1. the sample size is insufficient to detect the alternative in this situation [13] ;

2. It is partly due to the fact that the incident impact on speed is not in one direction. Although the speed on corridors covered by highway helper program can be increased (if any), the speed on corridors out of highway helper program won't necessarily decrease. Actually, incidents downstream the studied segment typically decrease its speed, while incidents upstream the segment might cause increase in its speed.

IV. HOV system:

In the analysis of the two kinds of HOV systems, the speed is for the general-purpose lanes. That's because we have no interest to test the HOV lanes' association with speed (they will have positive relationship); what we want to estimate is the impact of the operation of HOV lanes to the general-purpose lanes. The regression results in incident-free case show that all the 8 estimates (for both Concurrent HOV dummy and Barrier-separated HOV dummy) are negative and significant, which indicates that the operation of HOV lanes is associated with lower speed on the general-purpose lanes. For incident case, it is difficult to give the regression results a reasonable explanation due to the low data-quality. Incident log didn't record on which lane the incidents actually happened---HOV lanes or general-purpose lanes. So we didn't list the HOV regression results for incident case.

5. Case study II : Using incident rate as response variable

5.1 Data collection

TMC freeway incident record for Twin Cities metro area started from 1991, but we only used the data of Fall 2000 for this study. The earlier years' incident data can't be used for this systemwide analysis due to the following reasons:

1) The incident record started at different years for different corridors --- some corridors from 1991, while some others even as late as 1998;
2) Based on the incident record, the incidents increased tremendously in the past ten years. But this increase was partly caused by the addition of new cameras, the upgrade of equipment, and the improved monitoring methods.

We collected the incident data for two periods in Fall 2000 --- 37 workdays (from Aug. 22 to Oct. 13)before ramp metering system shut-down (Refer to <u>2001 Twin Cities Metro Area Ramp Meter Study Final report</u> [2]) and 37 workdays (from Oct. 16 to Dec. 07) during ramp metering system shut-down. Incident records during these two periods have much higher quality than before because during these two periods the camera monitoring system covered the whole network and was operated under the same monitoring strategies and equipment conditions. In addition, incident data was counted between 7:00AM to19:00 PM, which were the operational hours of the traffic management system.

As to incident types, since what we want to test is the association of incident rate and the traffic management system, we removed the incidents caused by vehicle mechanical malfunctions such as stalls and vehicle fires and the incidents caused by debris on road. Finally three kinds of incidents were included--- crash, rollover and spinout, where, crash incidents counted for more than 97% of all incidents.

5.2 Corridor selection

In total, 26 corridors were selected for this study which nearly cover the whole Twin Cities metro area freeway network (refer to Appendix 4). The unselected corridors were those outside of TMC camera monitoring. The facility status of each corridor was summarized in Appendix 5.

5.3 Regression model

It should be noted that with the short incident counting periods (37 workdays before and during ramp metering shut-down respectively) we can guarantee the quality of incident data; however, it is also due to the short incident counting periods we have to select long corridors to ensure a non-zero number of incidents. When the corridors are long, it is impossible to include some traffic or infrastructure characteristics as predictor variables although these characteristics may be relevant to the response variable. For example, some traffic stream characteristics -such as link speed, flow or density - should be the potential predictor variables of incident regression analysis, but for a long corridor (which has several segments), the speed, flow or density of the segments vary greatly and none of them could be represented by a single value. Also the geometric characteristics can't be represented by a uniform format for all the segments of a long corridor. Finally we included limited predictor variables in the regression model.

The multiple regression model can be represented as below:

Incident Rate = $\beta_0 + \beta_I \times$ Intersection Density + $\beta_R \times$ Ramp Meter (1,0) + $\beta_V \times$ VMS Density + $\beta_H \times$ Highway Helper Program (1,0) + $\beta_{C-35} \times$ Concurrent HOV in I-35W (1,0) + $\beta_{C-394} \times$ Concurrent HOV in I-394 (1,0) + $\beta_{B-394} \times$ Barrier-separated HOV in I-394 (1,0) + ε

Where,

the response variable is Incident Rate, which is the number of incidents per mile.

Each corridor has two directions, and each direction will have two observations--- Incident Rate before shut-down and Incident Rate during shut-down.

The predictor variables include Intersection Density, Ramp Metering Dummy, VMS Density, Highway Helper Dummy, Concurrent HOV in I-35W

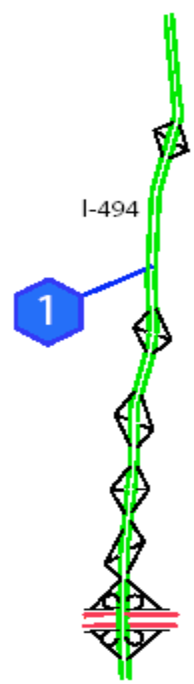


Figure 7. Intersections on Corridor 1

Dummy, Concurrent HOV in I-394 Dummy and Barrier-separated HOV in I-394 Dummy.

The intersection density is the number of intersections per mile. For example, Figure 7 shows that corridor 1 on I-494 has 6 intersections. Since it is impossible to include detailed traffic or infrastructure characteristics as predictor variables in this model, we use intersection density as a substitute. 'Busy' corridors tend to have higher intersection density, and in view of geometric structure intersection is more 'dangerous' than straight line in the metro area, therefore, the intersection density of a corridor should be strongly related to its incident rate.

Ramp Metering Dummy, Highway Helper Dummy, Concurrent HOV in I-35W Dummy, Concurrent HOV in I-394 Dummy and Barrier-separated HOV in I-394 Dummy are defined as:

Ramp Meter=1 if the corridor is under ramp metering control; otherwise, Ramp Meter=0.

Highway Helper =1 if the corridor is within highway helper program patrol area; otherwise, Highway Helper =0.

HOV=1 if the corridor has HOV lane(s) in operation; otherwise, HOV=0.

As to VMS, VMS density is a more reasonable measure than VMS impacting range for long corridors. VMS density is the number of VMSs per mile which is counted for both directions of each corridor.

5.4 Regression Result Analysis:

The regression results were summarized in Table 5. The R-squared value shows that the regression model only explains about thirty percent of the observations. That is because we included limited predictor variables in this model, but actually incident is such an irregular and complex phenomena, various reasons--such as driver factors, vehicle factors, traffic stream factors, and geometric structure or pavement quality factors--may contribute to its occurrence. Table 6 summarizes the regression results of each of the independent variables. Note: detailed regression results of case study II are in Appendix 14.

Table 5 : Summary of regression results

Number of observations	98
R-squared	0.3764
Adjusted R-squared	0.3279
F value	7.76
Prob > F	0.0000

Table 6 : Regression results of the independent variables

Independent Variables	Coefficient	P-value	Significant or not significant	Standard error	t-value
Intersection Density	1.302414	0.013	S	.5143032	2.532
Ramp Metering	-1.07134	0.001	S	.3246102	-3.300
VMS Density	4.172839	0.035	S	1.951534	2.138
Highway Helper	1.448543	0.003	S	.4695155	3.085
Concurrent HOV in I-35W	.2315502	0.788	NS	.8564734	0.270
Concurrent HOV in I-394	-.940457	0.280	NS	.8653702	-1.087
Barrier-separated HOV in I-394	2.46086	0.008	S	.9012703	2.730

Note: S---Significant; NS---Nonsignificant. The level of significance is 0.1 in this study.

Intersection Density has positive and significant relationship with incident rate, which indicates that the more intersections the higher incident rate. This result accords with our expectation. However, it should also be noted that more than half of the surveillance cameras are located at or near the intersections, 'the more intersections the higher incident rate' may be partly due to the fact that 'the more intersections the more cameras', and the more cameras, the more incidents reported.

