

Summary Report
Research Project T9903, Task 16
In-Vehicle Signing and Variable Speed Limit Evaluation

**SUMMARY:
TRAVELAID**

by

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16. ABSTRACT <p>This report discusses the effectiveness of using variable message signs (VMS) and in-vehicle traffic advisory systems (IVU) on a mountainous pass (Snoqualmie Pass on Interstate 90 in Washington state) for changing driver behavior. As part of this project, variable message and variable speed limit information were placed along a 61-km segment of I-90 between North Bend, Wash., and Cle Elum, Wash., where I-90 passes over the Cascade mountains through Snoqualmie Pass. The signs, which were implemented during the winter of 1997-98, provided weather and roadway information to motorists with the intention of reducing the number and severity of accidents.</p> <p>An analysis of accidents on Snoqualmie Pass was conducted with historical accident data. Several accident models were used to estimate accident frequencies severity. The report reviews the analysis of speed data over Snoqualmie Pass and reports on lane-mean speeds and deviations.</p> <p>Next, the potential users' needs for variable message information and their willingness to use in-vehicle information were assessed. A survey was distributed and analyzed to explore these questions. An econometric analysis was performed of potential speed reductions for various weather conditions. A second set of analyses was then performed on the surveys to investigate the characteristics associated with drivers who would use an in-vehicle system and those who would not use the information provided by the in-vehicle unit.</p> <p>A laboratory experiment was conducted on the use of an in-vehicle system and VMS. A driving simulator was used for this study. Mean speed and deviation from the mean speed were analyzed, as was the effectiveness of the systems over each 4.68-km (3-mile) stretch. The effect of VMS on the relationship between mean speeds and speed deviations was analyzed.</p>					
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FOREWORD

This report summarizes a 250-page report called *TravelAid* that fully documents several years of work on the TravelAid in-vehicle signing and variable speed limit evaluation for the Washington State Department of Transportation. The full report can be referenced by WSDOT WA-RD #511.1, November 2001. It can also be found at the Federal Highway Administration's ITS Joint Program Office's Electronic Document Library, www.its.dot.gov/welcome.htm or www.itsdocs.fhwa.dot.gov/jpodocs/repts_te/13610.html.

INTRODUCTION

This report examines the use of in-vehicle and out-of-vehicle information systems to provide real-time traveler information and whether better information provided to drivers while they are in their vehicles will enable them to make safer driving decisions.

As part of this project, variable message and speed limit signs were placed along the 61-kilometer segment of Interstate-90 between North Bend, Wash., (milepost 33) and Cle Elum (Easton), Wash. (milepost 71). This is where I-90 passes over the Cascade mountains through Snoqualmie Pass. This portion of I-90 is a two- to three-lane, divided freeway, with a 65 mph (104.6 km/h) speed limit. The alignment includes numerous curves and has grades of up to 5 percent. The study area is shown in Figure 1.

