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Traffic Management System Performance Using Regression Analysis:
A case study of Mn/DOT's Traffic Management Systems.
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Traffic Management System Performance

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Abstract

This study uses regression analysis to evaluate long-run traffic management system performance. Three important traffic management systems in the Twin Cities metro area - Ramp Metering, Variable Message Signs (VMS), and Freeway Service Patrol (the Highway Helper Program) were evaluated with multiple regression models to predict link speed and incident rate. We find that ramp meters increase freeway link speed and reduce incident rate. Freeway Service Patrols increase link speed when incidents are present. The results for variable message signs are ambiguous. Regression analysis can be a simple and effective research method for testing the macroscopic association between traffic management and traffic system performance.

Key Words: Traffic management system; Traffic system performance; Before-and-after study; Ramp Metering System; Variable Message Signs (VMS); Freeway Service Patrol; Highway Helper Program.

1. INTRODUCTION

The Minnesota Department of Transportation (Mn/DOT) Traffic Management Center (TMC) was founded in 1972 to centrally manage the freeway system in the Minneapolis – St. Paul (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, Variable Message Signs (VMS), Freeway Service Patrols (Highway Helpers), High Occupancy Vehicle (HOV) lanes, Loop Detectors, Closed Circuit TV (CCTV) cameras, and Traveler Information.

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 evaluates the system-wide performance of three important traffic management systems in the Twin Cities metro area - Ramp Metering, Variable Message Signs, and the Highway Helper Program using regression analysis. The traditional before-and-after study and the regression analysis method are compared, the outline of the regression analysis is presented and its limitations are stated. In the two case studies, both the link speed and incident rate are employed as response variables. Freeway loop detector data and incidents recorded by TMC staff using freeway cameras are used for this study.

2. Methodology

2.1 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 these methods will meet difficulties when the object of study is a long existing traffic management system. First, it is usually impossible to isolate the effects of traffic management from the effects of external variations [1]. A before-and-after study is persuasive for the evaluation of short-run impacts when 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 those from other changes also affecting the system. Second, 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. Third, the traffic management system itself is continuously changing - new facilities are gradually added and some old facilities are gradually removed. Even if we can find some freeway segment which has stable before-and-after phases, the limited analysis won't be representative of the whole system.

A famous example of evaluating traffic management system performance using a before-and-after study is the Twin Cities metro area ramp metering shutdown study [2,9]. During the eight-week ramp meter shutdown, 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 shutdown. But such 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, Minnesota state legislators suggested opening the HOV lanes on I-394 to general-purpose traffic for a limited period in 2001 for the before-and-after data collection. However, this plan was barred by the FHWA due to policy considerations.

A performance evaluation of the traffic management system can provide important information for planning and for the rationalization of operating budget allocations. We explore a simple and effective approach for this task, regression analysis. Compared with a before-and-after study, regression analysis doesn't try to design the stable external circumstances. Instead, regression isolates the effects of the object of study from the effects of combining factors. 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 the effects of traffic management systems on incident rates, we need to use several years' data to obtain a

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sufficiently large sample, in this case, it is meaningless to assume unvaried external circumstances. Regression analysis differs from a before-and-after study in that it tries to control for all the potential elements (including traffic management) that affect 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.

2.2 The response variable of 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 operational objectives of the traffic management system; 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 analyses. The reason for using speed instead of travel time is that the regression model will include observations from different corridor segments. Though travel time will present no more information than speed, it will be influenced by the differences in length of the corridor segments. Related measures, such as travel time, delays, and travel time reliability, can be derived directly from speed. Some other measures, including environmental impacts and fuel consumption, can also be derived from speed by combining with flow, vehicle type, and gasoline quality.

2.3 The framework of an ideal regression model

Ideally, we would employ 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 include capacity, geometric structure, pavement quality, and construction activity. Capacity has significant effects on speed, but when the detailed information of capacity is difficult to obtain, the number of lanes could be used as an indication of capacity if the corridors under study are similar, e.g., all are trunk highways. Geometric structure includes the elements of horizontal and vertical curvature, sight distance and intersection density (e.g. number of intersections per mile)**.** Pavement quality can be good or poor.

