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Impact of traveler advisory systems on driving speed: some new evidence

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Abstract

This paper explores the effects of driving behavior using in-vehicle and out-of-vehicle traffic advisory information relating to adverse weather and incident conditions. A full-size, fixed-based driving simulator is used to collect data on drivers' speed behavior under four different advisory-information conditions: in-vehicle messages, out-of-vehicle messages, both types of messages, and no messages. The findings of this study suggest an interesting phenomenon in that, while messages are significant in reducing speeds in the area of adverse conditions, drivers tend to compensate for this speed reduction by increasing speeds downstream when such adverse conditions do not exist. As a result, the net safety effects of such message systems are ambiguous.

Keywords: In-vehicle information systems; Driving simulator; Variable messages

1. Introduction

Strategies to reduce the frequency and severity of accidents have included changes in highway design standards and, more recently, providing real-time information that can be used by drivers to reduce the likelihood and severity of accidents. This paper focuses on the effect that real-time, environmental/incident-hazard information (using variable message signs and in-vehicle unit advisory systems) has on mean and variance of drivers' speeds (both contributing factors to the frequency and severity of vehicle accidents).

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As a means of delivering traveler information, variable message signs have long been used to provide out-of-vehicle messages and warnings (Emmerink et al., 1996; Maxwell and Beck, 1996; Lai and Wong, 2000). However, in severe weather conditions with limited visibility, information displayed on variable message signs may be difficult to process. In such situations, in-vehicle systems are an appropriate alternative and numerous studies have evaluated the effectiveness of such systems including those of Dingus et al. (1994), Schofer et al. (1996), Dingus et al. (1999), Eby and Kostyniuk (1999), Srinivasan (1997), and Srinivasan and Jovanis (1997). In-vehicle systems evaluations have considered not only advisory information but also navigational guidance (see Dingus et al., 1994; 1997; Graham and Mitchell, 1997).

The evaluation of in- and out-of-vehicle traveler information systems is well suited to laboratory techniques that have an advantage over roadway studies because they allow the examination of parameters of interest in difficult and critical driving situations without subjecting drivers to unnecessary risks. In addition, because elements of the experiment can be controlled, the use of driving simulators to assess the impact of innovative technologies on driver behavior has become increasingly popular. Examples of applications of driving simulators to study new technologies include the work of Vaughn et al. (1994), Adler and Kalsher (1994), Wallman (1997), Ward et al. (1995) and van Winsum and Godthelp (1996). Previous simulator studies such as these provide an important backdrop for work in assessing the impact of new technologies on driver behavior.

The intent of this paper is to build on the findings of previous driving simulation studies in an effort to evaluate driver responses to adverse travel conditions and to isolate the effect of in- and out-of-vehicle media warnings of these conditions. An area of particular concern is not only the immediate effect of media warnings on speed but also downstream effects as drivers may tend to compensate for speed reductions by driving faster than they normally would. Such compensation will have serious safety implications, possibly negating the safety benefits of warning messages. [1] Our experiment and statistical analysis of speed data will be designed to uncover any such compensating effects.

2. Methodology

The driving simulation used in this study was designed to represent a section of Interstate 90 (at Snoqualmie Pass) approximately 50 km east of Seattle, Washington. This chosen highway section is on a mountainous terrain in an area known for its inclement weather (Pacific weather fronts dump their moisture while passing eastward over the Cascade mountain range) and high accident rates. Interstate 90 is the most heavily traveled east-west route in Washington State and one of the most heavily traveled east-west routes on the west coast of the United States. It is used extensively by commercial vehicle operators, recreational drivers, and commuters.

Previous research has indicated that the frequency and severity of accidents increases dramatically on this section of highway over the winter months due to a combination of severe

[1] Evidence of such compensating behavior has been provided by Peltzman (1975) with regard to vehicle safety features and by Viscusi (1984) with regard to mandated safety features on other consumer products. Their studies show significant compensating behavior on the part of consumers when safety countermeasures are imposed—virtually eliminating the safety benefits of countermeasures.

weather conditions and complex roadway geometrics. For example, Shankar et al. (1995) examined the interactions between non-behavior-related factors (i.e., roadway geometry and weather) and their relationship to accident frequency on this section of Interstate 90 using accident data from 1991 to 1994. Their findings showed that interactions among roadway grades, horizontal curves, rainfall, and snowfall significantly influence accident frequency. For accident severity, Shankar et al. (1996) estimated a nested logit model and found that adverse weather conditions and roadway geometrics such as horizontal curve-lengths and the number of horizontal curves per kilometer of roadway significantly affected the severity of accidents.