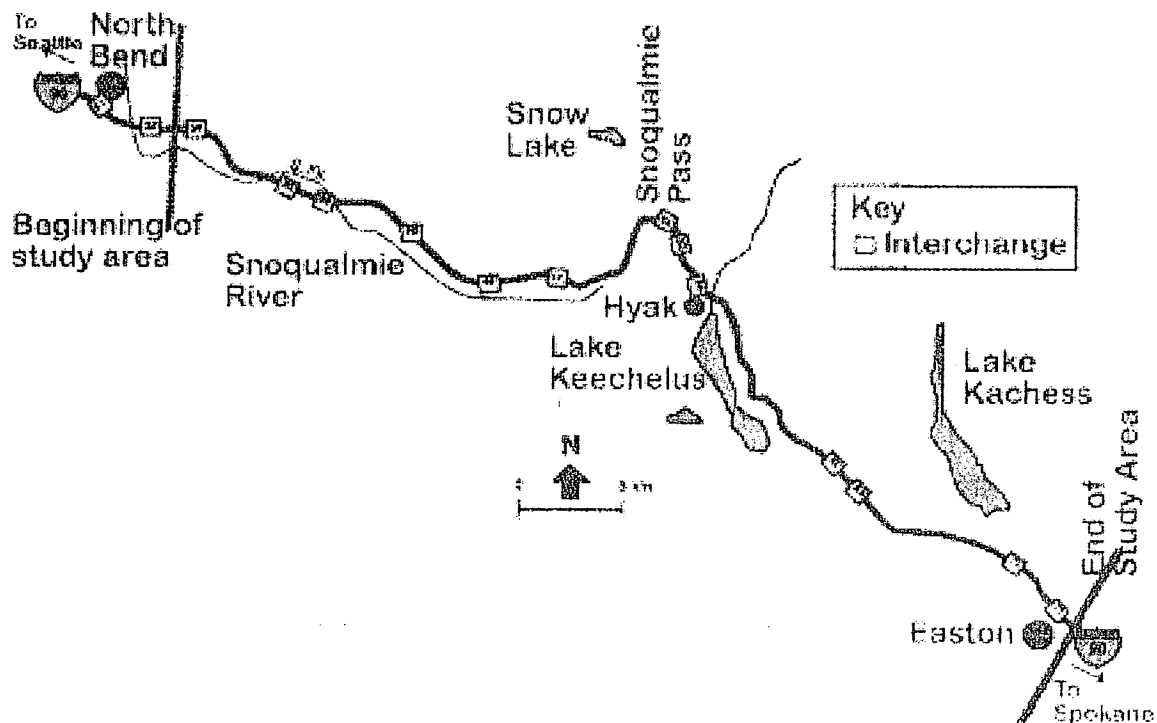


Figure 1. Study area: I-90 over Snoqualmie Pass, between North Bend, Wash., (milepost 33) and Cle Elum (Easton), Wash. (milepost 71).

The Snoqualmie Pass section of I-90 is prone to harsh weather conditions, with fog and rain in the summer and ice and snow in the winter. These conditions contribute to severe and frequent accidents. Data have shown that the number of accidents increases dramatically during the winter months because of the severe weather conditions and geometric configurations of the mountainous pass.

This project addressed the issues of driver information, speed control, and accident reduction through the deployment and analysis of in-vehicle units (IVUs), variable message signs (VMSs), and variable speed limits (VSLs).

Studies were undertaken to better understand driver behavior and performance on Snoqualmie Pass before the implementation of the TravelAid project. Accident frequencies and severities on Snoqualmie Pass and the factors that affect them were studied. The focus of these accident studies was on the non-behavioral determinants of accident risk, specifically roadway geometrics and weather conditions. Mean speed and speed deviations were also studied with loop detector data, data from a driver survey, and a driving simulator test. The simulator and survey data were also used to analyze driver behavior in the presence of the TravelAid traffic advisory systems. Finally, an in-service assessment of the impacts of VMSs on mean speeds and speed deviations was conducted. The focus of the assessment was the marginal impact of VSLs on mean speeds and speed deviations, and on the spatial transferability of relationships between speed and speed deviation with the use of ITS.

HISTORICAL ACCIDENT FREQUENCY AND SEVERITY ANALYSES

In measuring the impact of an ITS on overall vehicular safety, it is important to establish defensible safety-measurement criteria. Research has shown that the frequency and severity of accidents are two such measurement criteria.

The section of Interstate 90 shown in Figure 1.1 experiences a high number of vehicular accidents as a result of challenging roadway geometrics and adverse weather conditions. Factors that contribute to accidents include driver behavior, geometric characteristics, weather-related variables, interactions between geometrics and weather elements, and seasonal effects such as traffic volume, precipitation, and ambient temperature-related variations.

Precipitation, geometric, climatic, and accident data were collected. Accident frequencies and associated geometric and weather data were compiled along ten 3.7-mile-long (6.1-km) sections over the 37-mile study area. A total of 2,225 accidents were reported in the study area between January 1988 and May 1993.

Accident Frequency

The model produced insight into the combined effects of weather and geometric elements and significant implications for highway design standards. Current standards establish geometric design criteria on the basis of pavement-tire interactions on wet pavements. The model's findings showed that, to reduce accident likelihoods in areas that frequently experience adverse weather, design criteria should be established on the basis of more than wet pavements. Specifically, greater effort should be expended to avoid steep grades and horizontal curves with low design speeds in areas with adverse weather. Intuitively, this seems obvious, but the model provides a method of quantifying

the impacts of these geometric characteristics. For example, in the study area, eliminating all horizontal curves with a design speed of less than 60 mph (96.5 km/h) on a roadway section that experienced at least 2 in. (5.1 cm) of snowfall one or more days a month could reduce the monthly accident frequency by 47.3 percent. Although the model results were site-specific, a more global application of the approach could serve as a basis for a cost-benefit analysis that could guide geometric design policy more effectively than the current wet-pavement approach.