2. Traffic characteristics include density and the percentage of heavy commercial traffic. Heavy commercial traffic such as truck fleet has significant impact on freeway performance.

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

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

Figure 1 shows the framework of the ideal regression model, as well as presenting hypotheses about the direction of the expected effect of these predictor variables on speed and incident rate.

2.4 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 on the mainline caused by ramp metering (if any) offsets ramp delay. 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.

3. Speed as response variable

3.1 Regression Model

1. Predictor variables

Due to the data limitation we are unable to test all the potential predictor variables described in the ideal regression model. For infrastructure characteristics, we use capacity (number of lanes); for traffic characteristics, we use density; for traffic management strategies, we test Ramp Metering, Variable Message Signs, and the Highway Helper Program, and for other factors, we used traffic incident impact. We also added 22 corridor-specific dummy variables, among these we include segments with and without HOV. Since HOV lanes are rare in the Twin Cities, we could not distinguish between the corridor effects and the presence of HOV lanes (concurrent or separated) when analyzing speed.

2. Detect multi-colinearity

Since we are using multi-variate regression, we should use the correlation matrix to detect possible multi-colinearity. We diagnose multi-colinearity if the absolute value of the correlation between two predictor variables is larger than 0.6. From the correlation matrices (Table A1) we find that each correlation is less than 0.6, therefore, multi-colinearity between density and the TMS dummies is not a significant problem.

We pay specific attention to the low correlation between ramp metering and mainline density. It is often believed that a segment controlled by ramp metering will have lower density than a segment without metering. But an obvious linear relationship between ramp metering and mainline density can't be found from our data. The reason should be that density is a complex measurement which is associated with many factors (including upstream traffic flows), and ramp metering is just one of them.

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Ramp metering affects mainline speed through not only mainline density but also other traffic factors such as drivers' behaviors. When vehicles try to merge from a ramp onto the mainline, mainline drivers usually have to slow down or even change lanes to let them in. That is, entering cars will affect mainline drivers' behavior even if their merging doesn't increase mainline density significantly. (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, cars enter the freeway in a spaced and controlled manner. Even when that ramp metering doesn't significantly decrease mainline density, its reduction of merging disruption will increase mainline speed. Speed and density are both computed from loop detector data, following methods detailed in [9].

3. Model expression

Model 1 predicts speed in the incident-free case as:

Hourly average speed = $ß_0$ + $ß_D$× Density + $ß_{TMT1}$× Ramp Meter (1,0) + $ß_{TMT2}$× VMS (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;

$ß_{TMT1\sim TMT2}$ indicate the coefficients of Ramp Meter Dummy, VMS 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).

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

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

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

Model 2 predicts speed in the presence of an incident, as:

Hourly average speed = $ß_0$ + $ß_D$× Density + $ß_{TMT1}$× Ramp Meter (1,0) + $ß_{TMT2}$× VMS (1,0) + $ß_{TMT5}$× Highway Helper Program (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 + $ß_I$ × Incident + $ß_{IU1}$× IncidentUp1 + $ß_{IU2}$× IncidentUp2 + $ß_{ID1}$× IncidentDown1 + $ß_{ID2}$× IncidentDown2 + ε

Where,

$ß_I$, $ß_{IU1}$, $ß_{IU2}$, $ß_{ID1}$, and $ß_{ID2}$ indicate the coefficients of the five incident groups; Incidents are classified into the following five groups:

Incident - the incident occurred within the studied segment;

IncidentUp1 - the incident occurred in the first segment upstream of the studied segment;

IncidentUp2 - the incident occurred in the second segment upstream of the studied segment;

IncidentDown1 - the incident occurred in the first segment downstream of the studied segment;

IncidentDown2 - the incident occurred in the second segment downstream of the studied segment;

Note that the Highway Helper Program is not included in the incident-free case because when the studied segments are incident-free, the Highway Helper Program should have no effect;

3.2 Corridor selection and study periods

1. Corridor selection

In total, 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 Figure 2 and Table A2).