To study the possible safety impacts of messaging media, our focus is on driving speed and variance of speed, both of which have long been shown to be related to the frequency and severity of accidents (Carson and Mannering, 2001; Lee and Mannering, 2002). In studying speed, we will account for the effects that were previously found to influence the frequency and severity of accidents on this section of Interstate 90 (i.e., geometrics and weather) while isolating the effects of advisory messages. This is accomplished with a full-size driving simulator, which is used to establish a realistic setting for collecting data from drivers. The computer-generated driving scenes were fully interactive with the driver and the simulations gathered data on a number of driving performance measures including lane changes, speeds, and brake use.

The experimental approach used was broadly similar to that followed by previous researchers (Liu and Chang, 1995; Ford Motor Company, 1994). A total of 51 subjects ranging in age from 16 to 70 years participated in the study, which gives at least 12 subjects for each of the four signing conditions considered (no signing, out-of-vehicle signing only, in-vehicle-signing only, and in- and out-of-vehicle signing). [2] Participants were required to have previously driven over the study area (the section of Interstate 90 being studied) to qualify for the driving experiment because the intent of the study was to focus on users that are familiar with driving conditions in this area. Subjects were volunteers and recruited from the Puget Sound area of Washington State.

The study was designed to evaluate visual sensory feedback rather than the tactile sensory feedback. For that reason, the simulator emphasized visual information along with auditory beeps from the in-vehicle unit system being tested.

The driving simulator consisted of a Ford Escort car frame equipped with seats, steering wheel, windshield, dashboard, brake and gas pedals. A computer mouse was attached to the steering wheel and provided feedback to a Silicon Graphics Image (SGI) workstation giving vehicle location in the simulated image. A driving software program written in C++ provided the simulation images presented to the driver. Graphic visualization was provided with a 2.6-m by 1.9-m projection screen, with ceiling-mounted graphics projector and control unit. The graphic images were situated in front of the car in such a way as to have the driver feel immersed in the driving environment with a 60° field of view. [3] A micro-controller, connected to the SGI workstation, was

[2] This is consistent with other simulator studies on driving behavior (12 subjects per cluster in Wallman (1997) and Ranney et al. (2000), and 7 to 12 subjects per cluster in Deery and Fildes (1999)).

[3] This range of vision is used because it has been shown that a person's binocular field of view, or field of view seen with both eyes fixed at a central location, in this case, the back-lit projection screen, is 60° (NHTSA, 1987). This is also consistent with driving simulator studies conducted by Mollenhauer et al. (1995), van Winsum and Godthelp (1996), and Adams et al. (1995) where driving behavior in a simulator was analyzed for HUD use (50° field of view), for curved road driving (50° field of view), and for obstacle avoidance maneuvers (30° field of view), respectively.

used to provide digital readings of vehicle acceleration and deceleration information on driving speed and vehicle position with respect to the road was recorded every second. The in-vehicle unit used in the study provided a map of the area being driven, variable speed information, and variable messages on road conditions (e.g., fog ahead). This unit was mounted on the center of the windshield, directly above the dashboard.

3. Experimental procedure

Each subject was given a list of instructions and then drove through two simulation sessions. The first session encompassed an 8-km loop that was used to familiarize subjects with simulator configurations (braking, steering, and accelerating) and use of the in-vehicle unit. After a brief rest period, the second session was started. This session consisted of a 20-km graphical representation of an eastbound section of Interstate 90. A section of only 20-km was used in the simulation to avoid the possibility of simulator sickness that may occur in subjects (see Kolasinski et al., 1995). This entire roadway section consists of three 3.6-m wide lanes with 3.4-m shoulders (on both sides of the roadway) and a series of horizontal and vertical curves that are used to traverse the mountainous terrain. The terrain is such that there were no straight road sections longer than 500 m. Speed limit signs indicated a maximum speed of 105 km/h (65 mph).

One of four sign conditions (variable message sign only, in-vehicle unit only, both variable message signs and in-vehicle unit, and none) was randomly assigned to each subject. For each sign condition, two types of weather conditions (fog and no fog) and two types of incidents (presence of snowplows and no snowplows) were incorporated. These weather/incident conditions varied every 5 km and each subject was randomly assigned one of four different orders of weather/incident presentations.