Accident Severity

A total of 1,505 vehicular accidents reported from between 1988 and 1993 were used in this study. The majority were property damage only accidents, but some collisions also caused fatalities, evident injuries, and disabling injuries. Variables analyzed included speed; wet, icy, and snowy pavement; curve length; fixed objects; nighttime pavement; and driver sobriety.

The study provided a framework for estimating the likelihood of accident severity conditioned on the occurrence of an accident. Analysis concluded that a nested logit model that accounts for shared unobservables between property damage and possible injury accidents provides the best structural fit for the observed distribution of accident severities. This represents an important step in the methodological evaluation of the effects of ITS on accident safety. With a probabilistic model that contains several important variables representing geometric, weather, and human factors, the ambiguity and bias stemming from confounding effects in a partially specified model are eliminated.

In addition, this research provided suggestive results by using variables such as curve-sobriety interaction and curve-pavement surface interaction. Specifically, it suggests that ITS may be an effective means of compensating for adverse design, human, and weather conditions. A well designed ITS could significantly improve the driving task in the presence of adverse factors such as alcohol, inclement weather, and complex roadway geometrics. A significant shift in the distribution of accident severities toward less severe accidents, in combination with lower accident frequencies (Shankar *et al.*, 1995), would provide a measurement for ITS success. Further research that links the severity model to models of accident severity cost is needed to assess the potential for and extent of savings in accident cost.

Post-Deployment Analysis

Analysis of post-ITS deployment data and comparison of before-and-after data were not possible because of a failure of the state's accident database from fall 1997 to the present.

HISTORICAL SPEED DATA ANALYSIS

In general, the study section of I-90 experiences significant variations in speeds because of the combined impact of vehicle mix, inclement weather, seasonal effects (e.g., variations in traffic volume, precipitation, and ambient temperatures), and challenging roadway geometrics. These speed variations significantly contribute to the likelihood and severity of accidents on this portion of I-90.

The study's intent was to develop a model of mean speeds and speed deviations (measured over some time interval) for each lane of a multilane roadway. Variations in speed were studied by using standard multiple regression techniques and by developing

speed models for different classes of vehicles. The study analyzed speed and vehicle classification data that were available from three 6-ft dual loop detectors installed by lane in the study area. These collected data in eight 10-mph speed classifications, aggregated over one hour, for four vehicle classifications (based on vehicle length). Data were collected in the fall of 1994 and the winter, spring, and summer of 1995, before the VMS were deployed.

The researchers looked at the endogenous and exogenous relationships among the variables. Endogenous variables are "determined within the system" and indicate a causal link between variables. An exogenous variable is one that is determined outside the system of equations. In other words, it is "fixed" and not affected by causal links. For example, weather is an exogenous variable in a system of speed or speed deviation equations because the relationship is not conditioned on observed weather patterns. Higher speeds will not cause more precipitation. On the other hand, higher speeds may cause lower speed deviations or higher speed deviations, suggesting an endogenous relationship.

In fact, endogenous relationships within lane speeds and between lane speeds and speed deviations were found to be statistically valid. The westbound and eastbound directions of the study site experienced dissimilar effects related to the exogenous variables of grade, time-of-day, and time-of-week characteristics. On the other hand, in large part the endogenous relationships were similar, with estimated coefficients of like sign, means, and standard errors. The findings showed that in-lane speeds are affected only by adjacent-lane speeds, and in-lane speed deviations are affected progressively by adjacent-lane speed deviations, as well as by in-lane and adjacent-lane speeds. Coupled

with findings on the contemporaneous impact of temporal and vehicle-mix factors, such inferences corroborate the need for a comprehensive investigation into lane-mean speed and lane-speed deviation relationships. Further insights could also be gained from a more diverse data set that encompassed various regions and roadway functional classes.

SURVEY STUDIES

To enable a comparison of before and after data to understand the anticipated effect of the TravelAid ITS, a survey was designed and data were collected from Snoqualmie Pass drivers during winter 1995. The questionnaire asked motorists' about a typical trip on Snoqualmie Pass, frequency of trips, driving speed, the purpose of the trip, seatbelt usage, accident information, and the source and importance of weather and roadway information. Respondents also gave their opinions about safe driving speeds in dry, wet, and icy conditions, general safety aspects of the Pass, and the use of an in-vehicle display device. They also provided information about their age, income, sex, marital status, family size, and the number of vehicles owned by the family.