II. The selected corridors should include segments with and without ramp meters, with and without VMS, and with and without highway helpers.

2. Study periods

The study periods range from 1998 to 2000, which includes the periods before ramp meter start-up, ramp meter in full operation, and the eight-week ramp meter shutdown in 2000; before VMS start-up and VMS in full operation; and highway helper program in full operation.

It is noted that no 'before' data are included for 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.

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

1. Samples are gathered on 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 loop detector data, the length of gaps in 1998 range from 10 to 20 days.

3.3 Results

Observations collected in each of the four peak hours: 7:00AM—8:00AM, 8:00AM—9:00AM, 4:00PM—5:00PM, and 5:00PM—6:00PM formed four groups of independent samples. Regression was conducted on each of the four groups using the statistical software *Stata*. Then the effects on mainline speed in the four hours were tested. The regression results are summarized in Table 1 and Table 2.

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. The analysis is based on three years of system-wide data and the number of observations for the incident-free case is large, so we are not disappointed with the results. The regression results of density and the TMSs are analyzed as follows:

Density is an important referent which helps us understand the effects of the traffic management systems on speed, for example, in the incident-free case, comparing the coefficient of the 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 the incident-free case and incident case, 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 the incident-free case and incident case.

For the incident-free case, the estimates for the ramp meter dummy are positive and significant in all 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-week ramp meter shutdown data, while our study is based on three years' data (including data prior to the ramp meter start-up, ramp meter in full operation period, and eight-week ramp meter shutdown), 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 above, 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 actual effects of ramp metering should be even bigger.

For the incident case, 2 of the 4 estimates of the 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.

Unlike Ramp Metering which has 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 impact area of VMS. The impact area of VMS is defined as the segments that can 'see' the VMS messages and the 2 to 3 segments downstream of the VMS. Therefore, what we estimate here is actually the association between speed and VMS impact area.

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

1. VMS impacts drivers' behaviors. VMS devices installed along the roadside warn of special events such as congestion, incident, roadwork zone or speed limit to alert travelers of traffic problems ahead. The messages displayed affect driver behavior. 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 of the signs contributes to the negative association. Most of the signs in the Twin Cities metro area are located on freeway segments with high AADT. These segments are typically more congested and have lower mainline speed.

Then, should we stop using VMS since VMS impact area is associated with lower mainline speed? Probably not. Because the speed decrease on one corridor (VMS impacting area) may prevent congestion on some other corridors. Further study is need to evaluate VMS.

The Highway Helper Program is not included in the incident-free case because when the studied segments are incident-free, the 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 coefficient is positive in all 4 cases and significant in 2 cases. This indicates that when there are incidents, the corridor segments within Highway Helper patrol areas will be faster than the corridor segments without Highway Helpers.

4. Incident rate as response variable

4.1 Data collection

TMC freeway incident records for 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 system-wide 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 record, the number of incidents seemingly 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 shutdown [2] and 37 workdays (from Oct. 16 to Dec. 07) during the ramp metering system shutdown. 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 to 19:00 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 accounted for more than 97% of all incidents.

4.2 Corridor selection

In total, 26 corridors were selected for this study which nearly cover the whole Twin Cities metro area freeway network (refer to Figure 3). The unselected corridors were those outside of TMC camera monitoring. The facility status of each corridor was summarized in Table A3.

4.3 Regression model

It should be noted that despite the short incident counting periods (37 workdays before and during ramp metering shutdown respectively) we can guarantee the quality of incident data. However, it is also due to the short incident counting periods that 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 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 is 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) + ε

Where,

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

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.

VMS Density = the number of variable message signs per mile which is counted for both directions of each corridor.

Intersection density = the number of interchanges per mile.

Each corridor has two directions, and each direction will have two observations – Incident Rate before shutdown and Incident Rate during shutdown. 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 an intersection is more 'dangerous' than a straight segment, therefore, the intersection density of a corridor should be strongly related to its incident rate. As to VMS, VMS Density is a more reasonable measure than VMS impact area for long corridors.

