Risk Evaluation for In-vehicle Sign Information

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May 2016

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Technical Report Documentation Page

1. Report No. MN/RC 2016-18	2.	3. Recipients Accession No.
4. Title and Subtitle Risk evaluation for in-vehicle sign information		5. Report Date May 2016
		6.
7. Author(s) Erik J. Schlicht & Nichole L. Morris		8. Performing Organization Report No.
9. Performing Organization Name and Address Department of Mechanical Engineering HumanFIRST Program University of Minnesota 111 Church Street SE Minneapolis, MN 55455		10. Project/Task/Work Unit No. CTS #2015018
		11. Contract (C) or Grant (G) No. (c) 99008 (wo) 145
12. Sponsoring Organization Name and Address Minnesota Department of Transportation Research Services & Library 395 John Ireland Boulevard, MS 330 St. Paul, Minnesota 55155-1899		13. Type of Report and Period Covered Final Report
		14. Sponsoring Agency Code
15. Supplementary Notes http://www.lrrb.org/pdf/201618.pdf		

16. Abstract (Limit: 250 words)

The goal of the study was to examine the influence of in-vehicle signing (IVS) pertaining to four types of changing driving conditions and determine the utility and potential safety costs associated with the IVS information. Signage displayed on a personal navigation device was presented for specific zones within the simulation to assist drivers' preparation for transitioning to new driving conditions ahead. These zones included: speed zone changes within the same roadway, notification of school zones, notification of work zones, and notification of curves. Driving performance measures known to be related to distraction as well as subjective usability and workload measures were used to help identify potential distraction associated with the IVS information. Moreover, risk analysis was conducted to evaluate the safety associated with IVS technology compared to the known safety levels with standard roadside signage. The objective measures collected in this study (both driving performance and risk analysis) indicated that implementing IVS technology would impact driving performance in the following manner:

- When IVS was deployed in the absence of external signs, speeding behavior significantly increased relative to baseline levels. IVS technology was not observed to impact speeding behavior when external signs were also present.
- Risk analysis suggested that IVS technology (when used in conjunction with external signs) can improve the safety associated with frontal-impact crashes; however, risk analysis proved that safety across all crash types was significantly reduced below baseline levels when IVS was used without external signs.

Moreover, subjective usability results reinforced the driving performance findings.

17. Document Analysis/Descriptors driver information systems, risk analysis, speeding, safety, simulation		18. Availability Statement No restrictions. Document available from: National Technical Information Services, Alexandria, Virginia 22312
19. Security Class (this report) Unclassified	20. Security Class (this page) Unclassified	21. No. of Pages 48	22. Price

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Final Report

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May 2016

ACKNOWLEDGMENTS

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EXECUTIVE SUMMARY

The Minnesota Department of Transportation (MnDOT) conducted a demonstration project as part of the Connected Vehicles Program to design, build, and test three new software applications to run on a commercially available personal navigation device (PND). The three applications that run on the PND (e.g., TomTom or phone running Android) use global positioning satellite (GPS) technology to:

- Calculate and present mileage based user fees (MBUF) for the road on which a driver is traveling and an accumulated bill
- Present in-vehicle signing (IVS) to drivers about specific zones they encounter (e.g., construction)
- Present traveler information using probe vehicle data which will allow information to pass between vehicles and the infrastructure and allow drivers to see travel time information

The overall goals of the larger project, entitled Minnesota Road Fee Test, were to:

- Develop and validate the functionality of each vehicle acting as a probe and providing information to a central location
- Provide route-specific traveler information to vehicles
- Demonstrate the technical feasibility of a MBUF component,
- Identify drivers' opinions about the MBUF component and to identify the reaction to this component by the general public
- Demonstrate the feasibility of delivering time-specific safety and warning messages on an in-vehicle display

The goal of the study described in this report was to examine the IVS function for four zones and determine the utility and potential distraction associated with the IVS information. The specific zones of interest that were signed on the PND in this study were areas where speed zone changes occurred along the same roadway, notification of school zones, notification of construction zones, and notification of curves to assist drivers with preparing for transitions to new driving situations. Driving performance measures known to be related to distraction as well as subjective usability and workload measures were used to help identify potential distraction associated with the IVS information. Moreover, risk analysis was conducted to evaluate the safety associated with IVS technology, relative to status-quo safety levels.

Forty participants (balanced for gender and across age groups) completed the study and were divided into two IVS conditions. The first IVS condition included the IVS information in addition to external (roadside) sign information (IVS +ES). The second IVS condition included only the IVS information, in the absence of external signs (IVS -ES). All information was displayed using an Android phone mounted on the center console of the vehicle within the driver's view (i.e., in the same location where a manufacturer-installed navigation screen and controls would be located). A simulated driving route was developed in the HumanFIRST simulator using a real roadway network from southern Minnesota. Drivers in each condition drove the 24-mile-long simulated route that included freeway driving, two-lane rural road driving, and town driving with and without the PND system information activated. Baseline data

was collected regarding all participants' driving behavior when they drove the typical route with signage presented roadside and no IVS information displayed. Driving performance measures related to distraction (i.e., speed and lateral control) were collected during the drive. Participants also completed a series of usability questionnaires, as well as subjective measures of mental workload, for each of the driving conditions.

The objective measures collected in this study (i.e., both driving performance and risk analysis) indicated that IVS technology would impact driving performance in the following manner:

- When IVS is deployed in the absence of external sign information (IVS -ES), speeding behavior significantly increased relative to baseline levels. IVS technology was not observed to impact speeding behavior when external signs were also present (IVS +ES), however.
- Risk analysis suggested that IVS technology (when used in conjunction with external signs) can improve the safety associated with frontal-impact crashes; however, the risk analysis demonstrated that safety across all crash types was significantly reduced below baseline levels in the IVS -ES condition.
- Variability in speed reduced below baseline levels only when IVS information was presented in the absence of external signs (IVS -ES). Taken together with the speed data, it suggests that drivers in the IVS -ES conditions failed to appropriately adjust their speeds to the stated limit as frequently as did drivers in the other signage conditions.
- Finally, deviations in horizontal lane position were not affected by either IVS +ES or IVS -ES conditions, relative to baseline performance. This suggests that driver distraction and lateral vehicle handling was not affected by the presence of the IVS technology.

The subjective usability results provided additional information that clarified the driving performance findings:

- Total mental workload, as measured by NASA-RTLX, was found to be greater during IVS use in the absence of external signs (IVS -ES). Workload levels were similar, however, between baseline conditions (i.e., external signs and no IVS) and when IVS was used in conjunction with external signs (IVS +ES).
- Usability inventories found that subjective perceptions of the system's usefulness significantly decreased after system use for both IVS conditions (i.e. IVS +ES and IVS -ES). Satisfaction ratings were consistent between pre- and post-system use for the IVS +ES group, but significantly decreased for the IVS -ES condition. Usefulness and satisfaction were both still overall rated positively after use in the IVS +ES condition; however, satisfaction became negatively rated when IVS information was provided in the absence of external signs (IVS -ES).

Overall, the project was able to identify some of the preliminary driver effects that may occur when using a commercially available device with IVS information included. Some **recommendations** can be drawn from the results of this evaluation:

- It was discovered that using the IVS system in the absence of external signs (IVS -ES) resulted in increased speeding behavior due to participants failing to adjust their speeds according to the posted levels. This increased speed resulted in significantly decreased

levels of safety associated with various crash types. Moreover, subjective measures demonstrated both increased workload and decreased satisfaction associated with the IVS system in the absence of external signs. **Although using IVS information in the absence of external signs would presumably save money on infrastructure costs, it is recommended that the current IVS system not be utilized in substitution of external signs**.

- Notably, analysis of driving performance metrics demonstrated that using the IVS system in conjunction with external signs (IVS +ES) resulted in driving behavior that is comparable to baseline levels (i.e., external signs with no IVS present). In fact, risk analysis discovered that the reduction in speeding behavior associated with the IVS +ES condition resulted in improved safety outcomes in the event of a frontal-impact crash. Moreover, subjective measures showed that overall usefulness and satisfaction ratings were still positive after IVS system use (i.e., with external signs present) and the total mental workload was similar to baseline rates. **Therefore, it is recommended that the potential of using IVS information in conjunction with external signs be further explored.**

CHAPTER 1: INTRODUCTION

The Minnesota Department of Transportation (MnDOT) conducted a demonstration project as part of the Connected Vehicles Program to design, build, and test three new software applications to run on a commercially available personal navigation device (PND). The three applications that run on the PND (e.g., TomTom or phone running Android) that use global positioning satellite (GPS) technology to:

- Calculate and present mileage based user fees (MBUF) for the road on which a driver is traveling and an accumulated bill
- Present In-Vehicle Signing (IVS) to drivers about specific zones they encounter (e.g., construction)
- Present traveler information using probe vehicle data which will allow information to pass between vehicles and the infrastructure and allow drivers to see travel time information.

The overall goals of the larger project, entitled Minnesota Road Fee Test, were to:

- Develop and validate the functionality of each vehicle acting as a probe and providing information to a central location,
- Provide route-specific traveler information to vehicles,
- Demonstrate the technical feasibility of a MBUF component,
- Identify drivers' opinions about the MBUF component and to identify the reaction to this component by the general public, and
- Demonstrate the feasibility of delivering time-specific safety and warning messages on an in-vehicle display.