The driving program provided a standard fog function which allowed the visibility distance to be set at any desired value. The closer an object was to the eye, the less fog was applied and the more visible an object became. Using National Oceanic and Atmospheric Administration (NOAA) standards that designate fog as visibility, due to mist, <1 km (NOAA, 1998), the fog condition in the simulation began with a gradual reduction in visibility until the driver could not see past 1 km.

Fog was in view during one-half of the simulation run and designed such that some subjects started in fog while others started without fog. The pattern of fog and no fog did not change systematically—the order of presentation of the weather and incident type was counterbalanced using a Latin Square to reduce ordering effects and to minimize the effects of learning or pattern anticipations. The weather conditions chosen for each subject were randomly assigned and subjects were not told what order of presentation they were to receive.

Snowplows were represented by slow moving vehicles and occupied two of the three lanes. Two snowplows were present in each 5-km segment that was classified as a snowplow condition. As in the fog condition, the order of presentation of the incident type was counterbalanced using a Latin Square to reduce ordering effects.

The information displayed on the variable message signs (VMS) in the simulator scenes was identical to the VMS currently in use in the study area. There were three main messages viewed by the participants at various times for the VMS condition: fog ahead—slow down 45 mph

(72.6 km/h), curvy road—drive slowly, and snowplow ahead—slow down 35 mph (56.5 km/h). The VMS signs had a black background with amber color lettering and two lines of text. For the VMS condition, a total of eight messages were presented to each subject, 2.5 km apart.

Participants using the in-vehicle unit (IVU) were given additional instructions on the use of the in-vehicle unit. The system is equipped with a 100-mm diagonal liquid crystal display screen. Messages for the IVU were remotely activated and, the same eight messages and frequency of messages were given to both VMS and IVU conditions. [4]

4. Summary statistics

Several categories of information were collected from the 51 subjects participating in this experiment including computer data generated from the simulation run, information regarding their driving preferences over the simulated section of Interstate 90, and their socioeconomic characteristics.

Subjects' typical Interstate 90 socioeconomic characteristics were obtained from a survey given to subjects after the simulation portion of the experiment (see Table 1). The mean number of occupants (normally in the vehicle when they actually traveled over the studied section of highway) was 2.08 persons. As expected, subject-reported driving speeds on icy roads were reported to be lower than that of driving speeds on wet roads and speeds on dry roads were reported to be higher than speeds on icy or wet roads. It is also noteworthy the 15 females and 36 males ranged in age from 16 to 70 years. The percentage of males in this study is representative of that observed on this section of highway.

The average speed driven by subjects in the simulator was 85.63 km/h. In terms of differences observed for weather conditions, the average speed driven under the no-fog condition was 91.55 km/h (standard deviation = 16.44 km/h), and 79.71 km/h (standard deviation = 17.52 km/h) in the fog condition. When snowplows were present the average driving speed for subjects was 82.85 km/h (standard deviation = 18.00 km/h) as opposed to 88.41 km/h (standard deviation = 17.51 km/h) for segments where snowplows were not present.

5. Analysis of variance

Analysis of variance (ANOVA) techniques are appropriate in comparing multiple means of treatment combinations whose responses are normally and independently distributed. This method is suitable for testing whether there are any differences among groups (or treatment combinations) with a single probability associated with the test (Cody and Smith, 1997).

[4] Note that the objective of the study was not to look at false positive or false negative issues with respect to system information but to determine if information, assumed to be accurate, is effective in changing driver behavior. The simulator controlled for this effect by transmitting the same messages in each medium (i.e., VMS or in-vehicle) to each driver. Because all factors were controlled (i.e., weather, roadway, messages, and vehicle), any effects due to changes in the medium could be identified.

Table 1
Driving and socioeconomic characteristics of experiment participants (standard deviations in parentheses)

Variable	
Mean number of people typically in-vehicle while driving over the section of Interstate 90 used in the driving simulator	2.08 (0.88)
Mean driving speed in dry-road conditions while driving over the section of Interstate 90 used in the driving simulator	111.09 km/h (14.70 km/h)
Mean driving speed in wet-road conditions while driving over the section of Interstate 90 used in the driving simulator	96.28 km/h (15.13 km/h)
Mean driving speed in icy-road conditions while driving over the section of Interstate 90 used in the driving simulator	66.67 km/h (16.42 km/h)
Mean age in years	33.49 (14.08)
Annual household income	$34,800 ($24,317)
Gender (percent male/female)	70.6/29.4
Marital Status (percent married/single/divorced/other)	29.4/60.8/7.8/2.0
Educational level (percent some high school/high school diploma/technical–vocational/college degree/post graduate degree)	7.8/13.7/9.8/43.1/25.5
Seat belt usage (percent all the time/most of the time/some of the time)	82.3/15.7/2.0
Mean number of individuals in household	2.45 (1.31)
Mean number of licensed and operable vehicles	1.84 (1.07)
Primary driving purpose while driving over the section of Interstate 90 used in the driving simulator: percent recreation/visit family/business/errands/other	76/16/4/2/2