Ramp Metering has negative and significant relationship with incident rate, which indicates that ramp metering is very effective in reducing incidents. This result accords with the Twin Cities Metro Area Ramp Meter Study [2], which showed ramp metering results in annual savings of 1,041 crashes (four crashes per day).

The positive and significant relationship between VMS Density and incident rate indicates that corridors with higher VMS density are typically the corridors with higher incident rate.

Highway Helper is positive and significant, which indicates that the corridors under Highway Helper patrol are the corridors with higher incident rate;

Concurrent HOV in I-35W and Concurrent HOV in I-394 are both insignificant, which indicates that the operation of Concurrent HOV has no effects on the total incident rate of general purpose lanes and HOV lane.

It should be noticed that although Concurrent HOV didn't increase the total incident rate, it doesn't rule out the possibility that the increase of the incident rate on the general-purpose lanes was offset by the decrease of the incident rate on the HOV lane. The reason for making this hypothesis is that HOV lane typically carries much less traffic than the general-purpose lane. However, the incident log didn't record on which lanes the incidents actually happened---HOV lanes or general-purpose lanes, therefore, we can't test the hypothesis.

Barrier-separated HOV in I-394 is positive and significant (as high as 2.4), which indicates that the operation of Barrier-separated HOV is strongly associated with the increase in the total incident rate of general purpose lanes and HOV lanes. This result accords with public dissatisfaction about HOV ---- causing incident increase.

6. Conclusion:

This study used the multiple regression model to evaluate the long-run performance of four traffic management systems --- Ramp Metering System, Variable Message Signs (VMS), Highway Helper Program, and High Occupancy Vehicle (HOV) System in the Twin Cities metro area. Link speed and incident rate were employed as the response variable separately for case study I and case study II.

In case study I, a huge database of about 40,000 observations covering three years' data was established. The long-run and systemwide performances of the four traffic management systems were estimated for both incident-free and incident cases. The key findings are summarized as follows:

- For incident-free case, ramp metering is effective in increasing mainline speed. For example, from 7:00AM to 8:00AM, the corridor segment with ramp metering is estimated to be 4.8 mile/hr faster than the corridor segment without ramp metering; and the effect of one ramp meter on mainline speed is approximately equal to decreasing 60 vehicles per mile on a three-lane freeway segment. For incident case however, corridor segments with ramp metering are not necessarily faster or slower than corridor segments without ramp metering, which indicates the effects of the ramp metering in increasing mainline speed won't always offset the incident influences.
- For both incident-free and incident case, the corridor segment within VMS impacting range will be lower than the corridor segment outside. The negative relationship should be due to two reasons: 1. VMS messages' impacts on drivers' behaviors; 2. the geographic distribution characteristics of the VMSs .
- Highway Helper Program was evaluated only in the incident case. The Highway Helper Program dummy coefficient for 7:00AM-8:00AM and 8:00AM-9:00AM are positive and significant, which indicates that in this case, the corridor segments within highway helper patrol areas will be faster than the corridor segments out of the areas. However, the Highway Helper Program dummy coefficient for 4:00PM-5:00PM and 5:00PM-6:00PM are insignificant, which may be due to the sample size problem or may be due to the fact that the incident impact on speed is not in one direction ---although the speed on corridors covered by highway helper program can be increased (if any), the speed on corridors out of highway helper program won't necessarily decrease.
- In incident-free case, the operation of HOV lanes is associated with lower speed on the general-purpose lanes.

In case study II, incident rate analysis was based on the incident data collected for two periods in Fall 2000 --- before ramp metering system shut-down and during ramp metering system shut-down. The key findings are summarized as below:

- ❖ Ramp Metering system is associated with a lower incident rate; because we tested the same sections with and without meters, we believe this is a causal effect;
- ❖ Both the corridors with higher VMS density and the corridors under Highway Helper patrol are typically the corridors with higher incident rate;
- ❖ The operation of Concurrent HOV doesn't have a significant relationship with incident rate change; however, we can not rule out the possibility that the increase of the incident rate on the general-purpose lanes was offset by the decrease of the incident rate on the HOV lane (or vice versa);
- ❖ The operation of Barrier-separated HOV is associated with the increase of the total incident rate of general purpose lanes and HOV lanes;

In future work, improvement could be made through the following aspects:

- ✓ For ramp metering evaluation, the current speed regression model provided a 'conservative' estimate, which should be less than the full effects of ramp metering on mainline speed. An improved model should be able to estimate the part of ramp metering's effects on controlling mainline density which was not explained by the ramp metering dummy.
- ✓ Our study found the negative relationship between VMS impacting range and mainline speed. But we didn't' answer the question whether the speed decrease at one corridor (VMS impacting range) really help prevent more serious congestion at some other corridors. More detailed study should be done to give a comprehensive evaluation of VMS.
- ✓ For HOV system, we got the conclusion that the operation of HOV lanes is associated with lower speed on the general-purpose lanes. However, since the purpose of HOV system is to reduce system PHT (person hours traveled), further study must be done to determine whether the person-hours increase on general-purpose lanes (if any) could be offset by the person-hours decrease on HOV lanes (or vice versa).
- ✓ Decreasing data-limitations. A major issue in regression analysis is the quality of database. Regression analysis provides information on relationships between a response variable and predictor variables but only to the degree that such information is contained in the database [6]. Due to data quality, the analysis of HOV system can't be conducted in incident case. Also, the evaluation of VMS is limited by the lack of detailed activity log. In addition, restricted by the earlier years' incident data quality, we just used the incident data in Fall 2000 for incident rate

regression analysis. The limited study periods lead to the selection of long corridors, which prevented us from employing detailed link traffic and infrastructure characteristics as predictor variables.

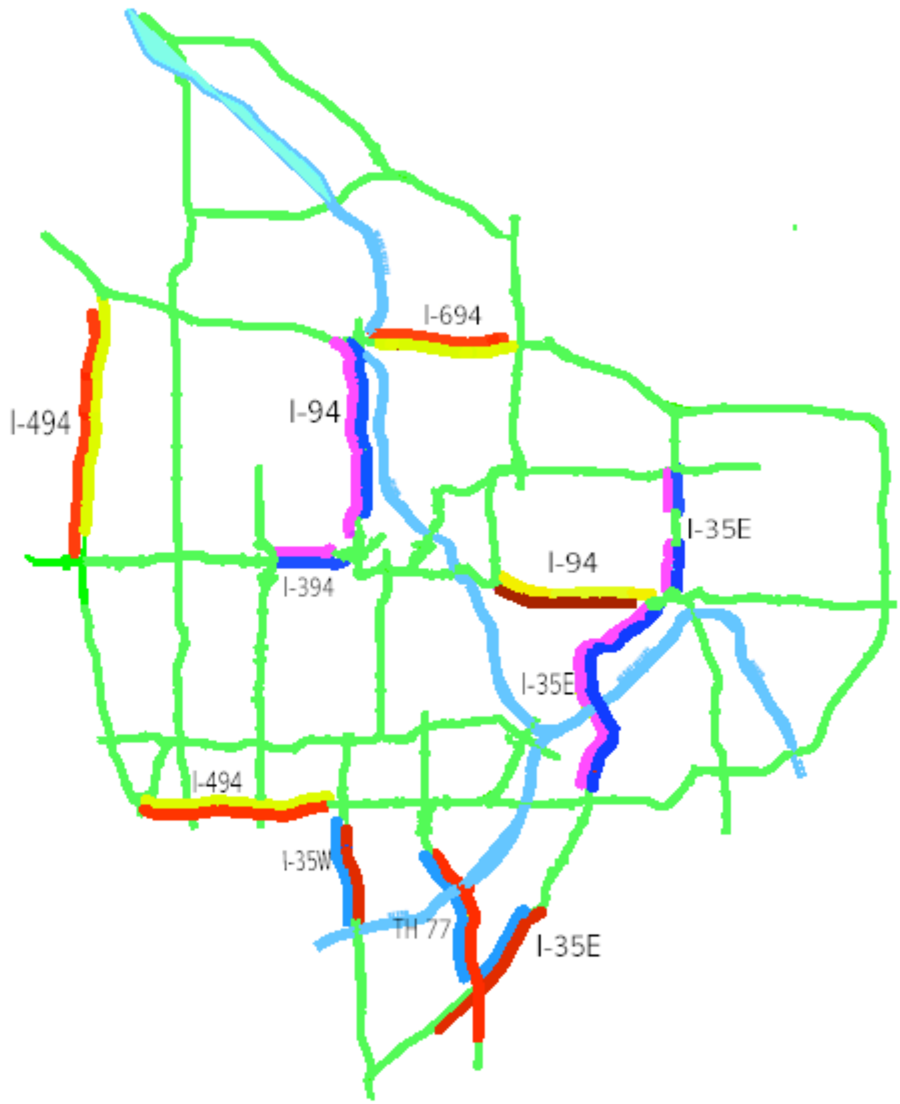
References:

1. Banks, James H. Kelly, Gregory (1997). Traffic Management Systems Performance Measurement Final Report. California PATH Research Report (UCB-ITS-PRR-97-53).
2. Cambridge Systematics, Inc (2001). Twin Cities Metro Area Ramp Meter Study. Final report prepared for Minnesota Department of Transportation. http://www.dot.state.mn.us/rampmeterstudy/reports.html.
3. Cambridge Systematics, Inc (2002). Twin Cities HOV Study. Final report prepared for Minnesota Department of Transportation. http://www.dot.state.mn.us/information/hov/.
4. Cook, R. Dennis. Applied regression including computing and graphics. Published by John Wiley & Sons, Inc. 1999.
5. DeGroot, Morris H. Probability and statistics, 2nd ed. Published by Addison-Wesley Pub. Co., c1986.
6. Gunst, Richard F. Mason, Robert L. Regression analysis and its application: a data-oriented approach. Published by M. Dekker, c1980, New York.
7. Hall, Fred L. Traffic Flow Theory: A State of the Art Report, Chapter 2: Traffic Stream Characteristics. Sponsored by the Transportation Research Board's Committee on Theory of Traffic Flow (A3A11), funded by Federal Highway Administration (FHWA) in June 1992. http://www-cta.ornl.gov/cta/research/trb/tft.html
8. Institute of Transportation Engineers (ITE). Manual of Traffic Engineering Studies, 3rd ed. Washington, 1964.
9. Levinson, David Zhang, Lei Das, Shantanu Sheikh, Atif (2002) Ramp Meters on Trial: Evidence from the Twin Cities Ramp Meters Shut-off. Presented at 81st Transportation Research Board Conference, Washington DC 2002 (TRB-02-2167).
10. Levinson, David (2002). Perspectives on Efficiency in Transportation. Presented at the 81st Transportation Research Board Conference, Washington DC 2002 (TRB-02-2015).

11. Minnesota Department of Transportation (2000 and 2001). Freeway Traffic Management Program Status Report. http://depts.washington.edu/trba3a09/status/jan2001/Minnesota.pdf . http://depts.washington.edu/trba3a09/status/jun2000/minnesota.pdf.

12. Minnesota Department of Transportation Traffic Management Center. http://www.dot.state.mn.us/tmc/.

Appendix 1. Case study I: Corridor selection



Appendix 2. Case study I: Corridor selection

Corridor	Geographic characteristics	From	To
I-494NB	Beltline freeway	CR 6	I-94
I-494SB	Beltline freeway	Bass Lake Rd	CR 6
I-494WB	Beltline freeway	I-35W	TH 169
I-494EB	Beltline freeway	TH 169	I-35W
I-694WB	Beltline freeway	I-35W	TH 252
I-694EB	Beltline freeway	TH 252	I-35W
I-94WB	Intercity connector	I-35E	TH 280
I-94EB	Intercity connector	TH 280	I-35E
I-94NB	Radial freeway within the I-494/I-694 beltline	Broadway	Humboldt
I-94SB	Radial freeway within the I-494/I-694 beltline	Humboldt	TH 55
I-394WB	Radial freeway within the I-494/I-694 beltline	I-94	TH 100
I-394EB	Radial freeway within the I-494/I-694 beltline	TH 100	I-94
I-35E NB (North of I-94)	Radial freeway within the I-494/I-694 beltline	I-94	TH 36
I-35E SB (North of I-94)	Radial freeway within the I-494/I-694 beltline	TH 36	I-94
I-35E NB (South of I-94)	Radial freeway within the I-494/I-694 beltline	I-494	ST. Clair
I-35E SB (South of I-94)	Radial freeway within the I-494/I-694 beltline	5TH Kellogg	I-494
I-35W NB	Radial freeway outside the I-494/I-694 beltline	Mississippi River	86TH
I-35W SB	Radial freeway outside the I-494/I-694 beltline	86TH	113TH ST.
I-35E NB (South of I-494)	Radial freeway outside the I-494/I-694 beltline	CR 11	Diffley RD.
I-35E SB (South of I-494)	Radial freeway outside the I-494/I-694 beltline	Diffley RD.	TH-77
TH-77 NB	Radial freeway outside the I-494/I-694 beltline	127TH	Old Shakopee
TH-77 SB	Radial freeway outside the I-494/I-694 beltline	Old Shakopee	I-35E

Appendix 3. Case study I: The correlation matrixes of predictor variables

I. Incident-free:

7:00AM-8:00AM	DENSITY	RM	VMS	ConHOV	BarHOV
DENSITY	1.00	0.19	-0.13	0.08	0.06
RM	0.19	1.00	0.01	-0.03	-0.03
VMS	-0.13	0.01	1.00	-0.05	-0.05
ConHOV	0.08	-0.03	-0.05	1.00	-0.05
BarHOV	0.06	-0.03	-0.05	-0.05	1.00

8:00AM-9:00AM	DENSITY	RM	VMS	ConHOV	BarHOV
DENSITY	1.00	0.19	-0.09	0.15	0.07
RM	0.19	1.00	0.02	-0.03	-0.03
VMS	-0.09	0.02	1.00	-0.04	-0.05
ConHOV	0.15	-0.03	-0.04	1.00	-0.05
BarHOV	0.07	-0.03	-0.05	-0.05	1.00

4:00PM-5:00PM	DENSITY	RM	VMS	ConHOV	BarHOV
DENSITY	1.00	0.09	0.07	0.15	0.08
RM	0.09	1.00	0.01	-0.03	-0.03
VMS	0.07	0.01	1.00	-0.05	-0.04
ConHOV	0.15	-0.03	-0.05	1.00	-0.05
BarHOV	0.08	-0.03	-0.04	-0.05	1.00

5:00PM-6:00PM	DENSITY	RM	VMS	ConHOV	BarHOV
DENSITY	1.00	0.07	0.07	0.12	0.13
RM	0.07	1.00	0.01	-0.02	-0.03
VMS	0.07	0.01	1.00	-0.05	-0.04
ConHOV	0.12	-0.02	-0.05	1.00	-0.05
BarHOV	0.13	-0.03	-0.04	-0.05	1.00