The goal of the project is to improve safety and mobility for drivers. The Minnesota Road Fee Test was led by the MnDOT Office of Traffic, Safety, and Technology with technical support provided by Mixon Hill Incorporated. Battelle Memorial Institute (BMI) was the development lead for the product while Science Application International Corporation (SAIC) was tasked with conducting functional evaluations. The project employed a robust product development strategy that included concept development, product functionality validation, and the identification of the initial product impressions by the general public to accomplish the overall project goals.

The goal of the study described in this report was to examine only the IVS function to determine the impact such information has on safety, and whether increased distraction was associated with using the IVS information. The purpose of the IVS application is to transmit roadway signing information from the infrastructure to a PND interface. The IVS information is intended to augment the ability of drivers to detect transition points in the road while driving that may occur due to changes in speed limits along a road, school zones, construction zones and upcoming curves. The design iteration tested in the current study evaluated the presentation of advance notification signs for upcoming zones and for signs that occurred within a zone requiring the driver to adopt a new speed (e.g., adopting a reduce speed in a construction zone).

Significant tenets associated with the development and design of in-vehicle technology are to create a product that 1) is perceived by drivers as being useful, 2) that is usable, and 3) that influences safety in a positive and expected way. If a product does not meet these basic tenets it will not be well received by drivers and would likely result in drivers not employing the product (and not benefiting from the product). In addition, if the product lacks usability, it could potentially contribute to unanticipated consequences during use (e.g., distraction). The project scope allowed for an initial investigation of the IVS application to be conducted with the general public to determine if their impression of the application meets the stated project goals of improving safety and mobility. This activity initially addresses the first tenet identified above.

The work covered in this study and reported here addresses the need to evaluate the second and third tenets of in-vehicle technology design and development as they relate to the IVS application. Specifically, the purpose was to determine the extent to which the IVS application developed by BMI will influence driver performance and perceptions of usability. A critical element of this phase was also to determine the impact the IVS technology has on estimated safety, and was accomplished through Monte-Carlo risk analysis. Finally, we evaluated the extent to which changes in driver performance and perceptions of usability may be indicative of driver distraction. For example, distraction due to the IVS application may result from a need to view the application for an extended period of time while driving.

1.1 Research Issues

The driver behavior we expected to see when using the IVS information was appropriate compliance with speed limits. This included drivers' adjusting their speed appropriately before entry into a new speed zone and maintaining the correct speed throughout the new speed zone. It also included drivers being aware of why changes in the speed zones are occurring (e.g., school zones, construction zone, curve, changes in speed limit along a roadway). A main goal of this study was evaluate the safety associated with the IVS technology, both when external signs are present and absent. Moreover, we wish to assess the level (if any) of distraction associated with the presented IVS information. Distraction can be defined as "a diversion of attention away from activities critical to safe driving toward a competing activity" [7]. In the case of the visual IVS information, drivers attending to that information may have their visual attention diverted away from the roadway at the same moment a critical incident occurs (e.g., lead vehicle performs emergency braking, child dashes into street). If attention to the IVS occurred during a critical event and reduced the ability of the driver to respond to such an event, it could be considered a distraction.

In this study, status quo driving conditions (i.e., IVS system turned-off) were included as a control condition in order to compare changes in relative safety and driving performance when using the IVS information. By comparing a baseline condition to the two IVS conditions, one in which IVS information appears in conjunction with external signs (IVS +ES) and one in which IVS information presented without any external sign information available (IVS -ES), it was expected that we would be able to identify any safety and distraction effects that may be associated with the IVS information. When measuring performance related to distraction, lateral control performance (e.g., lane position, lane position variability) is most sensitive to visual distraction (e.g., [3, 10]). In particular, lane keeping is often impacted by acquiring visual

information compared to voice information; therefore, assessing lateral performance measures will help us understand the impact of the IVS information on driver distraction.

Finally, in addition to driving performance measures and risk analysis, a subjective assessment of cognitive workload provided another way to determine if distraction or usability issues might be associated with the in-vehicle interface. The perceived mental workload reported by drivers was measured using the NASA Raw Task Load Index (NASA-RTLX) [5].

Overall, the goal of this study was to determine if safety or mental workload is impacted when using the IVS information. Driving performance measures known to be related to distraction, as well as risk analysis and subjective usability and workload measures were collected to help identify potential distraction associated with the IVS information.

CHAPTER 2: METHODS

2.1 Experimental Design

To evaluate the impact of in-vehicle sign (IVS) information on key driving performance measures, this study utilized a 2 x 2 mixed-factorial design with IVS Status (On, Off) as a within-subjects measure and External Sign Status (Present, Absent) as a between-subjects measure. Participants were randomly assigned to one of the two experimental external sign (ES) conditions. Participants assigned to group 1 were provided with IVS and external sign information (IVS +ES). Participants assigned to group 2 were provided with only IVS information, but no external signs were present (IVS -ES). This allowed evaluation of both the main-effects and interactions across driving performance measures of interest.

Table 2-1. Study conditions across the two participant groups.

	Baseline (IVS OFF)	**Experimental Condition (IVS ON)**
Group 1 (IVS +ES)	External Signs Only	In-Vehicle Signs with External Signs
Group 2 (IVS -ES)	External Signs Only	In-Vehicle Signs without External Signs

Note: The order of the within-subjects conditions (i.e. IVS OFF or ON presented first) were counterbalanced across participants.

2.2 Participants

Table 2-2. Participant information

Condition	**Gender**	**Age Group**	**Mean Age (*SD*)**	**Mean Years Licensed (*SD*)**	**Mean Weekly Mileage (*SD*)**
IVS +ES	12M, 9F	18-35: *n* = 7 36-54: *n* = 7 55+: *n* = 7	45.05 (*14.3*)	27.71 (*13.61*)	150.95 (*110.65*)
IVS -ES	9M, 10F	18-35: *n* = 7 36-54: *n* = 5 55+: *n* = 7	45.53 (*17.19*)	28.65 (*17.03*)	233.00 (*235.94*)

Overall, forty participants completed the study and all participants were used in the analyses. An attempt was made to balance age and gender in each group (Table 2-2). Three age groups were recruited for this study: 18-35, 36-54 and 55+. For the analyses, there were 21 participants in the IVS +ES group, and 19 participants in the IVS -ES group. There were no statistically significant differences between the groups for age, years licensed or mean weekly mileage (p's > 0.1).

2.3 HumanFIRST Driving Simulator

Figure 2.1 HumanFIRST Driving Simulator

This study was conducted in a partial motion-base driving simulator manufactured by Realtime Technologies (RTI). The simulator consisted of a 2002 Saturn SC2 full vehicle cab featuring realistic control operation and instrumentation including power-assist for the brakes and force feedback for the steering. Haptic feedback was provided by car body vibration and a three-axis electric motion system producing roll, pitch and yaw motion within a limited range of movement. The auditory feedback was provided by a 3D surround sound system. The driving environment was projected to a five-channel, 210-degree forward visual field screen (2.5 arc-minutes per pixel) with rear and side mirror views provided by a rear screen and vehicle-mounted LCD panels, respectively (see Figure 2.1).

2.4 Simulated Driving Route

A twenty-four mile long route was identified southwest of the Twin Cities that incorporates expressway, rural and local roads to accomplish the goals of testing the system alerts (see Figure 2.2). This driving route was chosen because it included speed zone and curve warning zones that were of interest for this study. In order to shorten the driving route, a small portion of low-speed town driving was eliminated to reduce the drive time by 5 minutes. The driving route took about 25 minutes to complete and was driven in a clockwise direction (see Figure 2.3). The drive included a segment of freeway driving, several segments of rural 2-lane road driving, and two segments of town driving. To allow drivers to easily navigate the route, the route was designed so drivers can only go in the desired direction and drivers in all conditions were provided with an auditory turn direction in advance of each turn. Barricades were placed at intersections and interchanges to prevent drivers from going the wrong way. IVS and navigation information were displayed to drivers on an Android cellular phone that was mounted to the center console of the vehicle within the driver's view. Oncoming traffic was presented in the simulation to that