The independent variables for this design included sign condition (four levels; IVU, VMS, both, and none), incident type (two levels; snowplow and no snowplow), and weather type (two levels; fog and no fog). Each subject drove through weather and incident types (the within-subjects effect) for a randomly assigned sign condition (the between-subject effect), giving a repeated-measures design. This experimental design is also referred to as a special case of a nested-factorial experiment (Hicks, 1993). Given that each subject went through one complete set of simulation tests before the next subject could go through the simulator, a restriction on randomization was identified and accounted for in the ANOVA model. Further, the within-subjects factors were counterbalanced using a Latin Square to reduce order effects. [5] The criterion for significance was set at $p < 0.05$, but lower p levels were recorded. Power of the main effects were greater than 0.80 and were computed using Cohen's power tables and calculations for fixed main effects in complex design (Cohen, 1988). As indicated by Winer (1971), this is adequate power to detect significant findings.

We first consider differences that may exist for the four sign conditions under different weather/incident conditions. For each weather/incident condition, the average speed, standard deviation of the average speed, maximum speed, and minimum speed over 5-km roadway segments were considered. These were determined using the speed data that were recorded at 1-s intervals.

The overall mean speeds for each cell in the nested-factorial model are shown in Table 2. The ANOVA results show that there were no significant differences in the average speeds driven by subjects whether they were provided additional information on an in-vehicle unit, variable

[5] Details of this technique are covered in experimental design texts such as Kirk (1982), Hicks (1993), and, Shaughnessy and Zechmeister (1994).

Table 2
Mean speeds (standard deviation) for each treatment combination in km/h

Condition	No fog		Fog	
	No snowplows	Snowplows	No snowplows	Snowplows
Both	87.5 (15.3)	76.2 (13.5)	74.5 (11.4)	70.4 (15.0)
IVU	98.1 (18.3)	92.7 (17.1)	82.7 (20.4)	79.0 (20.3)
VMS	97.2 (10.9)	90.1 (10.6)	82.1 (10.3)	77.8 (12.9)
None	97.7 (15.9)	91.1 (19.2)	86.2 (20.7)	83.7 (21.9)

message sign, both or none ($F(3,47) = 1.77$, $p > 0.05$). There were, however, significant differences in the average speed when encountering fog ($F(1,47) = 46.87$, $p < 0.01$), snowplows ($F(1,47) = 61.75$, $p < 0.01$), and for the two-way interaction between fog and snowplows ($F(1,47) = 7.03$, $p < 0.05$). As shown in Fig. 1, the mean speeds were higher in clear conditions than when fog and snowplows were present.

In terms of the variation among speeds (standard deviation), there were also no significant differences found among the four sign conditions over the 5-km segments ($F(3,47) = 0.49$, $p > 0.05$). There were differences observed for snowplows ($F(1,47) = 57.61$, $p < 0.01$), and the two-way interactions between snowplow and fog ($F(1,47) = 8.61$, $p < 0.01$). These significant findings are depicted graphically in Fig. 2.

For the minimum speeds driven by subjects, in any given roadway segment, there were no significant differences found among the four sign conditions ($F(3,47) = 1.01$, $p > 0.05$). There were significant differences observed in minimum speeds for foggy conditions ($F(1,47) = 9.35$, $p < 0.01$), and given the presence of snowplows ($F(1,47) = 36.63$, $p < 0.01$). However, there were no significant differences in interactions with snowplows and fog. Fig. 3 presents the overall minimum speeds driven by subjects in each weather/incident condition for each type. This figure shows, as expected, that subjects drove faster in clear conditions than in other weather/incident conditions.

For maximum speeds attained by drivers, there were differences found among the sign conditions ($F(3,47) = 2.41$, $p < 0.10$). The Duncan Multiple Range Test indicated that drivers under the no-sign condition (mean = 116.33 km/h) were more likely to have higher maximum speeds than drivers who were given both messages (IVU and VMS) (mean = 102.64 km/h). There were also differences observed between maximum speeds in fog conditions and no-fog conditions ($F(1,47) = 32.70$, $p < 0.01$) and this is shown in Fig. 4.

