

FORMATIVE EVALUATION OF ENGINEERING DESIGNS USING DRIVER PERFORMANCE IN AN IMMERSIVE DRIVING SIMULATOR

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Summary: The systems engineering approach employs iterative evaluation of human factors issues throughout the system design process. Formative evaluation and refinement of user interfaces promotes cost savings by continuously validating design concepts and defining needs for improving the designs at the earliest possible point in the engineering process. Testing may use varying levels of prototypes of the system or simulations of its responses and user interfaces. While human factors evaluation frequently uses paper or foam board mockups, immersive driving simulators enhance the process by incorporating realistic road geometries and traffic flows and by requiring driver perception, decision making, and control actions in realistic scenarios and timelines. Three studies conducted in the Western Transportation Institute driving simulation laboratory are summarized. These used an immersive driving simulator to evaluate drivers' responses to (1) Intelligent Transportation System (ITS) deployments on a rural highway, (2) the user interface to a lane departure warning system, and (3) a proprietary cooperative warning system for installation on the exterior of vehicles.

BACKGROUND

The WTI Immersive Driving Simulation Laboratory

WTI's Driving Simulation Laboratory is centered on a DriveSafety[®] 500C fixed-base simulator in a light- and sound-controlled 35-square-meter room. An adjacent office is used for subject reception, briefing and data analysis. Adjacent to these rooms is a 100-square-meter high bay room designed to house a future motion-based multi-cab simulator.

The DriveSafety[®] simulator cab is a quarter of a 1996 Saturn SL sedan with fully functional controls. An array of five rear-projection plasma displays is arranged in a semicircle around the front of the cab providing a 160-degree horizontal field of view. Rear-view mirrors are simulated on the displays. The simulator has 3-D auditory displays using five speakers, including a "seat shaker" subwoofer attached beneath the driver's seat. Vehicle dynamics and control responses are physics-based. The system currently runs on Vection and HyperDrive 1.9.8 simulation software using a network of seven simulation computers and a dedicated data collection and analysis computer. A FaceLAB[®] 4.3 eye tracking system records driver eye glances and blinks.

Visualization of an ITS System on a Rural Highway

The Design Problem. US Highway 191 in southwestern Montana has been identified as the location of a number of crash clusters, with a significant spike in 2006. The 25-mile Gallatin Canyon section of US 191 between Bozeman and Big Sky is a scenic mountain highway characterized by frequent sharp curves and a narrow right-of-way constrained by canyon walls and a major river. A large percentage of drivers are unfamiliar with the highway and with safe driving speeds at given locations and under different weather conditions. Crashes are frequently attributed to distracted drivers watching wildlife, whitewater rafters, or the scenery. Traffic flow is marked by a significant speed variance, with limited opportunities for passing slow-moving trucks and recreational vehicles. Because of the roadway geometry and the lack of practical alternative routes, crashes and incidents in this area have a disproportionate impact on transportation in this heavily traveled corridor. The Montana Department of Transportation identified a need to explore approaches to achieve voluntary compliance with statutory and advisory speeds in this area.

Speed limits posted on DMS signs have numerous advantages over those posted on static regulatory signs. The speeds posted on VMS signs may be adapted to account for roadway and traffic conditions. During roadway tests, VMS signs have a larger effect than static signs on driver speed, especially when a reason for reduced speed is perceived.

Methods. A rapid prototyping approach was used in the driving simulation laboratory at the Western Transportation Institute (WTI) to simulate approximately 22 miles of US 191 between the Big Sky Resort community and the northern mouth of the Gallatin Canyon. Custom roadway tiles for the simulation were designed and programmed from MDT's "as built" plans for the highway, topographic maps, and video taken from a vehicle driving the route.

For an initial demonstration, scenarios using "variable" speed limits posted on virtual DMS signs were selected for testing. Driver performance on the simulated roadway was tested with no posted speed limits, speeds posted at a 60-MPH limit on a DMS on a gantry over the road, and speeds posted at 50-MPH on a DMS gantry over the road.

A sample of licensed drivers representing a mix of genders and ages was recruited to represent the typical driving population of US 191. Fifteen drivers were recruited (8 males and 7 females). They ranged in age from 20 to 59 years ($m = 33.2$). After initial screening and acclimation to the simulator, drivers were assigned to one of three testing groups with a goal of equalizing the groups in mean age and gender distribution. The groups were a 50-MPH group, a 60-MPH group, and a group with no speed limit control.