represented light traffic flow. Scenario features, such as road striping, buildings, trees, grass and hills were incorporated into the drive to approximate the environmental landscape of the real-world route.
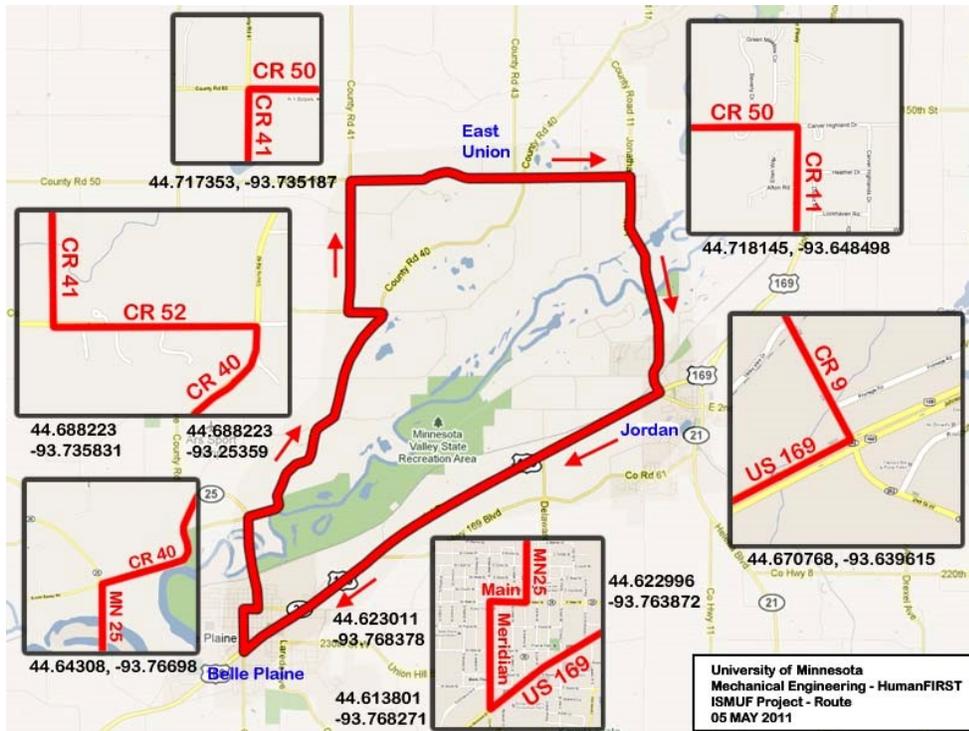

*Figure 2.2. Simulated route reflecting roadways*
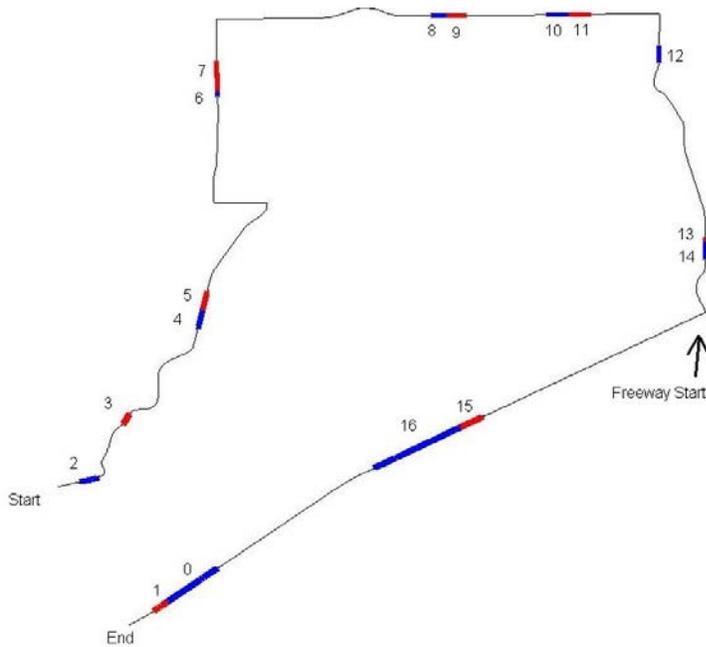
Figure 2.3. Simulated route reflecting route zones

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2.5 Route Zones and IVS Display

The route incorporated three speed, three curve, two school and two construction zone scenarios. In each scenario, the IVS notifications were intended to assist drivers with adopting the appropriate speed when they reached the new speed zone that was alerted. The speed, school and construction zones each had two sub-zones that included an advance notification zone and the actual zone of interest (Figure 2.2). The description of each zone type, the speed limit for the zone, what criteria was used to generate the IVS information presentation, and the images displayed for specific IVS information are shown in Table 2-3. IVS information was presented visually only. There was no accompanying auditory alert with the IVS information in this study. While redundant auditory messages may have bolstered compliance to the IVS information, auditory signals, even those that provide safety information, are often disabled by users who perceive them to be "annoying" [11]. The visual only presentation of the IVS information provides the minimal, and perhaps the expected, presentation that would be feasible for system's use in the real world.

Table 2-3. IVS Information across Zones

Zone	Description	IVS Information
Zone 0	Speed Reduction Warning – 55mph	
Zone 1	Speed Limit – 55mph	
Zone 2	Curve – reverse turn left – 30 mph advisory speed	
Zone 3	Curve – reverse turn right – 35 mph advisory speed	
Zone 4	School zone speed reduction warning – 35 mph	
Zone 5	School speed zone – 35 mph	
Zone 6	Work zone speed reduction warning – 40 mph	
Zone 7	Work zone speed limit – 40 mph	
Zone 8	Speed warning zone – 35 mph	
Zone 9	Speed zone – 35 mph	
Zone 10	School warning zone – 35 mph	
Zone 11	School zone – 35 mph	
Zone 12	Curve winding right – 40 mph	
Zone 13	Speed warning zone – 40 mph	
Zone 14	Speed zone – 40 mph	
Zone 15	Work zone speed reductions warning – 50 mph	
Zone 16	Work zone speed limit – 50 mph	

2.6 Procedure

Participants completed the informed consent process followed by a demographic questionnaire. Participants' vision was assessed to ensure it met minimum standards for licensing in Minnesota (20/40 corrected or uncorrected) and to ensure their color vision was unimpaired to continue with participation. A generic description of the system information they would potentially encounter during the drive was described to drivers and a pre-drive usability questionnaire administered (see Appendix A) to assess driver's perceived usefulness and satisfaction with the system's description prior to driving with it [9].

Participants were then provided with instructions for the practice drives and driving-related tasks. They completed a five-minute practice drive to become accustomed to the simulator and its controls.

Once the practice sessions were completed, participants received instructions for the experimental drives (Appendix B). Participants were encouraged to drive as they normally would and were not given explicit instructions about maintaining speed limits. They were asked to attend to the IVS information as needed during their drive. Participants were also told that the route was self-explaining (e.g., could only go one direction at intersections) and that an auditory message alerting them of an upcoming turn would play in advance of any turns they needed to make. Participant drives were counterbalanced so that half the participants in each group drove the IVS System Off condition first (i.e. roadside signs only) while the other half drove the IVS System On condition first. The Off and On conditions were counterbalanced to reduce learning and carry-over effects that can occur during experimental sessions in the simulator (e.g., fatigue in later drives can potentially have an effect on driver behavior; counterbalancing helps balance out any potential effects like this between the system conditions). After each drive, participants completed the NASA-TLX (see Appendix C) workload questionnaire [5]. A 5-10 minute break was given between drives to allow the participant to rest. Each experimental drive took approximately 25 minutes to complete.

After the experimental drives were completed, the participant completed a series of post-drive questionnaires. Participants completed a Usability Survey and the same Usability Scale questionnaire (see Appendix D) they completed prior to driving with the system to get a post-test rating of system usefulness and satisfaction. Once the questionnaires were completed, participants were debriefed, thanked, and remunerated for their time.

CHAPTER 3: RESULTS

In order to evaluate the impact of in-vehicle sign (IVS) information on driving performance, objective and subjective measures of participant driving performance were collected.

Objective measures include:

- **Average Percent Posted Speed:** Measures the extent to which drivers were able to adhere to speed limits across zones. Formally, percent posted speed was calculated for each subject (i) by mean percent posted speed in each zone (z). Percent posted speed ($p_{i,z}$) is defined as $p_{i,z} = (S_{i,z} / S^p_z) \times 100$, where S^p_z is the posted speed in zone z and $S_{i,z}$ is the observed speed for participant i in zone z.
- **System Risk Analysis**: High-level analyses were conducted to evaluate the relative risk associated with the IVS system by leveraging Monte-Carlo simulation. The simulation was conducted to estimate how IVS information influences safety in the event of different types of crashes.
- **Variability in Speed**: Measures the extent to which drivers adjusted their speed in each zone. Variance in $S_{i,z}$ was calculated to use as a variability measure.
- **Variability in Lane Position**: Measure of driver distraction [10]. The standard deviation in horizontal lane position $h_{i,z}$ was taken across each zone z and participant i. The center line of the lane served as the reference point.

In addition to objective measures, we also collected some subjective measures to assess the workload associated with using the system information and the usability of the interface:

- **NASA-RTLX**: Participant responses to the NASA-RTLX [5] were collected after each baseline and system condition drive. The NASA-RTLX consists of six subscales (mental demand, physical demand, temporal demand, effort, performance, frustration) that can be evaluated individually or combined to obtain a total workload score. Each individual scale is marked out of 100. Total workload is the sum of the six subscales divided by the number of subscales.
- **Usability Scales**: The Usability Scales [9] (see Appendices A and D) were administered pre and post-drive to allow for a comparison of hypothetical usability with actual usability of the system. The scale consists of 9 items which are scored and averaged to create two scales. Odd numbered items make up the *usefulness scores* while even numbered items make up the *satisfying scores*. Ideally, perceptions of system usefulness and satisfaction will be positive and improve or remain constant with actual use, indicating a satisfactory system design.

3.1 Impact on Average Speed

Mean percent posted speed $p_{i,z}$ for each participant i and zone z was computed. Figure 3.1a displays the median percent posted speed for each zone, averaged across participants in the IVS condition with external signs present, both when the system was on (i.e., IVS +ES - blue line) and off (i.e., baseline - green line) ±1 standard error.