4.4 Results

The regression results are summarized in Table 3. 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. However, incidents are 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. Nevertheless, we can still find important associations between incident rate and the TMS components from the regression results.

Intersection Density has a 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 a 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 weekday).

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. Unlike ramp metering, where we have observations with and without meters for the same corridor, we can make no claims of causality here, as the presence of VMS did not change on specific corridors.

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

Conclusions

This study used regression to evaluate the long-run performance of three traffic management systems - Ramp Metering, Variable Message Signs (VMS), and the Highway Helper Program, 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 database of about 40,000 observations covering three years' data was established. The long-run and system-wide performance of the traffic management systems were estimated for both the incident-free case and incident case. The key findings are summarized as follows:

- For the 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 the 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 the incident-free case and incident case, the speed of the corridor segment within the VMS impact area will be lower than the corridor segment outside. The negative relationship is due to two reasons: 1. VMS messages' impacts on drivers' behaviors; 2. the geographic distribution characteristics of the VMSs .
- The 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 the highway helper patrol areas will be faster than the corridor segments out of the areas.

In case study II, incident rate analysis was based on the incident data collected for two periods in Fall 2000 - before ramp metering system shutdown and during ramp metering system shutdown. 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;

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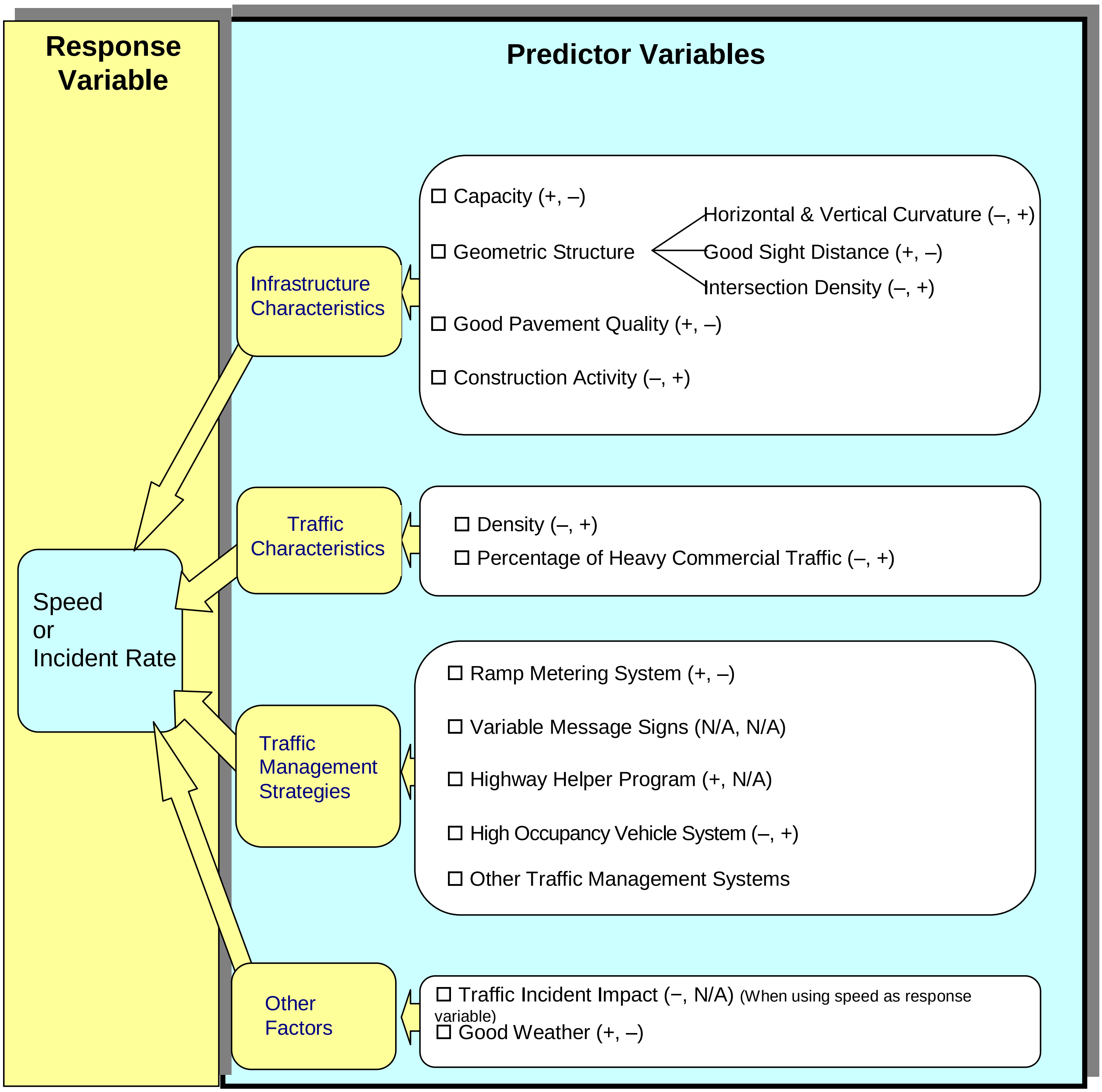
TABLES AND FIGURES