General Findings

Of the 1,960 questionnaires mailed out, 444 (23 percent) were returned. People reported traveling Snoqualmie Pass for recreational purposes (39 percent), family visits (28 percent), business (21 percent), errands (3 percent), and 9 percent for other reasons.

Responses indicated that 52 percent drove at or above the posted speed limit (65 mph) in dry roadway conditions. For wet conditions, 61 percent reported driving between 55 and 65 mph. The large number of motorists driving at or near 65 mph in wet conditions suggests that motorists may be driving beyond a safe speed. For icy conditions, 93 percent indicated that they drove slower than 55 mph.

Respondents were asked which kinds of information were “very important” to them. Seventy-four percent rated roadway conditions, 66 percent rated current weather conditions, and 44 percent rated weather forecasts as very important.

Among types of roadway information, 57 percent of the respondents indicated that the presence of an incident was very important, while only 35 percent said that the type of incident and level of congestion were very important. This suggests that motorists are more interested in knowing about the presence of a problem than its details.

Highway advisory radio was the preferred source of road and weather information (44 percent), followed by commercial radio stations (23 percent)

Many respondents (92 percent) indicated that they would use an in-vehicle information device if one was provided (at no cost). However, 60 percent of those respondents indicated that if the device told them to put on tire chains, they would obey only if conditions warranted it. Thirty-seven percent said they would obey immediately. If told to slow, 56 percent would obey immediately; 42 percent would slow only if conditions warranted it.

Speed Reductions in Adverse Conditions

The questionnaire asked respondents to indicate the speed driven on Snoqualmie Pass in different weather conditions. One model determined the likelihood of speed reduction in wet conditions. A second model determined the likelihood of speed reduction in icy conditions.

This analysis uncovered many important relationships between speeds driven in wet or icy conditions and the winter driving experience, accidents, seatbelt usage, gender, age, income, purpose of the trip, passengers in the vehicle, the size of the household, the

number of working family members, and the number of cars in the household. The diversity of variables found to influence the speed driven in adverse conditions suggests that many factors play a role in a driver's choice of speeds.

The analysis also uncovered a wide diversity of speeds reportedly driven in icy conditions, and that motorists drive as fast as the law allows and pay too little attention to prevailing roadway conditions. These results may indicate the cause and severity of winter-time accidents on Snoqualmie Pass. The installation and use of variable speed-limit signs on the Pass would require motorists to drive at speeds commensurate with current conditions. This should narrow the speed differential between motorists in wet or icy conditions, thus decreasing the potential for accidents on Snoqualmie Pass and reducing their severity

The accident rates of Pass users should eventually be studied to verify that the variable speed limits are indeed safer and do reduce the number of accidents. Without enforcement by the Washington State Patrol, variable speed limits may lose their effectiveness.

Reported Driver Behavior

To validate and compare the information from the simulation studies (discussed in the next section) to drivers' perceptions, an analysis of stated preference data was conducted. The data were used to establish drivers' stated desires for and use of an in-vehicle system on Snoqualmie Pass.

Three models analyzed whether drivers would use an in-vehicle system on Snoqualmie Pass; whether they would obey the system immediately if it told them to

slow down; and whether they would obey the system immediately if it told them to put on chains.

The first model revealed that people who drove the Pass more often and people who drove faster on wet roads were more likely to use an in-vehicle system. In addition, if they reported that increasing trip safety was “important to very important” they reported being more likely to use an in-vehicle system. Drivers who placed importance on information about snow/ice accumulation and the presence of accidents or hazards were more likely to use this system. Age, income, education, and type of households also had an effect on whether the surveyed drivers wanted to use an in-vehicle system.

A second model provided insight into the characteristics associated with drivers who are willing to immediately obey an in-vehicle traffic system. Of the 432 people who responded to this question, 42.8 percent said they would slow down only if conditions warranted it, while 57.2 percent said they would slow down immediately.

A third model predicted whether drivers would put on chains immediately if the system told them to. Of the 414 people who answered this question, 61.6 percent said they would put on chains only if conditions warranted it, and 38.4 percent said they would do it immediately.

SIMULATION STUDIES

A simulation study focused on how well traffic advisory messages will help drivers avoid potentially hazardous road conditions. The use of an in-laboratory driving simulator allowed the researchers to control the driving environment and isolate the effects of speed variations, lane changes, and braking as participants made their way through a graphical representation of the Snoqualmie Pass while being provided with

information from a unit located in the driver's car and variable message signs located on the road.