Moreover, Figure 3.1b shows the median percent posted speed for each zone, averaged across participants in the IVS condition *without* external signs, both when the system was on (i.e., IVS - ES - red line) and off (i.e., baseline - green line) ±1 standard error.

Finally, Figure 3.1c shows the median percent posted speed averaged across all participants i and zones z. The percent posted speed was found to be relatively consistent across system status (i.e. IVS on or off) for the baseline ($M = 106.79$, $SE = 1.10$) and IVS +ES condition ($M = 106.44$, $SE = 1.04$). There were differences, however, in median percent posted speed across system status for the baseline ($M = 106.42$, $SE = 0.94$) and IVS -ES ($M = 123.90$, $SE = 1.31$) conditions.

To explore if these differences were significant, a mixed-factorial ANOVA was performed on the data. The mixed-factorial ANOVA found the observed differences in speed to be significant, as there were significant main-effects of both system status $F(1,636) = 141.41$, $p < 0.01$ and IVS condition $F(1,636) = 25.66$, $p < 0.01$. Moreover, there was a significant interaction between system status and IVS condition $F(1,636) = 121.04$, $p < 0.01$, where those in the IVS -ES group displayed significantly greater speeds over posted limits than those in the other conditions.
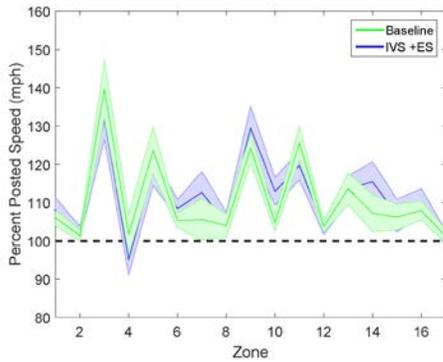
(a) Percent Posted Speed of IVS with External Signs compared to baseline
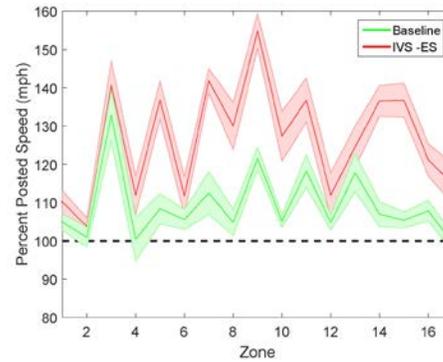
(b) Percent Posted Speed of IVS without External Signs compared to baseline
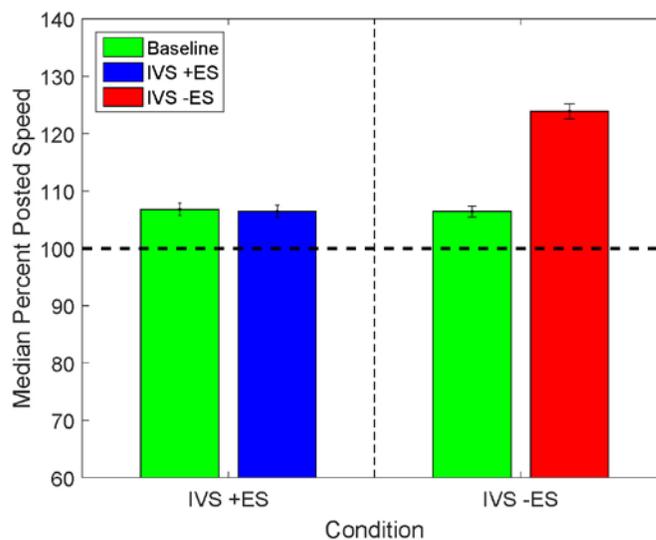
(c) Percent Posted Speed Group Averages

Figure 3.1. Impact of IVS on Percent Posted Speed

Although it is obvious that increased speed in the IVS -ES condition will result in increased property damage and injury severity in the event of a crash, it is unclear about the magnitude to which this is true. After all, if in-vehicle sign information were to replace external signs, it would presumably save money on infrastructure costs, **so it is desirable to understand the balance of these two factors in order to make an informed decision about the relative utility of IVS technology**.

In order to provide a proof-of-concept of how such an estimate could be established, a focus was placed on how the observed increases in speed will impact the expected lives lost, in the event of different types of crashes. The next section will overview the predictive model and risk analysis done to that end.

3.2 Risk Analysis

Figure 3.2. Bayesian Network for IVS Risk Evaluation
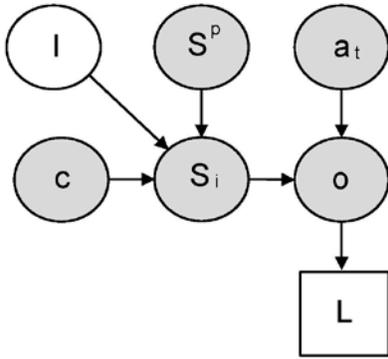
In order to estimate the risk involved with a system, performance needs to be evaluated across several conditions. It is intractable to run human-in-the-loop experiments over all types of people and situations. Moreover, it is impossible to leverage historic data when evaluating the risk associated with a system that has yet to be deployed. Therefore, it is desirable to develop a model that is able to *predict* human performance across the technological and environmental conditions of interest. The model can be used in Monte-Carlo simulation to evaluate the risk associated with deploying different types of IVS technology. This section will describe the model and assumptions used for these efforts

In the context of the current study, we would like to estimate the fatality risk associated with different IVS technology conditions (*c*). Figure 3.2 shows the Bayesian network used for the IVS Monte-Carlo simulation. Shaded circles represent observable random variables, white circles represent unobservable random variables, squares represent the loss function associated with realizing the possible outcomes (*o*), and arrows represent causal relationships between variables.

Formally, this directed-acyclic graph (DAG) represents the following probabilistic relationship:

$$\mathbb{E}(V_c(o)) = \sum_j L(o_j) \sum_{i \in I} p(o_j \mid a_t, s_i) p(s_i \mid s^P, i, c) p(s^P) p(i)$$
$$= \sum_j L(o_j) p(o_j \mid a_t, s) p(s \mid s^P, c) p(s^P) \tag{1}$$

where $\mathbb{E}(V_c(o))$ is the expected-value associated with IVS condition *c* across outcomes *o*. $L(o_j)$ is the loss associated with realizing outcome *j*, and $p_c(o_j \mid s, a_t)$ is the probability of realizing outcome *j*, given the speed *s* and crash type *t*. The conditional probability $p(s \mid s^P, c)$ represents the probability of observing speed *s* given the posted speed s^P and IVS condition *c*. This conditional probability was derived by marginalizing over individual participant factors, *I*, which

also impact rates of observed speed. Finally, $p(s^p)$ is the marginal probability of posted speeds across a region (temporal or geographical) of interest.

In the general case, $L(o_j)$ could quantify property damage, injury severity and fatality rates. However, for the purpose of the current study, we will utilize a loss-function that focuses on fatality rates. More specifically, our loss function simply provides a unit reward for a positive outcome $L(o = 1) = +1$, and a negative unit penalty for a fatality $L(o = 0) = -1$.

Notice that in order to reliably estimate $p(s \mid s^p, c)$, it requires that we quantify the distribution of observed speeds *in-the-wild* across various speed zones (s^p), operating under different IVS technology conditions c. This is intractable, as we can only use historic traffic data to estimate this distribution for the baseline condition $p(s \mid s^p, b)$; the IVS conditions do not occur outside our simulation, so we need to develop a model that can help us *predict $p(s \mid s^p, c)$* for the IVS +ES and IVS -ES conditions.

Candidate predictive models were proposed in the order of increasing complexity (i.e., in the number of features and model parameters). It was discovered that a quadratic model seemed to be the best balance between model simplicity and predictive performance. We converged on a very simple nonlinear model that uses only two features:

- Speed in the baseline condition for each zone (i.e., posted speed zone, z), averaged across participants s_z^p. Essentially, this feature encodes average speeding behavior for a particular posted speed zone when no IVS is present. Notice that this feature can be estimated via historic or simulation data.
- IVS condition indicator variable encoding the absence or presence of external signs $\delta_c = \{0,1\}$, respectively.

Specifically, the model takes-on the following form:

$$s_z^c = w_0 + w_1 * s_z^b + w_2 * \delta_c + w_3 * (s_z^b)^2 \tag{2}$$
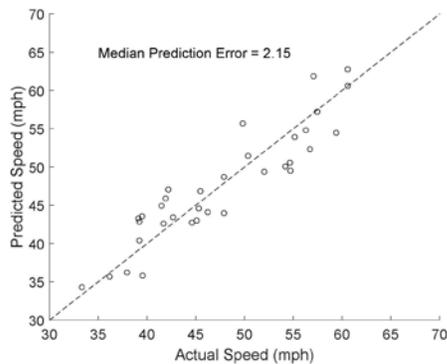
(a) Cross-validation predictive performance   (b) IVS Model Predictions
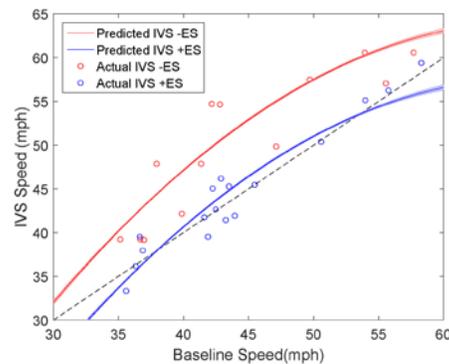
Figure 3.3. Percent Posted Speed Model Predictions

Figure 3.3a shows the predictive performance of the model. Predictive performance was evaluated using k-fold cross-validation, where the data set is partitioned into data that is used to estimate model parameters (i.e., training data) and data that is used to evaluate predictive performance (i.e., test data). This partitioning procedure is performed *k=10* times across the data and the results of the model's ability to predict the test data is shown on Figure 3.3a. If the model resulted in perfect prediction, all the data would fall on the dashed-line. As the figure shows, the quadratic model defined in Equation 2 is able to predict speed in each IVS condition from baseline data, with a median prediction error of ± 2.2 mph.