Figure 1 : The framework of an ideal regression model



Note:

1. *Hypotheses are given in parentheses* **-** *(The expected effect on speed, The expected effect on incident rate);*
2. *For a numeric predictor variable, if its increase is excepted to be associated with the increase in speed or incident rate, the expected effect is marked as '+'; if its increase is excepted to be associated with the decrease in speed or incident rate, the expected effect is marked as '-';*
3. *For a dummy predictor variable, if its presence (=1) is excepted to be associated with the increase in speed or incident rate, the expected effect is marked as '+'; if its presence is excepted to be associated with the decrease in speed or incident rate, the expected effect is marked as '-'.*

Figure 2. Speed Analysis: Corridor selection

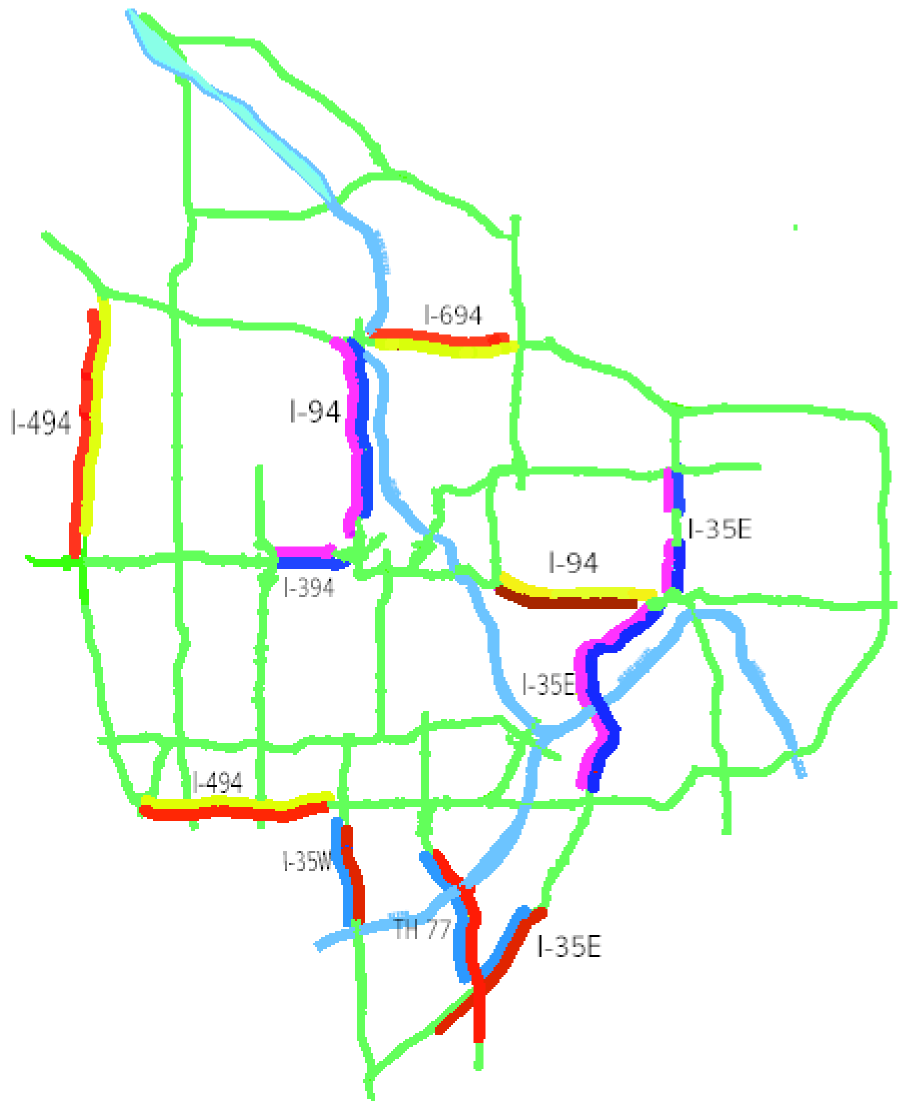