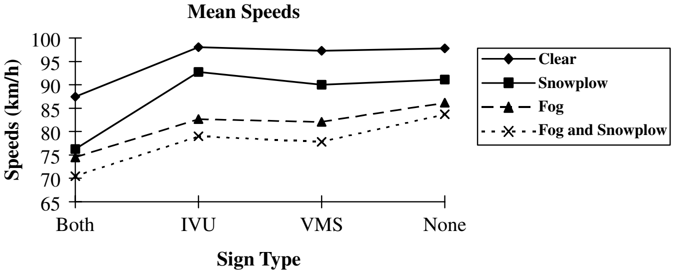

Fig. 1. Mean speeds of the four sign conditions in each weather/incident factor.

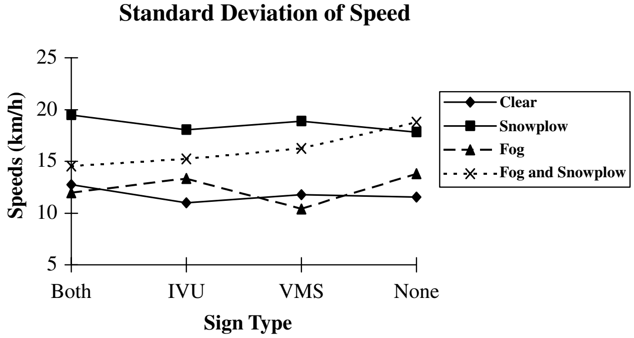

Fig. 2. Standard deviation of the four sign conditions in each weather/incident factor.

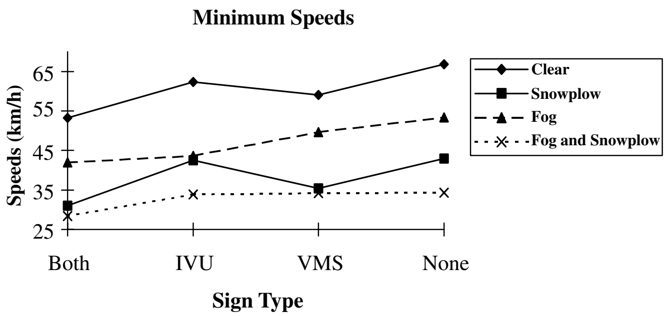

Fig. 3. Overall minimum speeds driven by subjects in each weather/incident condition for each sign type.

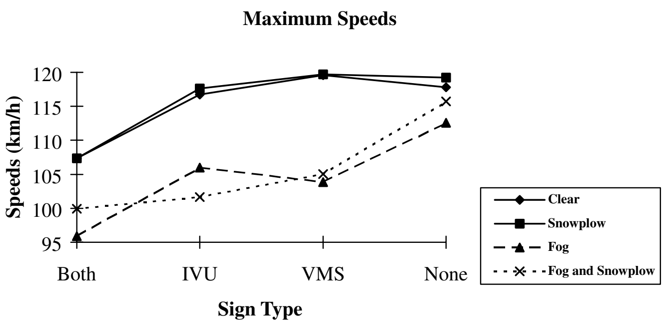

Fig. 4. Overall maximum speeds driven by subjects in each weather/incident conditions for each sign type.

The finding that advisory message media did not significantly affect mean speed and standard deviation appears to contradict the findings of some previous research. For example, Alm and Nilsson (2000) found that both VMS and IVU incident warning systems caused drivers to reduce their speeds. A likely reason that this was not observed in our ANOVA analysis is that compensating effects over the 5-km segments may be masking driver responses to messages. That is, drivers may be slowing down at the instant a message is presented, but then increasing their speed to compensate for the slow down once they feel there is no longer a need to maintain a low speed. To investigate this compensating behavior, we study mean speeds and speed deviations on shorter, 1-km road lengths.

6. Estimation of drivers mean speed and standard deviation

Because mean speeds affect speed deviations and speed deviations affect mean speed, a simultaneous equations system is appropriate (Ulfarsson, 1997; Shankar and Mannering, 1998). Such an equation system, for each 1-km speed observation, can be written as,

$$u = \beta_1 + \alpha_1 \mathbf{X}_1 + \phi_1 \sigma + \varepsilon_1$$
$$\sigma = \beta_2 + \alpha_2 \mathbf{X}_2 + \phi_2 u + \varepsilon_2$$

where u is the mean speed for each driver in a 1-km segment, and σ is the standard deviation of the speed over the segment. Speed and standard deviation are interrelated endogenous variables, $\mathbf{X}_1$ and $\mathbf{X}_2$ are vectors of roadway, environmental, information, and subject characteristics, β_1, β_2, ϕ_1, ϕ_2 are estimable scalars, α_1, and α_2 are estimable vectors, and ε_1, and ε_2 are normally distributed disturbance terms.