Figure 3.3b shows the model predictions across baseline speeds for each IVS condition. The solid colored line shows the mean prediction across each of the 10 model weights *w* estimated from the k-fold cross validation procedure, and the shaded regions represent ±1 SEM.
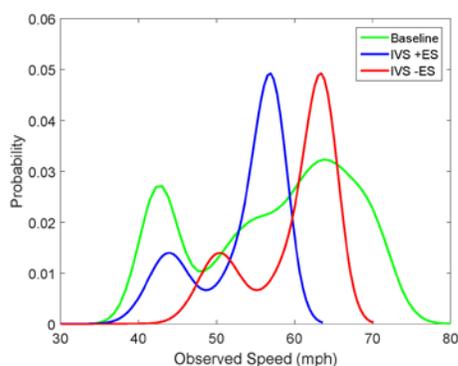
(a) Sampling Distributions
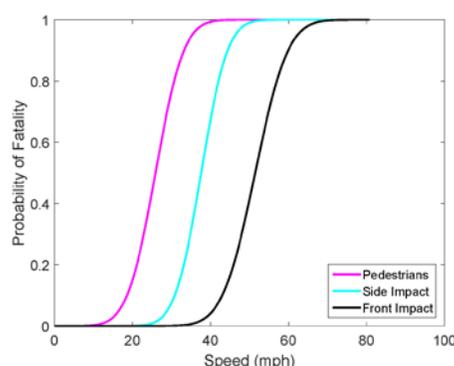
(b) Probability of Fatality
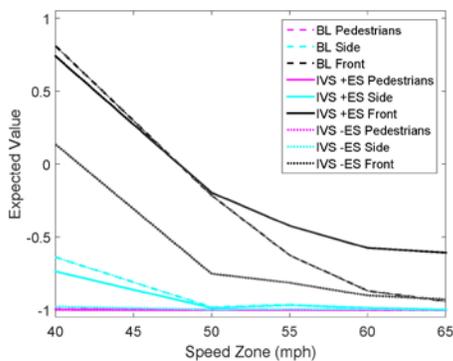
(c) Expected Value Across Speed Zones
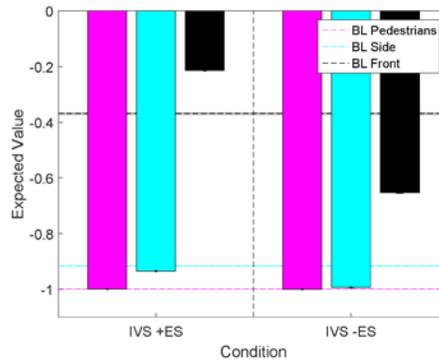
(d) Average Expected Value

Figure 3.4. Key components to the Monte-Carlo risk evaluation

In order to estimate $p(s_z^c \mid s_z, b)$, we used data from a 2014 MnDOT ATR report. Speed data was provided for four different speed zones (40, 50, 55, and 60 mph), and the frequency of the observed speeds for a given zone were binned using bin sizes of 5mph. Since we need to estimate the average baseline speed to use as a feature for our predictive model, we computed the

weighted average speed observed in each zone once an hour, and the resulting distribution of those hourly speeds was used to estimate $p(s_z^c \mid s_z, b)$. Using this historic speed data, we performed kernel density estimation on the average baseline speed distributions for each zone (z). Then, average speeds were sampled from the baseline distribution ($N = 10,000$), and the corresponding speeds for the different IVS technology conditions were predicted by using the baseline samples as inputs into Equation 2. Now that we have predicted observed speeds s_z^c for each IVS condition (c) and posted speed zone (z), we need to estimate $p(s_z^c \mid s_z, c)$. This was also accomplished by using kernel density estimation with a kernel width of two. Figure 3.4a shows the results of estimating distributions associated with each IVS technology condition, marginalizing over all posted speed zones $p(s^c \mid c) = \sum_z p(s_z^c \mid s_z, c)$.

The distribution $p_c(o_j \mid a_t{=}1,s)$ needs to be estimated from historic data, as we did not experience any crashes in simulation. This was accomplished by leveraging traffic data published by the Roads Corporation of Victoria, Australia (see pg. 16 in [12]). Probit regression was utilized to recreate the fatality curves for each of the three crash types (i.e., pedestrian, side-impact, and front-impact). More specifically, the probability of fatality for each speed and crash type was given by $p_c(o = 0 \mid a_t = t, s)$, and is depicted in Figure 3.4b. The probability of surviving a crash $p_c(o = 1 \mid a_t = t, s)$ is simply $1 - p_c(o = 0 \mid a_t = t, s)$. Although the data are from an international source, the results should be valid across a wide range of situations, as the data should not be strongly correlated with geographical factors. The marginal probability of crash type $p(a_t)$, however, may vary across regions, but this will not impact our results, as we are computing risk separately across crash types, as described below.

Finally, in order to simplify our expected value calculations, we only compute the expected-value associated with each IVS condition in the event of a crash. Moreover, we compute this separately for each crash type, which simplifies Equation 1 to:

$$\mathbb{E}(V_c^t(o)) = \sum_j L(o_j)p(o_j \mid a_t = t, s)p(s \mid s^p, c)p(s^p) \qquad (3)$$

Equation 3 is what was utilized to evaluate risk for the IVS conditions in this study. Leveraging the loss function and probability estimates described above, we were able to perform Monte-Carlo simulation (Algorithm 1) to produce the IVS risk estimates found in Figure 3.4c and 3.4d.

Figure 3.4c shows expected-value across IVS conditions and speed zones (± 1 SEM), while Figure 3.4d shows the average EV associated with different crash types across IVS conditions. In this formulation, expected-value can be intuited as the expected number of lives lost in the event of an unmitigated crash of type t. Expected-value, in this case, ranges between -1 and +1. The greater the expected-value, the greater the safety of the system. In this respect, we are able to evaluate the safety associated the IVS technology, and the goal of designing an IVS system should be to maximize the EV associated with the technology.
To compare relative safety of the IVS technology, we computed the EV associated with the baseline condition (Figure 3.4d, horizontal colored lines). It was found that EV in the baseline condition for a crash involving a pedestrian was the least safe ($M = {-}0.99$, $SE = 0.01$), and EV associated with a side- and ($M = {-}0.92$, $SE = 0.01$) front-impact was also negative ($M = {-}0.37$, $SE = 0.01$). The negative estimated risk is what would be expected from the fatality curves

depicted in Figure 3.4b, and the speed distributions that were provided by MnDOT and used for this simulation (Figure 3.4a). For example, the near negative-one EV associated with crashes involving a pedestrian results from the fact that almost all the observed speeds for which we had historic data are greater than the speed associated with $p(o_j = 0 \mid a_t = t, s_c) = 1$.

Algorithm 1 IVS Monte-Carlo Risk Simulation

1: **procedure** COMPUTEEV
2:     **for** $n \in N_{simulations}$ **do**
3:         $s_n^P \leftarrow sample \sim p(s^P)$
4:         **for** $c \in C$ **do**
5:             $s_c \leftarrow sample \sim p(s \mid s_n^P, c)$
6:             **for** $t \in T$ **do**
7:                 $p_c^t \leftarrow p(o_j = 0 \mid a_t = t, s_c)$
8:                 $ev_{c,n}^t \leftarrow (p_c^t \times L(o = 0)) + ((1 - p_c^t) \times L(o = 1))$
9:             **end for**
10:         **end for**
11:     **end for**
12:     $\mathbb{E}(V_c^t(o)) = \frac{1}{N} \times \sum_n ev_{c,n}^t$
13: **end procedure**

Expected-value for the IVS +ES condition demonstrates that the technology actually improved safety relative to baseline conditions in the case of a crash involving a front impact ($M = -0.21$, $SE = 0.01$). However, for crashes involving side-impact ($M = -0.94$, $SE = 0.01$) and pedestrians ($M = -0.99$, $SE = 0.01$), EV was comparable to levels in the baseline condition, suggesting that the IVS technology minimally impacts the safety associated with those crash types.

Finally, expected-value for the IVS condition without external signs (-ES) demonstrates that the technology significantly decreased safety relative to baseline conditions. This was true across crashes involving pedestrians ($M = -1.00$, $SE = 0.01$), side- ($M = -0.99$, $SE = 0.01$) and front-impact ($M = -0.65$, $SE = 0.02$). Clearly, the increases in speed observed (Figure 3.1) in the IVS -ES condition adversely impacts crash safety expectation.