Figure 3. Incident Analysis: Corridor selection

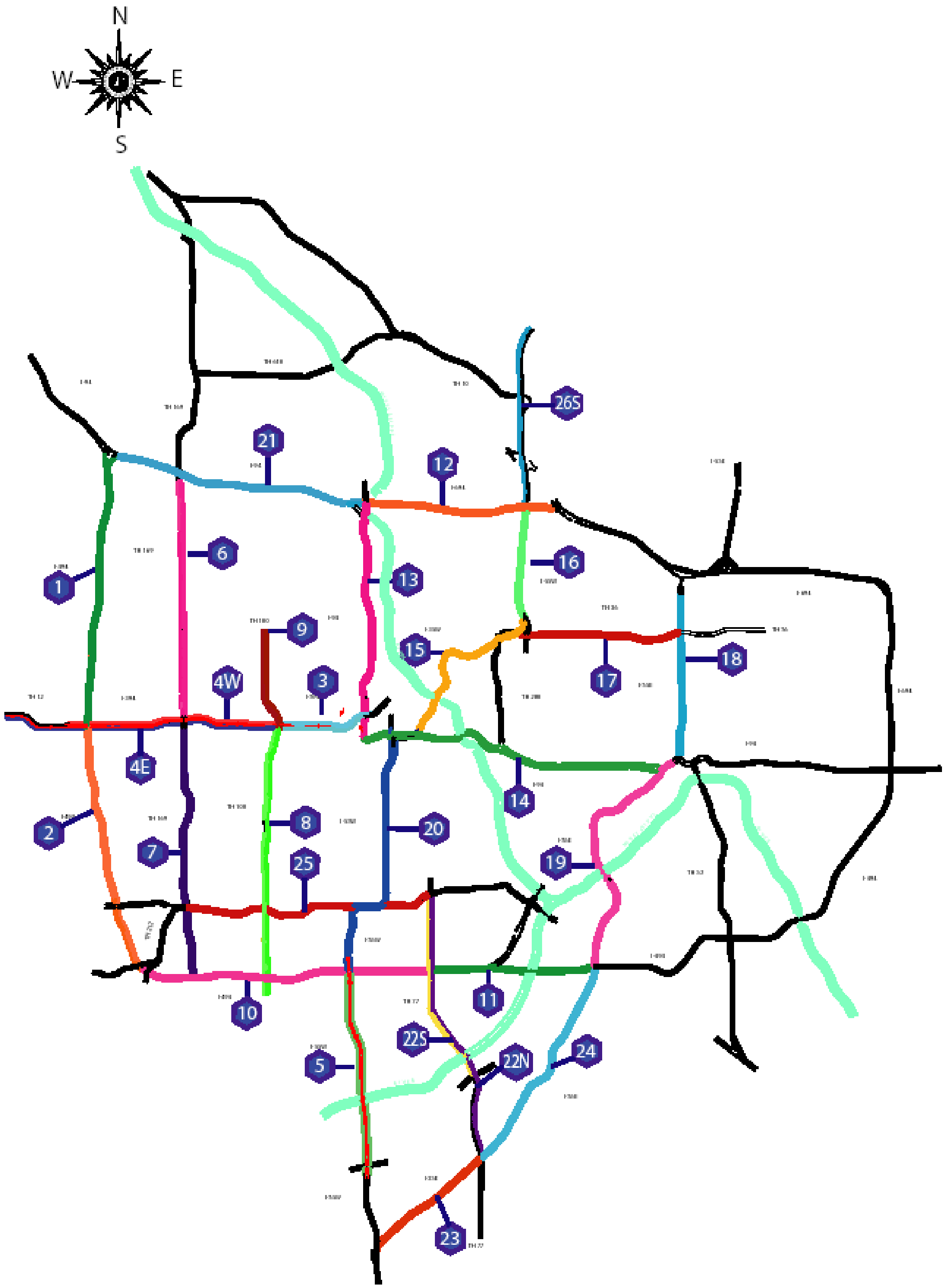


Table 1 : Summary of regression results of the incident-free case: Dependent Variable = Speed

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	
Predictor Variable	Coefficient $ß_j$	P-value	Coefficient $ß_j$	P-value	Coefficient $ß_j$	P-value	Coefficient $ß_j$	P-value
Density	-.25	0.000 (S)	-.25	0.000(S)	-.26	0.000(S)	-0.30	0.000(S)
RM	4.83	0.000(S)	2.32	0.000(S)	3.93	0.000(S)	4.80	0.000(S)
VMS	-2.70	0.000(S)	-2.98	0.000(S)	-3.12	0.000(S)	-3.32	0.000(S)

Note: S=Significant at 90% confidence level; NS=Not significant.

Table 2 : Summary of regression results of the incident case: Dependent Variable = Speed

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	
Predictor Variable	Coefficient $ß_j$	P-value	Coefficient $ß_j$	P-value	Coefficient $ß_j$	P-value	Coefficient $ß_j$	P-value
Density	-.75	0.000 (S)	-.58	0.000 (S)	-.50	0.000 (S)	-.47	0.000 (S)
Highway Helper	11.44	0.015 (S)	9.25	0.087 (S)	8.45	0.308 (NS)	-1.60	0.911 (NS)
RM	2.94	0.152(NS)	-.31	0.894 (NS)	4.10	0.054 (S)	6.54	0.010 (S)
VMS	-2.99	0.029(S)	-3.24	0.011(S)	-5.94	0.000 (S)	-3.75	0.010 (S)

Note: S=Significant at 90% confidence level; NS=Not significant.

Table 3 : Regression Results: Dependent Variable = Incident Rate

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

Independent Variables	Coefficient β.	P-value	t-value
Intersection Density	1.302414	0.013 (S)	2.532
Ramp Metering	-1.07134	0.001(S)	-3.300
VMS Density	4.172839	0.035(S)	2.138
Highway Helper	1.448543	0.003(S)	3.085
Concurrent HOV in I-35W	.2315502	0.788(NS)	0.270
Concurrent HOV in I-394	-.940457	0.280(NS)	-1.087
Barrier-separated HOV in I-394	2.46086	0.008(S)	2.730

Note: S=Significant at 90% confidence level; NS=Not significant.