Because ordinary least squares estimation of this equation system will produce biased and inconsistent coefficient estimates due to correlation between endogenous right-side variables (i.e., mean speed and standard deviation of speed) and the equation's disturbance term (Geraci, 1987; Washington et al., 2003; Greene, 1993; Mannering, 1998), three-stage least squares (3SLS) is used. Three-stage least squares generates coefficient estimates that are generally more efficient (asymptotically) than alternative simultaneous-equation estimation approaches such as two-stage least squares (2SLS), and limited-information maximum likelihood (LIML). [6] The 3SLS estimation procedure first calculates instruments for endogenous variables (mean speed and speed deviation) by regressing against all exogenous variables. These instruments are then regressed to estimate the contemporaneous variance–covariance matrix of disturbances (i.e., the relationship between ε_1, and ε_2). Using this matrix, generalized least squares (GLS) is applied to estimate model coefficients. See Greene (1993) for a complete description of this procedure. [7]

Table 3 gives estimation results for the mean-speed equation. This table shows that the standard deviation of mean speed had a negative effect on mean speed indicating that drivers with a

[6] An alternative estimation approach is full-information maximum likelihood (FIML), but the asymptotic variance–covariance matrices of FIML and 3SLS are equal, so there is no theoretical basis for selecting one approach over the other.

[7] Another estimation concern is the fact that we are using repeat observations from individuals (i.e., depending on the usability of the data, each subject can generate as many as 20 observations, one observation for each 1-km section of roadway). This sets up the possibility of disturbance term correlation across observations that could affect the efficiency of the coefficient estimates. Empirical studies have shown that the effect on efficiency is generally small (see Mannering and Winston, 1991, 1995). To test this, we used random number sub-samples that reduced the number of repeat observations from each individual. As expected, the smaller estimation sample size resulted in an increase in standard errors (3SLS estimates are consistent so larger sample sizes will reduce standard errors) but in all tested cases the estimation results were not significantly affected (the same variables were found to be significant in the sub-samples).

Table 3
Three-stage least squares estimation of the spot mean speed (in km/h)[a]

Variable	Estimated coefficient	t-Statistic
Constant	28.84	8.58
Standard deviation of mean speed (km/h)	−1.82	−19.61
One kilometer lag in spot mean speed (km/h)	0.623	25.48
One kilometer lag in standard deviation of mean speed	0.563	7.45
Fog-ahead message indicator (1 if driver encountered "Fog ahead slow down 45 mph" sign in VMS only condition, 0 otherwise)	−6.68	−3.20
Curvy road message indicator (1 if driver encountered "Curvy Road Drive Safely" message in IVU only condition, 0 otherwise)	6.01	3.08
Fog indicator (1 if fog was present in the 1-km section, 0 otherwise)	−2.34	−3.88
Fog indicator (1 if driver started simulation in a foggy section, 0 otherwise)	1.65	2.95
Vertical curve indicator (1 if section has vertical curves with grades greater than 4%, 0 otherwise)	−2.53	−3.25
Reported speed on Snoqualmie Pass in icy weather	0.257	5.91
Reported speed on Snoqualmie Pass in dry weather	0.164	3.86
Trip indicator (1 if typically go over Snoqualmie pass for family reasons and had IVU condition in simulator, 0 otherwise)	−4.96	−3.00
Trip indicator (1 if typically go over Snoqualmie Pass for family reasons and had VMS condition in simulator, 0 otherwise)	−2.14	−2.17
Education indicator (1 if college educated driver with the IVU condition in simulator, 0 otherwise)	−9.53	−9.34
Car indicator (1 if household has only one car, 0 otherwise)	−3.56	−4.26
Income (in thousands of dollars per year)	−0.066	−3.98
Male driver (1 if male, 0 if female)	2.87	4.00
Number of observations		881
R^2		0.64
Corrected R^2		0.63

[a] This is the mean of drivers' spot speeds (recorded every second) over a 1-km section of roadway.

high variation in speed were more likely to have lower mean speeds for that 1-km section. As suspected, the lag in speed had a positive effect on the current speed indicating that if the speed in the previous section was high/low, the speed in the next section was more likely to be high/low as well. This captures habitual behavior with those driving at high/low speeds likely to continue to drive at higher/lower speeds.