II. Incident:

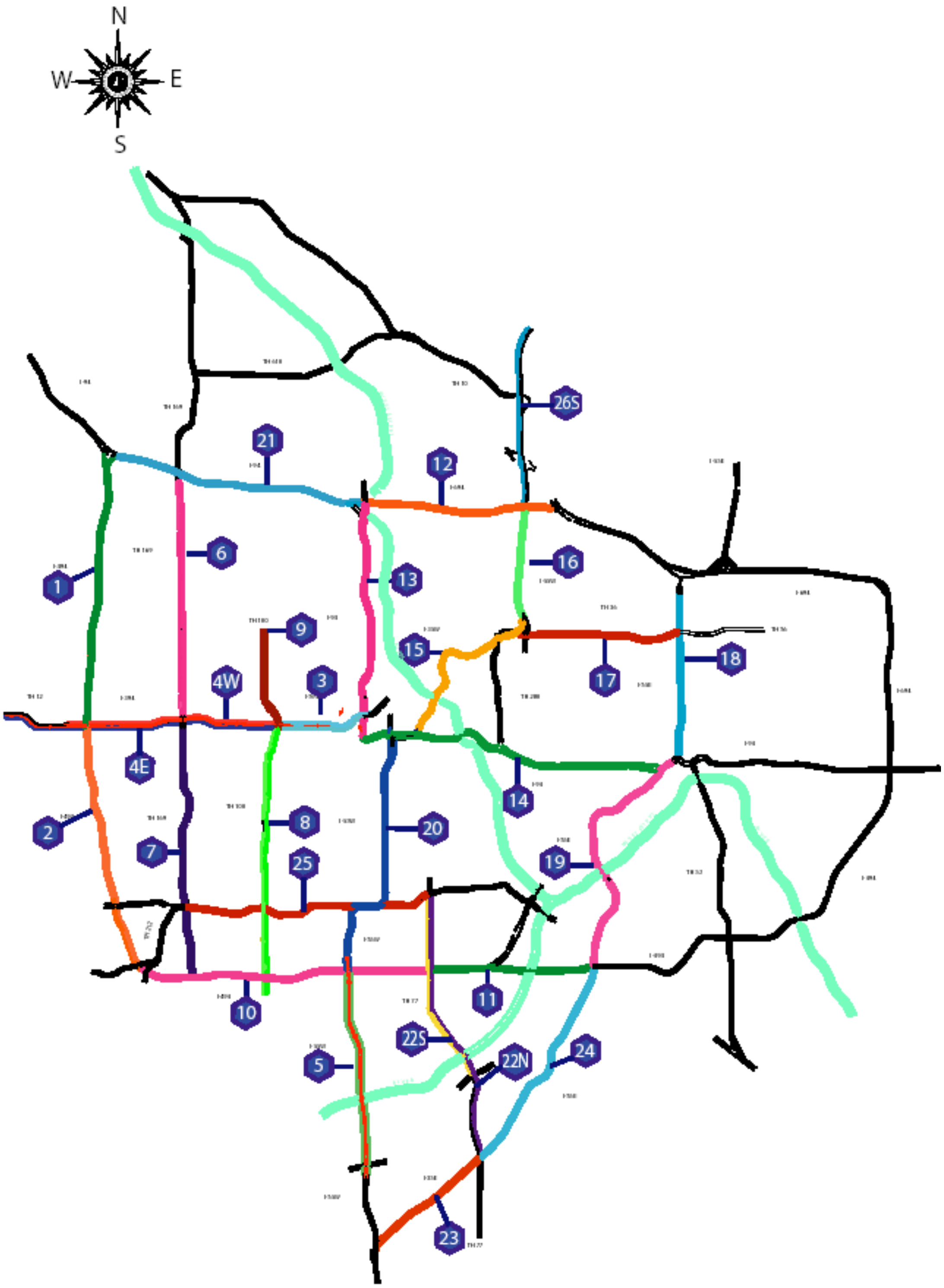
7:00AM-8:00AM	DENSITY	RM	VMS	HHELPER	ConHOV	BarHOV
DENSITY	1.00	-0.11	-0.32	-0.03	0.05	0.02
RM	-0.11	1.00	0.16	0.29	-0.12	-0.08
VMS	-0.32	0.16	1.00	0.25	-0.10	-0.04
HHELPER	-0.03	0.29	0.25	1.00	0.08	0.10
ConHOV	0.05	-0.12	-0.10	0.08	1.00	-0.05
BarHOV	0.02	-0.08	-0.04	0.10	-0.05	1.00

8:00AM-9:00AM	DENSITY	RM	VMS	HHELPER	ConHOV	BarHOV
DENSITY	1.00	0.10	-0.14	0.22	0.01	-0.02
RM	0.10	1.00	0.05	0.28	-0.07	-0.07
VMS	-0.14	0.05	1.00	0.17	-0.14	-0.03
HHELPER	0.22	0.28	0.17	1.00	0.04	0.13
ConHOV	0.01	-0.07	-0.14	0.04	1.00	-0.04
BarHOV	-0.02	-0.07	-0.03	0.13	-0.04	1.00

4:00PM-5:00PM	DENSITY	RM	VMS	HHELPER	ConHOV	BarHOV
DENSITY	1.00	0.02	0.10	0.12	0.03	0.02
RM	0.02	1.00	-0.03	0.32	-0.27	-0.11
VMS	0.10	-0.03	1.00	-0.07	-0.02	-0.17
HHELPER	0.12	0.32	-0.07	1.00	0.05	0.09
ConHOV	0.03	-0.27	-0.02	0.05	1.00	-0.07
BarHOV	0.02	-0.11	-0.17	0.09	-0.07	1.00

5:00PM-6:00PM	DENSITY	RM	VMS	HHELPER	ConHOV	BarHOV
DENSITY	1.00	-0.12	0.15	0.09	0.15	-0.02
RM	-0.12	1.00	-0.03	0.36	-0.37	-0.05
VMS	0.15	-0.03	1.00	0.10	0.07	-0.13
HHELPER	0.09	0.36	0.10	1.00	0.06	0.13
ConHOV	0.15	-0.37	0.07	0.06	1.00	-0.05
BarHOV	-0.02	-0.05	-0.13	0.13	-0.05	1.00

Appendix 4. Case study II: Corridor selection



Appendix 5. Case study II: Facility status for the 26 corridors

Corridor	Direction	Ramp Meter (1, 0)	# of Variable Message Signs	Highway Helper Program (1, 0)	Concurrent HOV in I-35W (1, 0)	Concurrent HOV in I-394 (1, 0)	Barrier-separated HOV in I-394(1, 0)
1	1N	1	1	1	0	0	0
	1S	1	1	1	0	0	0
2	2N	1	1	1	0	0	0
	2S	1	1	1	0	0	0
3	3W	1	1	1	0	0	1
	3E	1	1	1	0	0	1
4	4W	1	1	1	0	1	0
	4E	1	3	1	0	1	0
5	5N	1	1	1	1	0	0
	5S	1	0	1	1	0	0
6	6N	1	1	1	0	0	0
	6S	1	1	1	0	0	0
7	7N	1	1	1	0	0	0
	7S	1	2	1	0	0	0
8	8N	1	2	1	0	0	0
	8S	1	1	1	0	0	0
9	9N	1	0	0	0	0	0
	9S	1	1	0	0	0	0
10	10W	1	1	1	0	0	0
	10E	1	2	1	0	0	0
11	11W	1	1	0	0	0	0
	11E	0	0	0	0	0	0
12	12W	1	1	1	0	0	0
	12E	1	0	1	0	0	0
13	13N	1	1	1	0	0	0
	13S	1	1	1	0	0	0
14	14W	1	3	1	0	0	0
	14E	1	2	1	0	0	0
15	15N	1	1	1	0	0	0
	15S	1	1	1	0	0	0
16	16N	1	1	1	0	0	0
	16S	1	1	1	0	0	0
17	17W	1	1	1	0	0	0
	17E	1	1	1	0	0	0
18	18N	1	1	1	0	0	0
	18S	1	1	1	0	0	0
19	19N	1	1	0	0	0	0
	19S	1	1	0	0	0	0
20	20N	1	1	1	0	0	0
	20S	1	2	1	0	0	0
21	21W	1	1	1	0	0	0
	21E	1	1	1	0	0	0
22	22N	1	0	1	0	0	0
	22S	1	1	1	0	0	0
23	23N	1	1	1	0	0	0
	23S	0	0	1	0	0	0
24	24N	1	1	0	0	0	0
	24S	0	1	0	0	0	0
25	25W	1	2	1	0	0	0
	25E	1	2	1	0	0	0
26	26S	1	1	0	0	0	0

Note:
Ramp Meter=1 if the corridor is under ramp metering control; otherwise, Ramp Meter=0;

Highway Helper Program=1 if the corridor is within highway helper program patrol area; otherwise, Highway Helper Program=0;
HOV=1 if the corridor has HOV lane(s) in operation; otherwise, HOV=0;
For VMS, the number of VMSs per corridor per direction is counted.