Chen, Wei and D. Levinson (2006)
Traffic Management System Performance Using Regression Analysis:
A case study of Mn/DOT's Traffic Management Systems.
California PATH Working Paper for California Department of Transportation UCB-ITS-PWP-2006-5

Table A1. Case study I: The correlation matrices of predictor variables

I. Incident-free:

7:00AM-8:00AM	DENSITY	RM	VMS	ConHOV	BarHOV	8:00AM-9:00AM	DENSITY	RM	VMS	ConHOV	BarHOV
DENSITY	1.00	0.19	-0.13	0.08	0.06	DENSITY	1.00	0.19	-0.09	0.15	0.07
RM	0.19	1.00	0.01	-0.03	-0.03	RM	0.19	1.00	0.02	-0.03	-0.03
VMS	-0.13	0.01	1.00	-0.05	-0.05	VMS	-0.09	0.02	1.00	-0.04	-0.05
ConHOV	0.08	-0.03	-0.05	1.00	-0.05	ConHOV	0.15	-0.03	-0.04	1.00	-0.05
BarHOV	0.06	-0.03	-0.05	-0.05	1.00	BarHOV	0.07	-0.03	-0.05	-0.05	1.00

4:00PM-5:00PM	DENSITY	RM	VMS	ConHOV	BarHOV	5:00PM-6:00PM	DENSITY	RM	VMS	ConHOV	BarHOV
DENSITY	1.00	0.09	0.07	0.15	0.08	DENSITY	1.00	0.07	0.07	0.12	0.13
RM	0.09	1.00	0.01	-0.03	-0.03	RM	0.07	1.00	0.01	-0.02	-0.03
VMS	0.07	0.01	1.00	-0.05	-0.04	VMS	0.07	0.01	1.00	-0.05	-0.04
ConHOV	0.15	-0.03	-0.05	1.00	-0.05	ConHOV	0.12	-0.02	-0.05	1.00	-0.05
BarHOV	0.08	-0.03	-0.04	-0.05	1.00	BarHOV	0.13	-0.03	-0.04	-0.05	1.00

II. Incident:

7:00AM-8:00AM	DENSITY	RM	VMS	HHELPER	ConHOV	BarHOV	8:00AM-9:00AM	DENSITY	RM	VMS	HHELPER	ConHOV	Bar
DENSITY	1.00	-0.11	-0.32	-0.03	0.05	0.02	DENSITY	1.00	0.10	-0.14	0.22	0.01	-0.
RM	-0.11	1.00	0.16	0.29	-0.12	-0.08	RM	0.10	1.00	0.05	0.28	-0.07	-0.
VMS	-0.32	0.16	1.00	0.25	-0.10	-0.04	VMS	-0.14	0.05	1.00	0.17	-0.14	-0.
HHELPER	-0.03	0.29	0.25	1.00	0.08	0.10	HHELPER	0.22	0.28	0.17	1.00	0.04	0.
ConHOV	0.05	-0.12	-0.10	0.08	1.00	-0.05	ConHOV	0.01	-0.07	-0.14	0.04	1.00	-0.
BarHOV	0.02	-0.08	-0.04	0.10	-0.05	1.00	BarHOV	-0.02	-0.07	-0.03	0.13	-0.04	1.

4:00PM-5:00PM	DENSITY	RM	VMS	HHELPER	ConHOV	BarHOV	5:00PM-6:00PM	DENSITY	RM	VMS	HHELPER	ConHOV	Bar
DENSITY	1.00	0.02	0.10	0.12	0.03	0.02	DENSITY	1.00	-0.12	0.15	0.09	0.15	-0.
RM	0.02	1.00	-0.03	0.32	-0.27	-0.11	RM	-0.12	1.00	-0.03	0.36	-0.37	-0.
VMS	0.10	-0.03	1.00	-0.07	-0.02	-0.17	VMS	0.15	-0.03	1.00	0.10	0.07	-0.
HHELPER	0.12	0.32	-0.07	1.00	0.05	0.09	HHELPER	0.09	0.36	0.10	1.00	0.06	0.
ConHOV	0.03	-0.27	-0.02	0.05	1.00	-0.07	ConHOV	0.15	-0.37	0.07	0.06	1.00	-0.
BarHOV	0.02	-0.11	-0.17	0.09	-0.07	1.00	BarHOV	-0.02	-0.05	-0.13	0.13	-0.05	1.

Table A2. 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

Table A3: 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.