Model estimation results also show the impact of the standard deviation from the previous section. If this variable was high, the mean speed in the current section is more likely to be high as well. This provides evidence of compensating behavior (driving faster to compensate for earlier slow-downs).

Results show that the speeds were impacted by messages presented by the in-vehicle and out-of-vehicle systems. Drivers who encountered a VMS message that stated "fog ahead—slow down 45 mph" were more likely to slow down. When drivers in the IVU only condition encountered a message stating "curvy road drive safely," they were more likely to increase speed. Thus, drivers knowing that there was no threat of low visibility or road impediments, tended to drive faster than they normally would (recall that the entire study consisted of curvy roads so this did not present an unexpected hazard). This finding provides additional evidence that drivers may be exhibiting compensating behavior.

In support of the ANOVA findings, the 3SLS estimates also revealed that weather had a significant impact on drivers' speed (if a 1-km section was in the fog, drivers tended to drive slower). However, if the overall 20-km driving simulation began in the fog, drivers tended to drive faster. This is some supporting evidence of compensating behavior as subjects drive faster after a slow start in fog conditions to compensate for the fog slow-down.

Segments with steep vertical alignments created conditions that significantly decreased the likelihood of driving fast. This was expected because of lower vehicle acceleration on grades and lower driver confidence about the ability to decelerate on steep grades. Those drivers that indicated that they normally drive faster in icy conditions and in dry conditions also tended to drive faster in the simulator. This supports consistency between the simulator and actual driving behavior (if they normally drive faster than others do in actual road conditions, they tended to drive faster than others do in the simulator). As noted by Kaptein et al. (1996) and Riemersma et al. (1990), while the absolute speed used by drivers in simulators is not necessarily the same as the speed a driver would select in reality, the relative change in speeds is likely to be similar.

There were also socioeconomic impacts relating to this model. College educated drivers using the IVU in the simulator tended to drive slower. Those drivers who had the IVU condition or the VMS condition and who typically drove over the pass for family-related reasons tended to drive slower. Drivers with only one car per household tended to drive slower as did drivers who have higher incomes. Male drivers were more likely to drive fast, a finding supported by previous work by DeJoy (1992) and others.

Table 4 presents the 3SLS estimation results for the standard deviation portion of the equation system. These results show that those who drive at high speeds were more likely to have lower variations in speeds. Also, if their speeds were higher in one section, their change in speed tended to be higher in the very next section. This is likely a reflection of frequently changing conditions (geometric and scenic) that make it difficult to drive at consistently high speeds. Likewise, if drivers' standard deviation is high in the previous section, their standard deviation is also high in the next section, which likely reflects persistent driving habits.

The estimation of the standard deviation of mean speeds reveals that deviations in speeds were impacted by messages from both types of traveler information systems (i.e., IVU and VMS). Drivers receiving messages on curvy roads for a particular section were more likely to have larger changes in speeds, which is consistent with the earlier finding that showed that drivers who viewed the curvy road message were more likely to increase speed (indicating that the standard deviation would be more dramatic to achieve the desired speeds). When the fog-ahead message was encountered, drivers were more likely to maintain a consistent speed. The fog-ahead message was frequently viewed while drivers were immersed in fog because a fog section typically encompassed more than a single 1-km segment. Thus, this finding is quite feasible because receiving this message informs drivers of the continual impairment in visibility and results in drivers maintaining a stable driving speed.

Drivers who were given information on snowplows ahead were provided this information in the 1-km section previous to encountering snowplows. Drivers who viewed this message, whether it was encountered in the VMS condition, IVU condition, or both, were more likely to have larger deviations in speeds. Consistent with this finding is the impact of the snowplow indicator variable.