3.3 Impact of IVS on Speed Variability

Median speed variability $Var(S_{i,z})$ for each participant (i) and zone (z) was computed. Figure Figure 3.5a shows the median variance in speed for each zone, averaged across participants in the IVS condition with external signs present, both when the system was on (i.e., IVS +ES - blue line) and off (i.e., baseline - green line) $\pm$ 1 standard error.

Moreover, Figure 3.5b shows the median variability in speed for each zone, averaged across participants in the participant group with IVS presented *without* external signs (i.e., IVS -ES - red line) and when the IVS system was off, but with external signs (i.e., baseline - green line) $\pm$ 1 standard error.

Finally, Figure 3.5c shows the median variability in speed averaged across all participants i and zones z. We found that speed variability was relatively consistent across system status for the baseline ($M = 1.60$, $SE = 0.10$) and IVS +ES condition (M= 1.54, $SE = 0.10$). However, there

were differences in median speed variability across system status for the baseline ($M = 1.63$, $SE = 0.09$) and IVS -ES ($M = 1.01$, $SE = 0.14$) conditions.
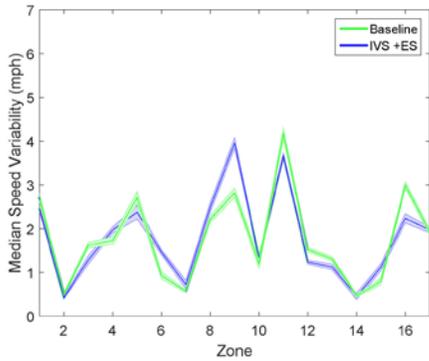
(a) Speed Variability of IVS with External Signs compared to baseline
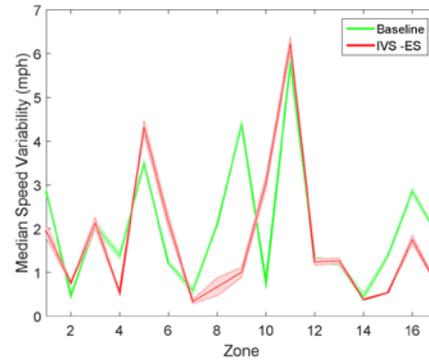
(b) Speed Variability of IVS without External Signs compared to baseline
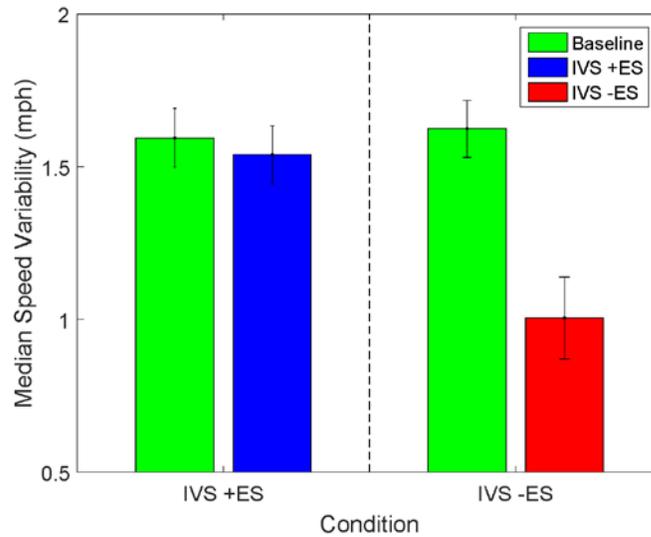
(c) Median Speed Variability across Zones

Figure 3.5. Impact of IVS on Speed Variability

To explore if these differences were significant a mixed-factorial ANOVA was performed on the log-transformed data. This log-transformation was done to meet the normality assumption of the hypothesis test used. The mixed-factorial ANOVA found the observed differences in speed variability to be significant, as there were significant main-effects of both system status $F(1,636) = 17.30$, $p < 0.01$ and IVS condition $F(1,636) = 4.09$, $p < 0.05$. Moreover, there was a significant interaction between system status and IVS condition $F(1,636) = 17.18$, $p < 0.01$, where those in the IVS -ES group displayed significantly less speed variability than those driving in the other conditions (i.e. baseline or IVS +ES).

3.4 Impact of IVS on Lane Position

The standard deviation on lane position SDLP: $SD(h_{i,z})$ for each participant (i) and zone (z) was computed. Figure 3.6a shows the median SDLP for each zone, averaged across participants in the IVS condition with external signs present, both when the system was on (i.e., IVS +ES - blue line) and off (i.e., baseline - green line) ± 1 standard error.
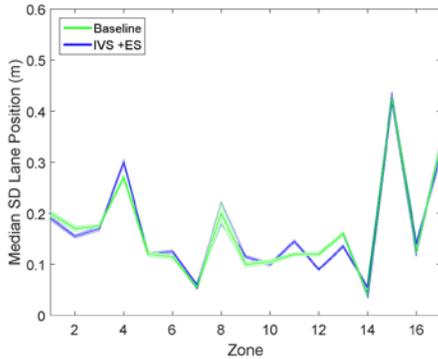
(a) Lane Position SD of IVS with External Signs compared to baseline
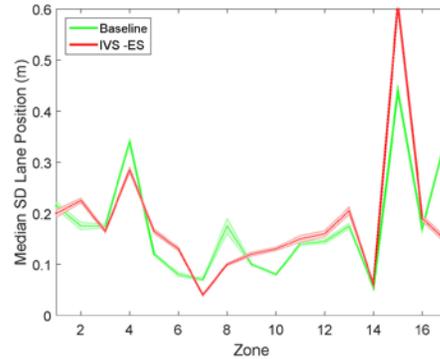
(b) Lane Position SD of IVS without External Signs compared to baseline
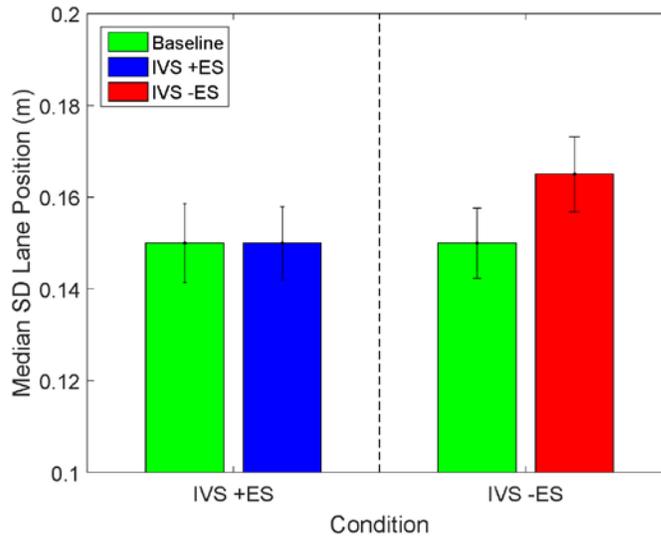
(c) Lane Position SD Group Averages

Figure 3.6. Impact of IVS on Lane Position Deviation

Moreover, Figure 3.6b shows the median SDLP for each zone, averaged across participants who drove in the IVS condition *without* external signs (i.e., IVS -ES - red line) and in the baselline condition with external signs only (i.e., baseline - green line) ± 1 standard error.

Finally, Figure 3.6c shows the median SDLP averaged across all participants i and zones z. We found that SDLP was relatively consistent across system status for the baseline ($M = 0.15$, $SE = 0.01$) and IVS +ES condition ($M = 0.15$, $SE = 0.01$). Moreover, there were only small

differences in SDLP across system status for the baseline ($M = 0.15$, $SE = 0.01$) and IVS -ES ($M = 0.17$, $SE = 0.01$) conditions.

To explore if these differences were significant, a mixed-factorial ANOVA was performed on the log-transformed data. This log-transformation was done to meet the normality assumption of the hypothesis test used. The mixed-factorial ANOVA found the observed no significant differences in speed variability, as there were no significant main-effects for both system status $F(1,636) = .95$, $p > 0.05$ and IVS condition $F(1,636) = 1.40$, $p > 0.05$. Moreover, there was no significant interaction between system status and IVS condition $F(1,636) = 0.15$, $p > 0.05$.

3.5 Subjective Measures

In addition to the objective measures described above, subjective measures were employed to assess the workload and usability of the IVS system. The next few sections overview the results of that effort.