Each driver completed the two drives on the simulation. They were instructed to obey traffic laws and drive normally. The simulation scenario included fair weather, a dry roadway, and no slower same-direction traffic that would require slowing or passing. A moderate level of opposite direction traffic driving autonomously and obeying all traffic laws was included. For the drivers with a posted speed limit, a gantry with an appropriate dynamic message sign was placed over the roadway approximately one-half mile from the beginning of the drives. For drivers in the control group, there were no speed limits posted on any signs.

Speed (miles per hour) and lane positions (absolute value of distance from lane center) were measured at or within 2 meters after each milepost. A total of 1350 speed measures were taken (an average of 90 measurements per driver.) The roadway geometry was designated at each measurement point as straight, entering a curve, in a curve, leaving a curve, or on a narrow bridge. It must be noted that the simulator cab did not have cruise control capability, so vehicle speed was under active control of the drivers.

Results. Speeds measured in the simulator with no posted speed limits and with 60-MPH limits posted on DMS signs were very similar (see Figure 1). There was little difference in overall driving behavior between drivers with no posted limits (85th percentile speed = 53.15 MPH) and those with a 60-MPH (85th percentile speed = 53.65 MPH) limit posted. Drivers with a posted 50-MPH limit reduced their speeds by approximately 6 MPH (85th percentile speed = 47.65 MPH). The decrease in speeds was greater in straight sections and less in curving sections.

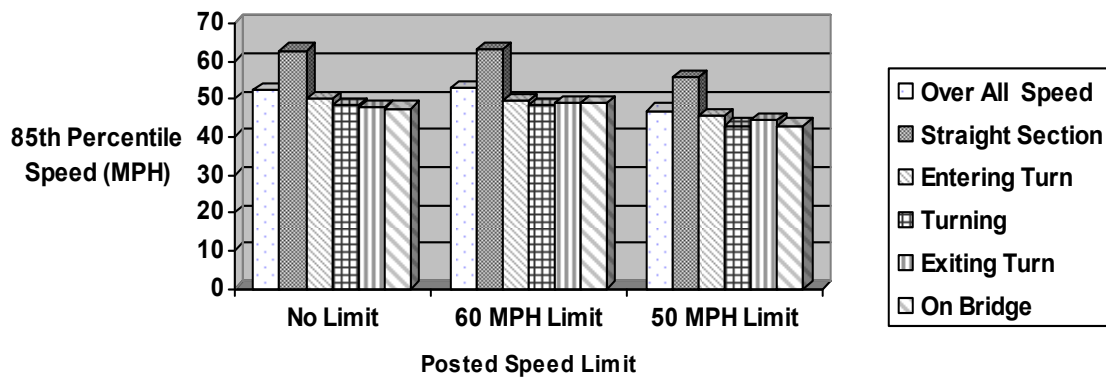


Figure 1. Simulator speeds with three different speed limits

The mean driving speeds with the posted 60-MPH limit and with no posted limit in the simulator seem very realistic when compared with measured driving speeds experienced on the actual highway during a 2005 speed study. The spot speed study found 85th percentile speeds in the mid-60s on straight sections and in the low-50s on curving sections. Figure 2 compares 85th percentile speeds measured during the 2005 speed study at locations judged to be straight, entering a curve, or leaving a curve with those of similar sections during Drive 1 and Drive 2 with a posted 60-MPH limit in the simulator.

Driver Response to a Lane Departure Warning System

The Design Problem. Roadway lane departure fatalities accounted for 55 percent of all roadway fatalities in the United States in 2003. In an effort to reduce the number of roadway departures, many transportation agencies have introduced static rumble strips using physical alterations of the roadway surface in shoulder and/or centerline sections of the roadway. Recently, more advanced technology has been developed in the form of in-vehicle advanced lane departure warning systems that automatically detect the vehicle's lane position and warn of possible roadway departures. These systems are currently showing their value in some commercial trucks in Europe, and are now available in some U.S. passenger cars. Two critical factors will govern

their ultimate success; (1) their ability to warn the driver in an effective and timely manner to make the correct action, and (2) their success in gaining driver trust and acceptance. The primary goal of this research was to better understand basic human factors principles of haptic and auditory cues as lane departure warnings.