Table 4
Three-stage least squares estimation of the standard deviation of spot speeds (in km/h)[a]

Variable	Estimated coefficient	t-Statistic
Constant	13.40	12.17
Mean speed (km/h)	−0.298	−13.84
One kilometer lag in mean speed (km/h)	0.202	11.51
One kilometer lag in standard deviation (km/h)	0.283	10.02
Curvy road message indicator (1 if encountered "curvy road drive slowly" message in IVU only condition, 0 otherwise)	2.15	2.66
Foggy message indicator (1 if encountered "fog ahead slow down 45 mph" sign in VMS only condition, 0 otherwise)	−2.02	−2.39
Snowplow message indicator (1 if encountered "snowplow ahead: slow down 35 mph" message in IVU only condition, 0 otherwise)	1.33	1.69
Snowplow message indicator (1 if encountered "snowplow ahead, slow down 35 mph" sign in VMS only condition, 0 otherwise)	3.33	4.64
Snowplow message indicator (1 if encountered "snowplow ahead" messages in both IVU and VMS condition, 0 otherwise)	3.41	3.54
Snowplow indicator (1 if encountered snowplows in section, 0 otherwise)	3.94	8.40
Snowplow message indicator (1 if encountered a snowplow warning message within first 2.5 km of simulation, 0 otherwise)	−3.52	−3.93
Alert signal indicator (1 if encountered a beep in the 1-km segment prompted by a new IVU message in simulation, 0 otherwise)	0.827	1.78
Vertical curve indicator (1 if section has vertical curves with grades greater than 4%, 0 otherwise)	−0.588	−1.85
Reported driving speed in icy conditions	0.0788	4.43
Family/IVU indicator (1 if Snoqualmie trip purpose family oriented and used IVU in simulator, 0 otherwise)	−2.44	−3.83
Car indicator (1 if household owns only one car)	−1.39	−4.29
Income (in thousands of dollars per year)	−0.0219	−3.28
Education indicator (1 if college educated driver using IVU in simulator)	−3.13	−8.04
Number of observations		881
R^2		0.31
Corrected R^2		0.30

[a] This is the standard deviation of spot speeds (recorded every second) over a 1-km section of roadway.

This variable shows that if a snowplow was in a particular section, regardless of whether or not a driver received a message, drivers were more likely to have a higher standard deviation. Interestingly, if the snowplow message was presented to the driver within the first 2.5 km, the increase in standard deviation was less and even decreased for the IVU only condition (this results from having two snowplow-indicator variables active; one of the standard ones that all increase standard deviation, at various levels, depending on signing condition, and snowplow-in-first-2.5-km indicator that decreases standard deviation). This may be an artifact of the simulation in that comfortable speeds may not have been established for those few drivers that encountered a snowplow early in the simulation.

Drivers in one of the two IVU conditions (IVU only or IVU and VMS) heard an alert signal (beep) only when a unique message was displayed. If the next message was identical to the previous message, no beep was heard. Drivers who heard this beep were more likely to have a larger deviation in speed. This shows the change in speeds due to the anticipation of a new message and indicates that auditory cues had a significant impact on drivers. Finally, all the socioeconomic characteristics incorporated in the model (i.e., family purpose indicator, car indicator, income, and education) produced negative coefficients (i.e., they decreased the deviation in mean speeds). [8]

7. Summary and conclusions

The purpose of this study was to examine driver behavior with in-vehicle and out-of-vehicle information systems. Use of a driving simulator provided the ability to control variables not normally controlled in actual road conditions, such as weather and the number of cars on the road, and this allowed us to isolate the variables affecting speed behavior. Four sign conditions (VMS, IVU, both, and none), two weather conditions (fog, and no fog) and two incident conditions (snowplows, and no snowplows) were analyzed with regard to drivers' speed. The expectation was that information displayed on messaging media would help drivers avoid collisions and other hazardous situations and that this would be reflected in their speed behavior.

The ANOVA results show that over longer roadway segments there was no significant difference in the mean speed and the standard deviation of speed. The 3SLS analysis suggests that differences in the information systems existed only for the section that the message is presented to the driver. Once the message is out of range or no longer valid, drivers tend to compensate by driving faster to make up for the lost time when they had previously been warned to slow down. This phenomenon has obvious safety implications in that warning systems could increase the standard deviation of speeds down stream to such an extent as to negate the positive safety effects in the area of the environmental or incident hazard.

There are several areas for further research. While this and other studies have suggested that driver behavior can be changed with appropriate travel information, there is a continuing need on how to best tailor this information while realizing that providing too much information could result in information overload. Most importantly, our finding that drivers tend to compensate for slow downs by driving faster after the slow-down has significant safety implications that need to be explored further in additional simulation and field studies.

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[8] It is interesting that driver age was one of the other variables tested but not found to be statistically significant. This may be surprising to readers since other studies have shown that age was a significant determinant for various driving maneuvers (Szlyk, 1995; Staplin, 1995; Cox et al., 1999). It is speculated that age-related effects are being captured by other socioeconomic variables such as income and education.

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