3.5.1 <u>NASA-RTLX</u>
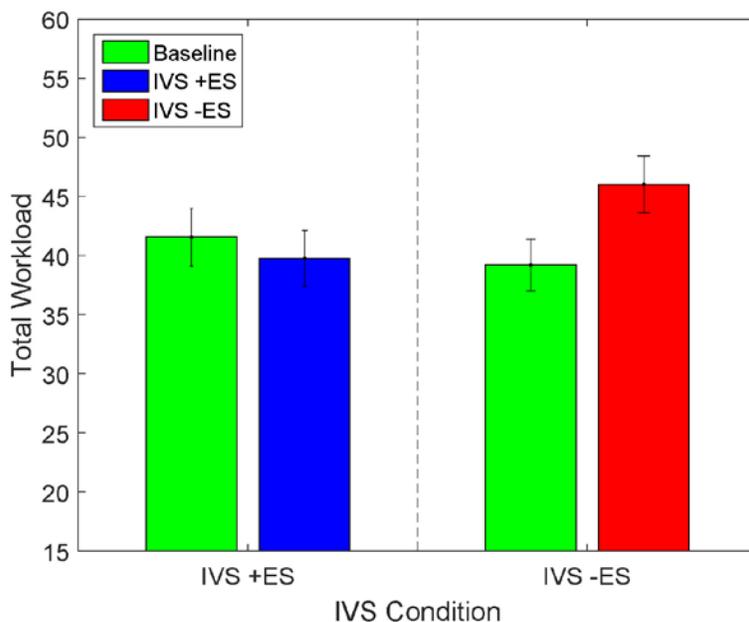
Figure 3.7. Impact of IVS on Subjective Mental Workload (NASA-RTLX)

The NASA-RTLX consists of six subscales (mental demand, physical demand, temporal demand, effort, performance, frustration) that can be evaluated individually or combined to obtain a total workload score. Each individual scale is marked out of 100. Total workload can be computed by averaging across the subscales. Figure 3.7 shows the mean total workload across conditions, ± 1 SEM.

Average total workload ratings during IVS conditions when external signs were present (IVS +ES) were relatively similar ($M = 39.80$, $SE = 2.35$) to baseline conditions, when the system was not activated ($M = 41.56$, $SE = 2.43$). To evaluate if the small changes in (ordinal) workload

ratings between conditions was significant, a Wilcoxon Signed-Ranks Test was used and proved that baseline and IVS +ES conditions resulted in statistically similar total workload ratings ($p > 0.05$).

Moreover, average total workload ratings during IVS conditions when external signs were absent (IVS -ES) were greater ($M = 46.03$, $SE = 2.40$) than baseline conditions when the system was not activated ($M = 39.21$, $SE = 2.19$). To evaluate if the increase in (ordinal) workload ratings during the IVS condition was significant, a Wilcoxon Signed-Ranks Test was used and proved that baseline and IVS -ES conditions resulted in statistically significant increase in total workload ratings ($p > 0.05$).

3.5.2 Usability Scales
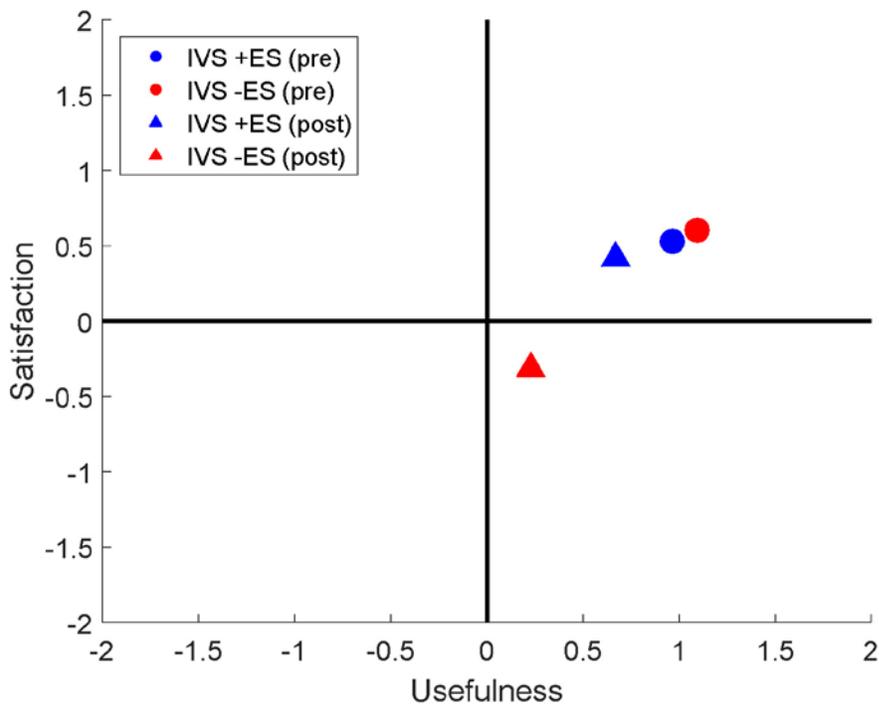
Figure 3.8. Pre- and Post-Experimental Usability

The usability scales assess drivers' perceptions of a system's usefulness and their satisfaction, both prior to using the system (based on a written description of the system in this study) and after they are able to interact with it while driving. The upper right quadrant of the graph indicates systems that are perceived as useful and satisfying to some degree. Overall, the two IVS systems were perceived to be somewhat useful and satisfying before system use, but this belief was reduced after use (see Figure 3.8).

More specifically, average usefulness ratings before system use in the IVS +ES ($M = 0.96$, $SE = 0.11$) and IVS -ES ($M = 1.10$, $SE = 0.09$) groups were greater than ratings after system use for both IVS +ES ($M = 0.67$, $SE = 0.13$) and IVS -ES ($M = 0.23$, $SE = 0.12$) conditions. To evaluate if the reduction in (ordinal) ratings was significant, a Wilcoxon Signed-Ranks Test was

used and proved this reduction in usefulness ratings to be statistically significant for both IVS groups ($p < 0.02$).

Moreover, average satisfaction ratings before system use in the IVS +ES ($M = 0.53$, $SE = 0.11$) and IVS -ES ($M = 0.61$, $SE = 0.12$) groups were greater than ratings after system use for both IVS +ES ($M = 0.42$, $SE = 0.14$) and IVS -ES ($M = -0.32$, $SE = 0.12$) conditions. To evaluate if the reduction in (ordinal) ratings was significant, a Wilcoxon Signed-Ranks Test was used and proved the reduction in usefulness ratings to be statistically significant ($p < 0.01$) for the IVS -ES group, but not for the IVS +ES condition.

CHAPTER 4: CONCLUSIONS

The goal of the current investigation was to evaluate if in-vehicle sign (IVS) information could be used in conjunction with or in the absence of external signs. The analyses included objective and subjective measures and are summarized below.

First, it was discovered that using the IVS system in the absence of external signs (IVS -ES) resulted in less compliance with the change in speed zones as a result of drivers failing to adjust their speeds according to the posted levels. The increased speed resulted in significantly decreased levels of safety associated with various crash types. Moreover, subjective measures demonstrated both increased workload and decreased satisfaction associated with the IVS system in the absence of external signs.

Moreover, it was discovered that using the IVS system in conjunction with external signs (IVS +ES) resulted in driving behavior that was comparable to baseline levels. In fact, risk analysis found that speeding behavior associated with the IVS +ES condition resulted in improved safety in the event of a crash involving front-impact. Moreover, subjective measures showed that overall usefulness and satisfaction ratings were still positive after system use, and the total mental workload was similar to baseline rates.

The outcome of these analyses supports the following recommendations regarding the use of IVS information:

- Although using IVS information in the absence of external signs would presumably save money on infrastructure costs, it is recommended that the current IVS system not be utilized in the absence of external signs.
- It is further recommended that the potential of using IVS information in conjunction with external signs be explored further. This could involve additional simulation studies, in combination with higher-fidelity risk analysis, to ameliorate the limitations of the current effort (see below).

Although the current effort attempted to be comprehensive, there are some fundamental limitations associated with this study:

- Drivers in the simulation were not penalized for driving above posted speeds. In real-world driving, there exists a non-zero probability of receiving a traffic ticket for driving above posted speeds, so future investigation will address this inconsistency. This may decrease the extent to which participants speed during IVS -ES conditions, thereby increasing the safety associated with the technology.
- The IVS presented speed information through visual presentation only and did not include auditory redundancy (e.g., verbal message announcing new speed ahead). Drivers' adherence to changes in speed limits could likely be improved to support better coherence to changes once they occur rather than relying on drivers to make frequent glances to the IVS for any changes in the displayed image.
- Distraction was measured exclusively through deviations in lane position. Future investigations could include eye-tracking or other physiological metrics as additional objective measures of distraction.

- The risk analysis performed in this study made several simplifying assumptions and used data from disparate sources to estimate the model parameters. Future investigations could offer a higher-fidelity risk simulation (e.g., the loss function could consider monetary damage), in addition to using data from a similar region of interest (i.e., geographical and temporal) to estimate its parameters. Moreover, obtaining data from lower speed zones would help make the risk simulation more sensitive/interesting, as crashes involving side-impact and pedestrians would be more likely to distinguish between conditions.
- The work has potential to be expanded to examine the role of compliance and distraction to emerging IVS systems, which may communicate connected vehicles (i.e., vehicle-to-vehicle) information to reduce vehicle speeds at points of conflicts (e.g., intersections, work zones). Specifically, understanding how drivers respond to dedicated IVS systems like those that could assist emergency vehicles in creating a cleared path or encouraging drivers to comply with "move over" laws would provide valuable insight into how such systems could enhance safety.