Appendices 6-13: Case study I regression results:

Appendix 6:

Regression Result:	Incident Free	7:00 AM – 8:00 AM		
Source	SS	df	MS	Number of obs = 8988 F(27, 8960) = 287.13 Prob > F = 0.0000 R-squared = 0.4639 Adj R-squared = 0.4623 Root MSE = 9.3646
Model	679868.109	27	25180.3003	
Residual	785752.454	8960	87.6955864	
Total	1465620.56	8987	163.082292	

Response Variable : Speed

Predictor Variable	Coef.	Std. Err.	t	P>|t|	[95% Conf. Interval]	
Density	-.2520507	.0052265	-48.226	0.000	-.2622958	-.2418056
Ramp Meter	4.828919	.2686687	17.974	0.000	4.302266	5.355571
VMS	-2.703652	.266009	-10.164	0.000	-3.22509	-2.182213
Concurrent HOV	-29.90661	1.013276	-29.515	0.000	-31.89286	-27.92036
Barrier-separated HOV	-36.27597	.9902992	-36.631	0.000	-38.21718	-34.33475
Two-Lane	7.535965	1.073159	7.022	0.000	5.432328	9.639602
Three-Lane	6.130187	1.012318	6.056	0.000	4.145812	8.114562
Four-Lane	-2.731895	.6449748	-4.236	0.000	-3.996193	-1.467596
I-35E NB (South of I-94)	-28.1754	.837144	-33.657	0.000	-29.8164	-26.5344
I-35E SB (South of I-94)	-28.99105	.8952893	-32.382	0.000	-30.74602	-27.23607
I-394WB	9.828056	.935602	10.505	0.000	7.994062	11.66
I-394EB	dropped					
I-35W NB	2.605788	.9482397	2.748	0.006	.7470215	4.464555
I-35W SB	dropped					
I-94WB	-18.63839	1.127802	-16.526	0.000	-20.84914	-16.42764
I-94EB	-14.47175	1.166032	-12.411	0.000	-16.75744	-12.18606
I-94NB	-12.9372	1.18577	-10.910	0.000	-15.26158	-10.61282
I-94SB	-18.07189	1.177862	-15.343	0.000	-20.38077	-15.76302
I-494NB	-32.74104	.8589865	-38.116	0.000	-34.42485	-31.05723
I-494SB	-37.8641	.8656379	-43.741	0.000	-39.56095	-36.16726
I-694WB	-31.94825	.9041072	-35.337	0.000	-33.72051	-30.17599
I-694EB	-29.9193	.9404882	-31.813	0.000	-31.76287	-28.07573
I-494WB	-37.04412	.8026948	-46.150	0.000	-38.61759	-35.47066
I-494EB	-32.70793	.7902354	-41.390	0.000	-34.25697	-31.15888
I-35E NB (North of I-94)	dropped					
I-35E SB (North of I-94)	-24.03749	.8791755	-27.341	0.000	-25.76087	-22.3141
TH-77 NB	-27.85155	.8477757	-32.852	0.000	-29.51338	-26.18971
TH-77 SB	-24.50227	.8223942	-29.794	0.000	-26.11435	-22.89019
I-35E NB (South of I-494)	-21.71335	.8592039	-25.271	0.000	-23.39758	-20.02911
I-35E SB (South of I-494)	-23.27922	.9095992	-25.593	0.000	-25.06224	-21.49619
Constant	85.7969	1.363444	62.927	0.000	83.12424	88.46956

Appendix 7:

Regression Result:	Incident Free	8:00 AM – 9:00 AM		
Source	SS	df	MS	Number of obs = 9030 F(27, 9002) = 294.99 Prob > F = 0.0000 R-squared = 0.4694 Adj R-squared = 0.4678 Root MSE = 9.1722
Model	670057.196	27	24816.9332	
Residual	757332.421	9002	84.1293514	
Total	1427389.62	9029	158.089447	

Response Variable : Speed

Predictor Variable	Coef.	Std. Err.	t	P>|t|	[95% Conf. Interval]	
Density	-.250744	.0048934	-51.241	0.000	-.2603362	-.2411518
Ramp Meter	2.32501	.3405388	6.827	0.000	1.657476	2.992543
VMS	-2.976521	.2591904	-11.484	0.000	-3.484594	-2.468449
Concurrent HOV	-14.84777	1.189239	-12.485	0.000	-17.17895	-12.5166
Barrier-separated HOV	-17.19873	.9781615	-17.583	0.000	-19.11614	-15.28131
Two-Lane	3.985557	1.050768	3.793	0.000	1.925813	6.045301
Three-Lane	2.447195	.9903281	2.471	0.013	.5059265	4.388463
Four-Lane	-2.807352	.6272801	-4.475	0.000	-4.036964	-1.577741
I-35E NB (South of I-94)	-8.54995	1.022211	-8.364	0.000	-10.55372	-6.546185
I-35E SB (South of I-94)	-11.62804	1.075206	-10.815	0.000	-13.73569	-9.520388
I-394WB	8.339799	.9353119	8.917	0.000	6.506375	10.17322
I-394EB	dropped					
I-35W NB	2.864719	.9247433	3.098	0.002	1.052012	4.677427
I-35W SB	dropped					
I-94WB	-5.100248	.7153619	-7.130	0.000	-6.50252	-3.697976
I-94EB	-.7432851	.7306705	-1.017	0.309	-2.175566	.6889953
I-94NB	dropped					
I-94SB	-3.079926	.63322	-4.864	0.000	-4.321181	-1.838671
I-494NB	-16.7402	1.071966	-15.616	0.000	-18.8415	-14.6389
I-494SB	-21.30695	1.042088	-20.446	0.000	-23.34968	-19.26422
I-694WB	-16.12696	.9598869	-16.801	0.000	-18.00856	-14.24537
I-694EB	-15.96904	.9537183	-16.744	0.000	-17.83855	-14.09954
I-494WB	-19.48569	1.003758	-19.413	0.000	-21.45328	-17.5181
I-494EB	-14.49763	1.02189	-14.187	0.000	-16.50076	-12.49449
I-35E NB (North of I-94)	17.21254	1.160998	14.826	0.000	14.93672	19.48836
I-35E SB (North of I-94)	.4036325	1.087084	0.371	0.710	-1.727299	2.534564
TH-77 NB	-6.986283	1.04779	-6.668	0.000	-9.040189	-4.932376
TH-77 SB	-9.453598	1.034841	-9.135	0.000	-11.48212	-7.425074
I-35E NB (South of I-494)	-6.233243	1.07325	-5.808	0.000	-8.337058	-4.129428
I-35E SB (South of I-494)	-9.912644	1.13259	-8.752	0.000	-12.13278	-7.69251
Constant	72.88782	.7421147	98.216	0.000	71.43311	74.34254

Appendix 8:

Regression Result:	Incident Free	4:00 PM – 5:00 PM		
Source	SS	df	MS	Number of obs = 8937
Model	1025131.45	27	37967.8313	F(27, 8909) = 456.73 Prob > F = 0.0000
Residual	740601.928	8909	83.1296361	R-squared = 0.5806
Total	1765733.37	8936	197.597737	Adj R-squared = 0.5793 Root MSE = 9.1175