Methodology

The in-vehicle system evaluated for this study was called TrafficMaster (see Figure 2). This unit provides various scenes and includes a map of the area being driven, variable speed information, and messages about road conditions (e.g., fog or incidents ahead). It is mounted on the center of the windshield above the dashboard.

A fixed-based driving simulator was used for the experiments. The simulator consisted of a Ford Escort car frame equipped with seats, steering wheel, windshield, dashboard, and brake and gas pedals. A color screen projector displayed a life-size graphical representation of the driving scene.



Figure 2: View of TrafficMaster mounted in car.

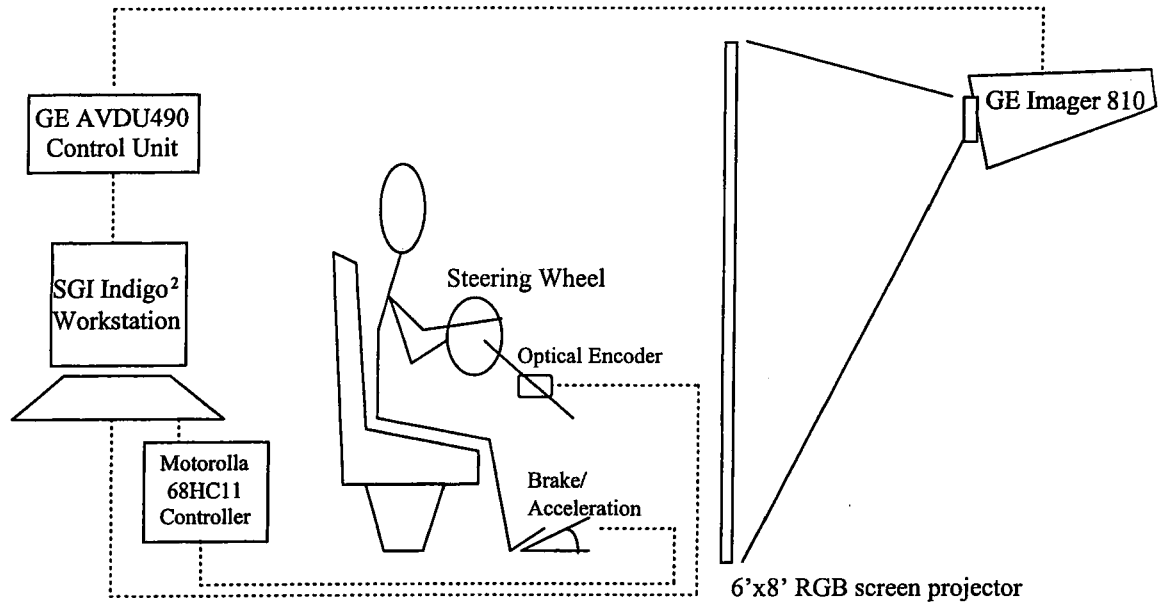


Figure 3: Driving simulator set-up.

A total of 51 subjects participated. Subjects drove through two simulation sessions. The first familiarized them with the simulator and the IVU. The second session involved a 12-mile (19.31-km) graphical representation of Snoqualmie Pass.

One of four sign conditions was randomly assigned to each subject: presence of on-road variable message signs, presence of in-vehicle message signs, presence of both on-road and in-vehicle message signs, and absence of messages (control condition).

Along their drive, participants encountered four randomized scenery conditions: clear weather conditions, clear weather conditions and a snow plow blocking one to two lanes, foggy weather conditions, and foggy weather conditions and a snow plow blocking one to two lanes.

Driving performance measures collected from the simulator experiment included lane changes, speeds, braking, position, and the time and the presence of fog.

At the end of the experiment, all subjects were given more detailed information about the IVU and asked to complete a survey on it, whether or not they had used it in the experiment.

Analysis of Mean Speed and Deviation

This study aimed to examine the mean driving speed on Snoqualmie Pass in a simulator study. The goal was to create a mathematical model that would describe mean speed and speed deviation as a function of geometric, socioeconomic, and other variables measured by the driving simulator and surveys. The presentation of information from VMSs and an IVU also allowed the researchers to analyze the effects of these different methods of information dissemination.