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APPENDIX A: SYSTEM USABILITY QUESTIONNAIRE (PRE-DRIVE)

System Description: Today you will be driving with an in-vehicle information system that provides roadway information to assist you with driving decisions. This system runs on a smartphone and uses visual icons to indicate changes in the speed limit as well as upcoming curves, construction zones and school zones (see example below). This information will be provided within a reasonable distance of the actual road sign and is intended to help you better identify these traffic zones and situations so you can respond accordingly. Based on this description of the system and how it operates, please complete the questionnaire below.

Example of the system's information that shows an upcoming change in the speed limit.

Once you have read and understood this system description, please complete the questionnaire on the next page.

Imagine the system described on the previous page and rate your opinion about it based on the descriptors below and how you think you might find using such a system while driving. Please rate your opinion for each descriptive item below (please tick one box for each item).

> For example, if you thought the system was very easy to use but required a lot of effort to learn, you might respond as follows:
>
> Easy   ☒   ☐   ☐   ☐   ☐   Difficult
>
> Simple   ☐   ☐   ☐   ☒   ☐   Confusing

Please continue to rate your opinion of the system for each descriptive term below:

1. **Useful**   ☐ ☐ ☐ ☐ ☐   **Useless**

2. **Pleasant**   ☐ ☐ ☐ ☐ ☐   **Unpleasant**

3. **Bad**   ☐ ☐ ☐ ☐ ☐   **Good**

4. **Nice**   ☐ ☐ ☐ ☐ ☐   **Annoying**

5. **Effective**   ☐ ☐ ☐ ☐ ☐   **Superfluous**

6. **Irritating**   ☐ ☐ ☐ ☐ ☐   **Likeable**

7. **Assisting**   ☐ ☐ ☐ ☐ ☐   **Worthless**

8. **Undesirable**   ☐ ☐ ☐ ☐ ☐   **Desirable**

9. **Raising Alertness**   ☐ ☐ ☐ ☐ ☐   **Sleep-inducing**

Thank you for completing this questionnaire.

APPENDIX B: PRACTICE DRIVE INSTRUCTIONS

1. **Practice Drive 1**: "This first drive will take about 5 minutes and will be used to get you familiar with how the simulator works and feels while you are driving. The goal is to drive as you normally would and just get a feel for how the simulator feels in comparison to real driving. It will not feel just like 'real driving' and that is ok. The aim is simply to get familiar with how it feels so you are comfortable with accelerating, stopping, and other driving maneuvers."

2. **Practice Drive 2**: "The second practice drive will also take about 5-10 minutes to complete. During this drive you will not only drive the vehicle but will complete a visual detection task. There will be colored rectangles located along the left and right side of the road. There are targets and non-targets. When you see one of the targets, you will respond by pushing the button on the steering wheel. The goal is to respond as soon as possible after you identify a target. You also want to try to be as accurate as possible (i.e., only responding to targets).

   There are two targets you are looking for: a rectangle with a BLACK TOP or a rectangle with a GREEN BOTTOM. If you see either of these, you should push the button on the steering wheel as quickly as possible. You only have to see one at a time. We recommend that you keep your thumb on the steering wheel button during the drive so you are able to respond quickly when you see a target.

   There will be other rectangles in the driving environment that are not targets. Your job is to find the targets and respond only if you see a target (BLACK TOP or GREEN BOTTOM only). "

   Show picture of targets.

   Show Steering Wheel button.

Experimental Drives – Instructions

Baseline Drive

"In this drive, you will be driving on highways and on town streets. The drive takes approximately 25 minutes to complete. Your goal is to drive as you normally would in the real world. You will be guided through the route by barricades on the roadway that will allow you to only go one direction at an intersection or interchange (e.g., construction barriers, etc). There will also be an auditory instruction advising you of the next turn prior to needing to turn. You will need to pay attention to these in order to follow the route. The turns can be a bit tight so make sure to slow down appropriately to make the turns. During this drive you will also be completing the visual search task that you practiced during the practice session. Please identify targets by pressing the button on the steering wheel as soon as you detect a target. Your goal is to respond as quickly and accurately as possible when you see one of the targets appear."

Show participants the targets again (BLACK TOP or GREEN BOTTOM) and remind them to keep their thumb on the button so they can respond quickly.

Ask participant if they have any questions. If not, start the appropriate drive (refer to order list for participant).

IVS Drive

"In this drive, you will be driving on highways and on town streets. The drive takes approximately 25 minutes to complete. Your goal is to drive as you normally would in the real world. You will be guided through the route by barricades on the roadway that will allow you to only go one direction at an intersection or interchange. There will also be an auditory instruction indicating an upcoming turn prior to reaching a turn. You will need to pay attention to these in order to follow the route.

During this drive you will notice there is a cell phone mounted on the center console that may display information about road signs or navigation. The information this system provides is designed to help you better identify changes in the driving environment. You are encouraged to use this information as needed during the drive. During this drive you will also be completing the visual search task that you practiced during the practice drives. Please identify targets by pressing the button on the steering wheel as soon as you detect a target. Your goal is to respond as quickly and accurately as possible when you see one of the targets appear."

Show participants the targets again (BLACK TOP or GREEN BOTTOM) and remind them to keep their thumb on the button so they can respond quickly.

Ask participant if they have any questions. If not, start the appropriate drive (refer to order list for participant).

APPENDIX C: MENTAL WORKLOAD RATINGS

Please rate the drive you just completed, considering all driving and in-vehicle tasks, and place a vertical line through each scale for the six characteristic summarized below:

Mental Demand: How much thinking, deciding, remembering, looking searching did you need to do?	LOW ├─────────────────────────────┤ HIGH
Physical Demand: How much physical activity was required	LOW ├─────────────────────────────┤ HIGH
Time Pressure: Did you feel under pressure to complete the driving task in the available time?	LOW ├─────────────────────────────┤ HIGH
Performance: How satisfied were you with your performance level?	POOR ├─────────────────────────────┤ GOOD
Effort: How hard did you have to work?	LOW ├─────────────────────────────┤ HIGH
Frustration Level: How insecure, discouraged, irritated, stressed, and annoyed were you during the drive?	LOW ├─────────────────────────────┤ HIGH

APPENDIX D: USABILITY SURVEY (POST-DRIVE)

You have driven a vehicle that is fitted with an in-vehicle information system that runs on a smartphone. Based on your driving experience with this in-vehicle information system in comparison to driving without it, please indicate how much you agree with the following statements:

"I view this system that supports my driving as"   (please circle your response)

	Disagree Completely				Agree Completely
1. A system to improve safety	1	2	3	4	5
2. A system to enhance performance	1	2	3	4	5
3. A source of confusion or distraction	1	2	3	4	5
4. Useful in urban areas	1	2	3	4	5
5. Useful in rural areas	1	2	3	4	5
6. Useful on highways	1	2	3	4	5
7. Useful in stop and go traffic	1	2	3	4	5
8. Increasing mental (and visual) effort	1	2	3	4	5
9. Increasing driver comfort	1	2	3	4	5
10. Making the driver less vigilant	1	2	3	4	5
11. Making the driver less stressed	1	2	3	4	5
12. Making the passengers less stressed	1	2	3	4	5
13. Unreliable in its operations	1	2	3	4	5
14. The information presented on the in-vehicle device was helpful.	1	2	3	4	5

15. Did you use the information presented on the in-vehicle device to help you identify changes in the driving environment (e.g., changes in speed limit)?

☐Yes ☐No

If "yes", please explain what information you used or how you used the information to make your decision of when to cross? If **"no"**, please explain why you did not use the information presented on the sign.

System Usability Questionnaire (post-drive)

Now that you have driven with the in-vehicle information system, please rate your opinion of it based on your experiences driving with it. Please rate your opinion for each descriptive item below (please tick one box for each item).

For example, if you thought the system was very easy to use but required a lot of effort to learn, you might respond as follows:

Easy   ☒ ☐ ☐ ☐ ☐   Difficult

Simple   ☐ ☐ ☐ ☒ ☐   Confusing

Please continue to rate your opinion of the system for each descriptive term below:

1. Useful	☐ ☐ ☐ ☐ ☐	Useless
2. Pleasant	☐ ☐ ☐ ☐ ☐	Unpleasant
3. Bad	☐ ☐ ☐ ☐ ☐	Good
4. Nice	☐ ☐ ☐ ☐ ☐	Annoying
5. Effective	☐ ☐ ☐ ☐ ☐	Superfluous
6. Irritating	☐ ☐ ☐ ☐ ☐	Likeable
7. Assisting	☐ ☐ ☐ ☐ ☐	Worthless
8. Undesirable	☐ ☐ ☐ ☐ ☐	Desirable
9. Raising Alertness	☐ ☐ ☐ ☐ ☐	Sleep-inducing

Situation Awareness Survey

1. How many construction zones did you drive through in the last drive? _____

2. How many school zones did you drive through in the last drive? _____

3. Did you see the following icon presented on the phone's screen during the drive?

   Yes
   No
   (please circle answer)

4. Did you see the following icon presented on the phone's screen during the drive?

   Yes
   No
   (please circle answer)

Continued on next page.

5. Did you see the following icon presented on the phone's screen during the drive?

Yes
No
(please circle answer)

6. Did you see the following icon presented on the phone's screen during the drive?

Yes
No
(please circle answer)

7. Did you see the following icon presented on the phone's screen during the drive?

Yes
No
(please circle answer)

End of Questions