Response Variable : Speed

Predictor Variable	Coef.	Std. Err.	t	P>|t|	[95% Conf. Interval]	
Density	-.2617367	.0048644	-53.806	0.000	-.2712721	-.2522014
Ramp Meter	3.931768	.2635107	14.921	0.000	3.415226	4.44831
VMS	-3.115385	.2563565	-12.153	0.000	-3.617903	-2.612867
Concurrent HOV	-22.04745	1.198693	-18.393	0.000	-24.39717	-19.69774
Barrier-separated HOV	-27.93467	.9876593	-28.284	0.000	-29.8707	-25.99863
Two-Lane	3.267593	1.050682	3.110	0.002	1.208015	5.327171
Three-Lane	1.42601	.984605	1.448	0.148	-.5040425	3.356062
Four-Lane	-4.313578	.625837	-6.892	0.000	-5.540363	-3.086793
I-35E NB (South of I-94)	-15.93184	1.023887	-15.560	0.000	-17.9389	-13.92479
I-35E SB (South of I-94)	-20.43802	1.077617	-18.966	0.000	-22.5504	-18.32564
I-394WB	7.170408	.9321031	7.693	0.000	5.343271	8.997544
I-394EB	dropped					
I-35W NB	5.530335	.9157479	6.039	0.000	3.735258	7.325412
I-35W SB	dropped					
I-94WB	-6.202389	.7246358	-8.559	0.000	-7.622842	-4.781936
I-94EB	-12.82244	.745279	-17.205	0.000	-14.28335	-11.36152
I-94NB	dropped					
I-94SB	-12.21012	.6634801	-18.403	0.000	-13.51069	-10.90954
I-494NB	-23.20866	1.104958	-21.004	0.000	-25.37463	-21.04269
I-494SB	-27.36845	1.055263	-25.935	0.000	-29.43701	-25.29989
I-694WB	-18.40719	.9556491	-19.261	0.000	-20.28049	-16.5339
I-694EB	-22.41605	.9589654	-23.375	0.000	-24.29584	-20.53626
I-494WB	-28.239	1.001128	-28.207	0.000	-30.20144	-26.27656
I-494EB	-31.8136	1.023151	-31.094	0.000	-33.81921	-29.80799
I-35E NB (North of I-94)	1.193324	1.157474	1.031	0.303	-1.075592	3.46224
I-35E SB (North of I-94)	-1.511027	1.090152	-1.386	0.166	-3.647977	.6259223
TH-77 NB	-12.31031	1.058612	-11.629	0.000	-14.38543	-10.23518
TH-77 SB	-6.749128	1.01518	-6.648	0.000	-8.739115	-4.759141
I-35E NB (South of I-494)	-14.73363	1.085274	-13.576	0.000	-16.86102	-12.60625
I-35E SB (South of I-494)	-8.384499	1.104516	-7.591	0.000	-10.5496	-6.219394
Constant	81.2317	.7315499	111.041	0.000	79.79769	82.66571

Appendix 9:

Regression Result:	Incident Free	5:00 PM – 6:00 PM		
Source	SS	df	MS	Number of obs = 8888
Model	1232647.11	27	45653.5968	F(27, 8860) = 497.54 Prob > F = 0.0000
Residual	812976.66	8860	91.758088	R-squared = 0.6026 Adj R-squared = 0.6014
Total	2045623.77	8887	230.181588	Root MSE = 9.579

Response Variable : Speed

Predictor Variable	Coef.	Std. Err.	t	P>|t|	[95% Conf. Interval]	
Density	-.3012855	.0050181	-60.040	0.000	-.3111221	-.2914489
Ramp Meter	4.802929	.277239	17.324	0.000	4.259476	5.346382
VMS	-3.321087	.2704075	-12.282	0.000	-3.851148	-2.791025
Concurrent HOV	-9.621244	1.241572	-7.749	0.000	-12.05501	-7.187475
Barrier-separated HOV	-17.54004	.9975423	-17.583	0.000	-19.49545	-15.58462
Two-Lane	1.175207	1.107088	1.062	0.288	-.9949418	3.345355
Three-Lane	-.6882897	1.036549	-0.664	0.507	-2.720166	1.343586
Four-Lane	-5.102936	.6597504	-7.735	0.000	-6.3962	-3.809673
I-35E NB (South of I-94)	-3.42142	1.023239	-3.344	0.001	-5.427206	-1.415634
I-35E SB (South of I-94)	-9.533662	1.091208	-8.737	0.000	-11.67268	-7.394641
I-394WB	3.123899	.9828605	3.178	0.001	1.197265	5.050534
I-394EB	dropped					
I-35W NB	8.649375	.9564371	9.043	0.000	6.774537	10.52421
I-35W SB	dropped					
I-94WB	4.070565	.6725108	6.053	0.000	2.752288	5.388842
I-94EB	-2.511493	.6818111	-3.684	0.000	-3.848001	-1.174986
I-94NB	11.30397	.6962579	16.235	0.000	9.93914	12.66879
I-94SB	dropped					
I-494NB	-9.051848	1.145056	-7.905	0.000	-11.29642	-6.807273
I-494SB	-14.25209	1.04764	-13.604	0.000	-16.30571	-12.19847
I-694WB	-5.903079	.9476044	-6.229	0.000	-7.760603	-4.045555
I-694EB	-10.85954	.9358015	-11.605	0.000	-12.69393	-9.025151
I-494WB	-14.13135	1.017796	-13.884	0.000	-16.12647	-12.13624
I-494EB	-19.42545	1.068696	-18.177	0.000	-21.52034	-17.33056
I-35E NB (North of I-94)	13.97171	1.219328	11.459	0.000	11.58155	16.36188
I-35E SB (North of I-94)	11.52134	1.112561	10.356	0.000	9.340462	13.70222
TH-77 NB	.4110926	1.050325	0.391	0.696	-1.647788	2.469973
TH-77 SB	5.749565	1.025583	5.606	0.000	3.739185	7.759945
I-35E NB (South of I-494)	-1.510314	1.091921	-1.383	0.167	-3.650733	.6301047
I-35E SB (South of I-494)	5.516165	1.127045	4.894	0.000	3.306896	7.725434
Constant	71.344	.644671	110.667	0.000	70.08029	72.6077

Appendix 10:

Regression Result:	Incident	7:00 AM – 8:00 AM		
Source	SS	df	MS	Number of obs = 365 F(32, 332) = 28.27 Prob > F = 0.0000 R-squared = 0.7315 Adj R-squared = 0.7057 Root MSE = 8.1208
Model	59662.0535	32	1864.43917	
Residual	21894.3756	332	65.9469146	
Total	81556.4291	364	224.056124	