The study found that the speed limits set by the IVU and VMS did affect drivers. The speed limits changed depending on the scenery conditions. Drivers with only an IVU drove faster than others on the average. Drivers exposed only to VMSs drove faster than those exposed to both systems or no system in clear and foggy areas, but in snowplow sections they drove at approximately the same mean speed as those with no system. Drivers with both systems drove at the lowest mean speed. The reason for this may be that drivers who saw every message twice were more affected by the messages than those with either an IVU or the VMSs. Thus, drivers who received help from the IVU or the VMSs seem to have put some trust in the messages to warn about upcoming dangers. The IVU and VMS drivers may have had an added sense of security, suggested by the higher speeds in the areas they considered safe, i.e., sections without snowplows.

The implications for advanced traveler information systems are interesting. Erroneous messages could prove to be more dangerous than no message at all. Therefore, care must be taken in designing such systems to ensure message correctness.

This study also showed that if the traffic stream contains some vehicles with IVUs and others without any information system, the standard deviations and the speed characteristics of the two groups will be different, which could increase the risk of accidents. If all vehicles had an IVU or saw VMSs of some sort and the result was higher mean speeds, that would not necessarily be bad if the risk for accidents decreased because drivers might drive faster in safe areas but slower in unsafe areas.

Traffic Advisory Systems and Driving Behavior

For average speeds driven by subjects, no significant differences were found, regardless of whether drivers received additional information from an IVU, VMS, both, or none. However, significant differences in average speed occurred when drivers encountered fog or snowplows and for the interaction between fog and snowplows.

Tests indicated that drivers in the "no sign" condition were more willing to drive at higher speeds than drivers who received messages from both an IVU and VMSs. Differences were also observed between the maximum speeds attained under a "fog" condition and a "no fog" condition.

Market Analysis

Drivers' stated preference to use the system did not increase with usage. However, participants' overall opinions of the system were reasonably good. Subjects willing to use the TrafficMaster reported being willing to pay an average of \$136.78 for

the unit. Those who were willing to pay for a monthly service said they felt \$13.80, on average, was acceptable.

POST VMS INSTALLATION RESEARCH

One study was conducted after the installation of variable message signs (VMSs) on I-90 at Snoqualmie Pass. This study analyzed the effect of variable speed limits (VSLs) on the relationship between mean speeds and speed deviations by using a simultaneous equations approach. The relationships were examined both at a VSLs site and at a site close by but outside the influence of the VMSs for comparison.

After the deployment of the VSLs, dual magnetic loop detectors were used to collect data from late August 1997 until April 1998. Data were collected from two different locations on I-90. The main location was within the influence of the VSLs (around milepost 53), and the secondary location was further west (around milepost 47), downhill toward Seattle and outside the VSL area.

The reduction in mean speed and increase in speed deviation were significantly greater at the VSLs site than at the non-VSL site, indicating that the effect of the VSLs was to reduce mean speed and increase speed deviation. However, the effect did not extend beyond the VSL site. Therefore, the VSLs appear to have significantly reduced mean speed at the VSL site but increased speed deviations slightly. This is not surprising, since drivers can be expected to obey VSLs to different degrees, thereby increasing speed deviation.

In comparing the results at the VSL site with the results for the non-VSL site, the VSLs had little effect on either mean speed or speed deviation at the non-VSL site. The lack of significance of the VSL variable at the non-VSL site in the westbound direction

suggests that the effects of the VSLs do not last long after drivers exit the VSL area. In fact, average mean speed at the non-VSL site when a VSL was in effect was similar to the average mean speed when the speed limit was not reduced.

An important result from this study is that drivers traveled at significantly lower mean speeds at the VSL site when a VSL was in effect, but drivers' speeds at the non-VSL site were similar in both cases. This suggests compensatory driver behavior: drivers accelerated faster when exiting the VSL zone when the speed limit was reduced than when it was not. Greater acceleration exiting the zone could possibly increase accident frequency in that area or negate the safety benefits of lower mean speeds when the speed limit is reduced, and this finding warrants a separate study.

CONCLUSIONS AND RECOMMENDATIONS

Historical Data Analyses

The analysis of the historical accident data led to a general model that can be used to examine accident frequency as a function of geometric and weather-related variables. This model can be used to examine the effects of VMSs and IVUs on accident frequency by collecting accident data after these systems have been introduced and then estimating a model similar to the ones produced in this research. Such "after" data were not available for this study because of an extended failure of the state's accident database.