Response Variable : Speed

Predictor Variable	Coef.	Std. Err.	t	P>|t|	[95% Conf. Interval]	
Density	-0.75134	0.032952	-22.801	0.000	-0.81616	-0.68652
Ramp Meter	2.939419	2.046835	1.436	0.152	-1.08698	6.96582
VMS	-2.99125	1.364806	-2.192	0.029	-5.676	-0.30649
Highway Helper	11.43915	4.688912	2.44	0.015	2.215424	20.66287
Concurrent HOV	14.56425	8.622303	1.689	0.092	-2.39698	31.52548
Barrier-separated HOV	2.413348	8.40736	0.287	0.774	-14.1251	18.95176
Two-Lane	4.212426	5.05391	0.833	0.405	-5.7293	14.15415
Three-Lane	-1.638	4.779645	-0.343	0.732	-11.0402	7.764205
Four-Lane	-1.27011	3.567741	-0.356	0.722	-8.28834	5.748116
I-35E NB (South of I-94)	20.69129	6.626659	3.122	0.002	7.655754	33.72682
I-35E SB (South of I-94)	11.50293	6.597234	1.744	0.082	-1.47472	24.48058
I-394WB	8.098844	4.009917	2.02	0.044	0.210796	15.98689
I-394EB	(dropped)	NA	NA	NA	NA	NA
I-35W NB	(dropped)	NA	NA	NA	NA	NA
I-35W SB	-22.1672	5.121883	-4.328	0.000	-32.2426	-12.0918
I-94WB	4.734422	8.564856	0.553	0.581	-12.1138	21.58265
I-94EB	3.885279	8.752871	0.444	0.657	-13.3328	21.10336
I-94NB	-6.0732	9.246285	-0.657	0.512	-24.2619	12.11549
I-94SB	5.600905	9.137713	0.613	0.54	-12.3742	23.57602
I-494NB	-4.55976	8.865655	-0.514	0.607	-21.9997	12.88018
I-494SB	0.457884	8.416718	0.054	0.957	-16.0989	17.0147
I-694WB	2.798716	8.14038	0.344	0.731	-13.2145	18.81194
I-694EB	4.039595	9.96327	0.405	0.685	-15.5595	23.63869
I-494WB	1.94348	8.224489	0.236	0.813	-14.2352	18.12216
I-494EB	3.825642	7.975405	0.48	0.632	-11.8631	19.51434
I-35E NB (North of I-94)	15.29128	9.786638	1.562	0.119	-3.96036	34.54292
I-35E SB (North of I-94)	15.64729	8.032848	1.948	0.052	-0.1544	31.44899
TH-77 NB	14.09674	7.490849	1.882	0.061	-0.63877	28.83225
TH-77 SB	-7.48323	8.621944	-0.868	0.386	-24.4438	9.477295
I-35E NB (South of I-494)	(dropped)	NA	NA	NA	NA	NA
I-35E SB (South of I-494)	(dropped)	NA	NA	NA	NA	NA
Second Upstream	3.9141	3.415065	1.146	0.253	-2.80379	10.63199
First Upstream	6.565187	3.483028	1.885	0.06	-0.2864	13.41677
Within	2.593488	3.513752	0.738	0.461	-4.31854	9.505513
First downstream	4.42073	3.433384	1.288	0.199	-2.3332	11.17466
Second downstream	5.527177	3.389026	1.631	0.104	-1.1395	12.19385
Constant	59.1202	8.437715	7.007	0.000	42.52208	75.71833

Appendix 11:

Regression Result:	Incident	8:00 AM – 9:00 AM		
Source	SS	df	MS	Number of obs = 370 F(31, 338) = 33.72 Prob > F = 0.0000 R-squared = 0.7557 Adj R-squared = 0.7333 Root MSE = 7.9486
Model	66054.0979	31	2130.77735	
Residual	21355.1839	338	63.1810173	
Total	87409.2818	369	236.881522	

Response Variable : Speed

Predictor Variable	Coef.	Std. Err.	t	P>|t|	[95% Conf. Interval]	
Density	-0.58161	0.025821	-22.525	0.000	-0.6324	-0.53082
Ramp Meter	-0.30668	2.295615	-0.134	0.894	-4.82218	4.208806
VMS	-3.24461	1.267541	-2.56	0.011	-5.73788	-0.75135
Highway Helper	9.254188	5.386158	1.718	0.087	-1.34042	19.8488
Concurrent HOV	-9.42419	8.124675	-1.16	0.247	-25.4055	6.557106
Barrier-separated HOV	-4.58715	7.47346	-0.614	0.54	-19.2875	10.1132
Two-Lane	9.255993	5.985023	1.547	0.123	-2.51659	21.02858
Three-Lane	5.030859	5.725138	0.879	0.38	-6.23053	16.29225
Four-Lane	3.760379	4.824998	0.779	0.436	-5.73043	13.25118
I-35E NB (South of I-94)	13.46424	5.05378	2.664	0.008	3.523422	23.40507
I-35E SB (South of I-94)	8.833973	5.14211	1.718	0.087	-1.28059	18.94854
I-394WB	9.948754	2.862385	3.476	0.001	4.318422	15.57909
I-394EB	(dropped)	NA	NA	NA	NA	NA
I-35W NB	(dropped)	NA	NA	NA	NA	NA
I-35W SB	(dropped)	NA	NA	NA	NA	NA
I-94WB	-2.68063	7.83222	-0.342	0.732	-18.0867	12.7254
I-94EB	0.278481	8.087543	0.034	0.973	-15.6298	16.18674
I-94NB	(dropped)	NA	NA	NA	NA	NA
I-94SB	9.17277	8.681812	1.057	0.291	-7.90442	26.24996
I-494NB	-8.78545	7.66078	-1.147	0.252	-23.8543	6.283365
I-494SB	-10.9113	7.472835	-1.46	0.145	-25.6104	3.787851
I-694WB	-6.12374	7.432362	-0.824	0.411	-20.7433	8.495773
I-694EB	-8.97463	7.984406	-1.124	0.262	-24.68	6.730754
I-494WB	-8.32298	7.310257	-1.139	0.256	-22.7023	6.056346
I-494EB	-3.9852	7.119562	-0.56	0.576	-17.9894	10.01903
I-35E NB (North of I-94)	32.43377	8.535746	3.8	0.000	15.6439	49.22364
I-35E SB (North of I-94)	5.057576	7.278934	0.695	0.488	-9.26014	19.37529
TH-77 NB	5.548112	6.789061	0.817	0.414	-7.80602	18.90224
TH-77 SB	-8.73279	8.196889	-1.065	0.287	-24.8561	7.39055
I-35E NB (South of I-494)	2.848957	7.739737	0.368	0.713	-12.3752	18.07308
I-35E SB (South of I-494)	(dropped)	NA	NA	NA	NA	NA
Second Upstream	-2.13123	1.796087	-1.187	0.236	-5.66415	1.401683
First Upstream	0.133774	1.791197	0.075	0.941	-3.38952	3.657072
Within	-4.36745	2.088316	-2.091	0.037	-8.47518	-0.25972
First downstream	0.631739	1.81047	0.349	0.727	-2.92947	4.192946
Second downstream	1.665056	1.835205	0.907	0.365	-1.94481	5.274918
Constant	63.18793	7.581401	8.335	0.000	48.27526	78.1006

Appendix 12:

Regression Result:	Incident	4:00 PM – 5:00 PM		
Source	SS	df	MS	Number of obs = 387 F(32, 354) = 34.25 Prob > F = 0.0000 R-squared = 0.7559 Adj R-squared = 0.7338 Root MSE = 8.7708
Model	84309.3485	32	2634.66714	
Residual	27232.0062	354	76.9265712	
Total	111541.355	386	288.96724	