Such an analysis would be important because it would not test simply for differences in before and after accident frequencies but would help isolate the true causality of these differences by controlling for the complex interactions between geometrics and weather conditions. A more simplistic comparison of before and after data could easily lead to erroneous conclusions.

In addition to being able to determine whether the proposed signing system was effective at reducing accident frequencies, an analysis of changes in coefficient elasticities and the magnitudes of indicator variables would allow a more precise isolation of the effectiveness of the signing system. For example, it might allow researchers to specifically state that the signing system mitigated the adverse effects of high snowfall on grades of greater than 2 percent. Such specificity would be needed to make definitive statements regarding the ITS technologies.

The historical accident data were also used to analyze accident severity as a function of various geometric, weather, and human factors. The model can be used to examine whether VSLs lead to a significant shift toward less severe accidents by comparing data collected before and after the installation of VSLs. This can provide the basis analysis of accident cost savings with the use of the VSLs.

Speed data collected at a single site were used to examine lane mean speeds and speed deviations from the mean before the introduction of VMSs and IVUs. Relationships between lane speeds and speed deviations were found to be statistically valid. Lane speed is affected by adjacent lane speed, and lane speed deviations are affected by adjacent lane speed deviations. This research showed that this method of modeling mean speeds is promising. Future research should explore variations in the geometric, seasonal, and weather factors that may vary among sites. In addition, more microscopic data could be used to uncover dynamic effects in traffic flow. Such knowledge would be beneficial to the design and planning of advanced traffic management systems intended to improve traffic flow and safety.

Survey Analyses

To further analyze accident frequency and severity, a model of reported speed reduction under adverse weather conditions was estimated by using survey data. Survey participants reported driving at very diverse speeds under adverse conditions. One goal of installing VMSs and/or IVUs that set variable speed limits is to limit this diversity and thus increase safety.

The survey found many relationships between socioeconomic factors and reported speed reductions. One general conclusion is that drivers generally drive as fast as the law allows and give little consideration to road conditions. The variable speed limits set by the VMSs and IVUs should thus increase safety by setting the limits according to current conditions. However, this will not work if drivers believe that the variable speed limits are merely suggestions but not an enforced legal limit. Enforcement is therefore likely to play a big part in the success of variable speed limits.

The survey was also used to analyze whether drivers would use an IVU and what socioeconomic factors would contribute to that decision. The perception of conditions was found to play a big role. Drivers indicated that they would generally only obey information from IVUs if they believed that conditions warranted it, especially the command to put on chains.

Simulation Analyses

Among the studies performed on the data from the simulation experiment was the modeling of mean speed and deviation by estimating an endogenous system of equations. That study focused on the effect of geometric and socioeconomic variables on mean speed and deviation along a 12-mile stretch of a computer-simulated version of I-90 at

Snoqualmie Pass. The effects of VMSs and IVUs were also tested. The results indicate that drivers put some trust in the system and drove faster when the system did not indicate danger than drivers without a system, who had to be on the lookout themselves.

These results indicate that erroneous messages may prove to be more dangerous than no messages. Further research into the effect of inaccurate messages on drivers is therefore needed. These results also show that VSLs may increase speed deviation. This can lead to safety concerns, especially if the traffic stream comprises drivers both with and without information systems because these two groups are likely to have different speed profile, which may increase accident risk. Further research into the effect of IVUs in a mixed traffic stream is therefore necessary.

In-Service Evaluation

An in-service evaluation of VSLs on mean speeds and speed deviations showed that the endogenous relationship between mean speed and speed deviation was significant and valid under ITS. The VSLs were shown to significantly reduce mean speed, but they also significantly increased speed deviation. This increase in speed deviation could possibly increase accident frequencies in the VSL zone, thus tempering the effect of the lower mean speeds.

The effect of the VSLs was not found to be significant at a site 10 km west of the VMS site and past the end of the VSL zone. This, along with the simple aggregate results for average mean speeds and average speed deviation, suggests that drivers show compensatory behavior. That is, they accelerate more quickly beyond the VSL zone when the speed limit is reduced than when the speed limit is not reduced to compensate for their slower speed. Compensatory behavior like this could increase accident frequencies

in the area between the sites and reduce or negate the safety benefits of lower mean speeds when a reduced speed is posted. A separate study to examine this effect is necessary to fully understand the safety effects of the VSLs on I-90 at Snoqualmie Pass, Washington.