Response Variable : Speed

Predictor Variable	Coef.	Std. Err.	t	P>|t|	[95% Conf. Interval]	
Density	-0.50266	0.024991	-20.114	0.000	-0.55181	-0.45352
Ramp Meter	4.101622	2.119897	1.935	0.054	-0.06755	8.270798
VMS	-5.93651	1.422739	-4.173	0.000	-8.73459	-3.13842
Highway Helper	8.453485	8.276665	1.021	0.308	-7.82413	24.7311
Concurrent HOV	-15.7892	6.549702	-2.411	0.016	-28.6704	-2.90799
Barrier-separated HOV	-12.5542	5.96706	-2.104	0.036	-24.2896	-0.81889
Two-Lane	7.865736	6.172571	1.274	0.203	-4.27379	20.00526
Three-Lane	4.896097	5.818955	0.841	0.401	-6.54797	16.34016
Four-Lane	0.361771	4.701626	0.077	0.939	-8.88486	9.608402
I-35E NB (South of I-94)	-6.28741	8.299102	-0.758	0.449	-22.6092	10.03434
I-35E SB (South of I-94)	-2.06567	6.979932	-0.296	0.767	-15.793	11.66168
I-394WB	(dropped)	NA	NA	NA	NA	NA
I-394EB	-2.84497	3.235557	-0.879	0.38	-9.2083	3.518355
I-35W NB	11.66681	4.886601	2.388	0.017	2.056392	21.27723
I-35W SB	(dropped)	NA	NA	NA	NA	NA
I-94WB	-0.06946	4.729215	-0.015	0.988	-9.37035	9.231431
I-94EB	-8.31375	4.546734	-1.829	0.068	-17.2558	0.628263
I-94NB	(dropped)	NA	NA	NA	NA	NA
I-94SB	-5.35033	4.932028	-1.085	0.279	-15.0501	4.349429
I-494NB	-14.1119	6.54738	-2.155	0.032	-26.9885	-1.23521
I-494SB	-17.8651	8.305069	-2.151	0.032	-34.1986	-1.53166
I-694WB	-8.79731	5.993604	-1.468	0.143	-20.5849	2.990238
I-694EB	-16.3445	5.493882	-2.975	0.003	-27.1493	-5.53977
I-494WB	-20.1711	5.547078	-3.636	0.000	-31.0804	-9.2617
I-494EB	-17.6815	5.592347	-3.162	0.002	-28.6799	-6.68311
I-35E NB (North of I-94)	6.590165	5.998975	1.099	0.273	-5.20795	18.38827
I-35E SB (North of I-94)	1.114478	6.045083	0.184	0.854	-10.7743	13.00327
TH-77 NB	-1.82628	7.101842	-0.257	0.797	-15.7934	12.14083
TH-77 SB	0.62628	6.122055	0.102	0.919	-11.4139	12.66645
I-35E NB (South of I-494)	(dropped)	NA	NA	NA	NA	NA
I-35E SB (South of I-494)	10.07079	9.044946	1.113	0.266	-7.71779	27.85938
Second Upstream	-3.80463	1.868951	-2.036	0.043	-7.48028	-0.12899
First Upstream	-3.92623	1.805705	-2.174	0.03	-7.47749	-0.37497
Within	-4.96945	1.893313	-2.625	0.009	-8.693	-1.24589
First downstream	-1.74078	1.705062	-1.021	0.308	-5.09411	1.61254
Second downstream	-0.20719	1.790329	-0.116	0.908	-3.72821	3.313829
Constant	71.22278	9.356426	7.612	0.000	52.82161	89.62395

Appendix 13:

Regression Result:	Incident		5:00 PM – 6:00 PM	
Source	SS	df	MS	Number of obs = 426 F(33, 392) = 26.44 Prob > F = 0.0000 R-squared = 0.6900 Adj R-squared = 0.6639 Root MSE = 9.897
Model	85473.1091	33	2590.09422	
Residual	38396.3819	392	97.9499538	
Total	123869.491	425	291.457626	

Response Variable : Speed

Predictor Variable	Coef.	Std. Err.	t	P>|t|	[95% Conf. Interval]	
Density	-0.46693	0.023679	-19.719	0.000	-0.51348	-0.42038
Ramp Meter	6.54014	2.523434	2.592	0.01	1.578982	11.5013
VMS	-3.75248	1.443685	-2.599	0.01	-6.59082	-0.91415
Highway Helper	-1.59986	14.23486	-0.112	0.911	-29.5861	26.38636
Concurrent HOV	-1.01735	16.35707	-0.062	0.95	-33.1759	31.14121
Barrier-separated HOV	-6.80054	15.05689	-0.452	0.652	-36.4029	22.80182
Two-Lane	16.08981	6.328272	2.543	0.011	3.648209	28.53141
Three-Lane	11.46823	6.047429	1.896	0.059	-0.42122	23.35768
Four-Lane	6.510261	4.646011	1.401	0.162	-2.62395	15.64448
I-35E NB (South of I-94)	-6.07534	4.673565	-1.3	0.194	-15.2637	3.11305
I-35E SB (South of I-94)	-9.9797	5.11016	-1.953	0.052	-20.0264	0.067051
I-394WB	(dropped)	NA	NA	NA	NA	NA
I-394EB	-1.44766	3.5831	-0.404	0.686	-8.49216	5.596832
I-35W NB	(dropped)	NA	NA	NA	NA	NA
I-35W SB	-9.74654	8.226623	-1.185	0.237	-25.9204	6.427283
I-94WB	0.994062	15.41102	0.065	0.949	-29.3045	31.29266
I-94EB	-3.21353	15.44811	-0.208	0.835	-33.585	27.15798
I-94NB	33.62636	15.90456	2.114	0.035	2.357456	64.89527
I-94SB	5.636396	15.9536	0.353	0.724	-25.7289	37.00171
I-494NB	-9.4713	15.35901	-0.617	0.538	-39.6676	20.72504
I-494SB	-13.8898	15.5389	-0.894	0.372	-44.4398	16.6602
I-694WB	-2.41808	15.50913	-0.156	0.876	-32.9096	28.0734
I-694EB	-8.4114	15.08743	-0.558	0.577	-38.0738	21.251
I-494WB	-14.5966	14.92183	-0.978	0.329	-43.9334	14.74028
I-494EB	-13.1667	14.8881	-0.884	0.377	-42.4372	16.10379
I-35E NB (North of I-94)	-0.15714	15.29187	-0.01	0.992	-30.2215	29.90719
I-35E SB (North of I-94)	3.382067	15.24969	0.222	0.825	-26.5994	33.36348
TH-77 NB	-1.21196	17.83895	-0.068	0.946	-36.2839	33.86002
TH-77 SB	6.303295	15.09286	0.418	0.676	-23.3698	35.97636
I-35E NB (South of I-494)	-4.04761	10.82699	-0.374	0.709	-25.3338	17.23863
I-35E SB (South of I-494)	(dropped)	NA	NA	NA	NA	NA
Second Upstream	-1.76824	2.556126	-0.692	0.489	-6.79367	3.257191
First Upstream	-3.80982	2.466949	-1.544	0.123	-8.65992	1.040291
Within	-5.89884	2.565083	-2.3	0.022	-10.9419	-0.8558
First downstream	-2.45132	2.396035	-1.023	0.307	-7.16201	2.259363
Second downstream	-0.20307	2.507712	-0.081	0.935	-5.13332	4.727172
Constant	62.85835	7.85513	8.002	0.000	47.41489	78.3018

Appendix 14: Case study II regression results:

Source	SS	df	MS	
Model	138.948393	7	19.8497705	Number of obs = 98
Residual	230.244303	90	2.55827003	F(7, 90) = 7.76 Prob > F = 0.0000 R-squared = 0.3764
Total	369.192696	97	3.80611027	Adj R-squared = 0.3279 Root MSE = 1.5995

Response Variable : Incident Rate

Predictor Variable	Coefficient	Std. Err.	t	P>|t|	[95% Conf. Interval]	
Intersection Density	1.302414	.5143032	2.532	0.013	.2806611	2.324167
Ramp Meter	-1.07134	.3246102	-3.300	0.001	-1.716235	-.4264451
VMS Density	4.172839	1.951534	2.138	0.035	.2957767	8.049901
Highway Helper	1.448543	.4695155	3.085	0.003	.5157689	2.381318
Concurrent HOV in I-35W	.2315502	.8564734	0.270	0.788	-1.469984	1.933084
Concurrent HOV in I-394	-.940457	.8653702	-1.087	0.280	-2.659666	.7787519
Barrier-separated HOV in I-394	2.46086	.9012703	2.730	0.008	.670329	4.25139
Constant	-1.23387	.7712802	-1.600	0.113	-2.766153	.2984125