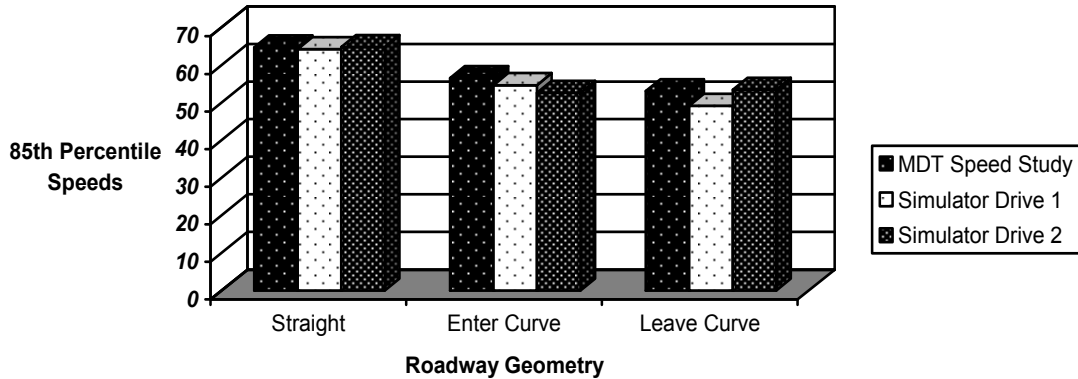


Figure 2. Comparison between simulator speeds and those from a spot speed study

Methods. A sample of 15 licensed drivers (mean age = 32 years) was recruited to participate in this simulator testing. Drivers drove along a straight, two-lane road. At intervals, they were distracted by a secondary task requiring reading and memorizing digits on an index card. Twice during each drive, while they were encountering the distractor task, a simulated wind gust was introduced that caused the vehicle to begin a lane departure to the left or right side of the lane. A zero-order lane departure algorithm triggered an auditory alarm, a seat vibration, or a combination of the two.

Results. The haptic warning modality produced significantly faster reaction times than the auditory or combined haptic/auditory modalities (Figure 3). The auditory modality produced more erratic and maximum steering responses than the haptic or combined modalities. This resulted in a greater number of steering reversals and a longer time to return to steady state.

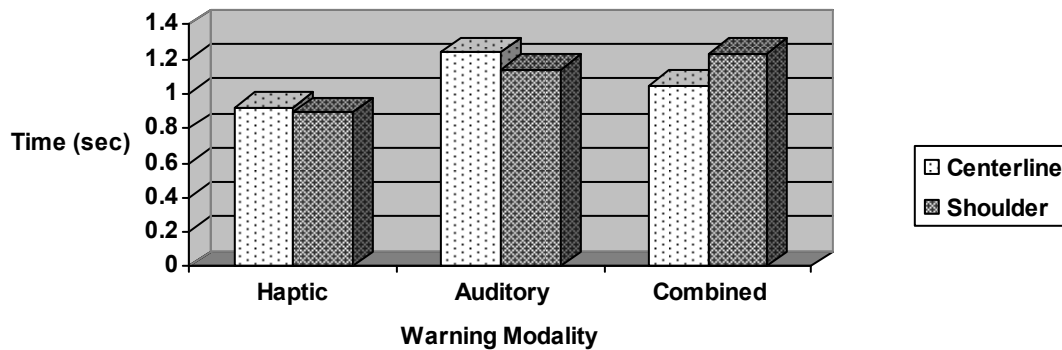


Figure 3. Response times to three warning modalities

Lane departure warnings have been shown to produce a high number of incorrect responses, that is, turning further in the direction of lane departure before beginning correction. Of special concern is that all three warning modes influenced a number of drivers who had crossed the centerline to turn further into what might be oncoming traffic. Noyce and Elango (2004) reported that over 20 percent of their participants corrected toward the left when warned of centerline crossing. In the WTI study, approximately 27% of the participants initially corrected toward the left (see Figure 4).

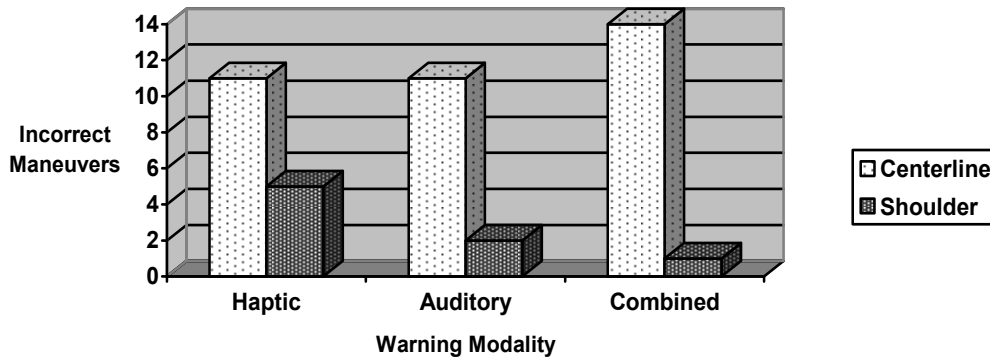


Figure 4. Inappropriate responses to lane departure warnings

Participants reported that the haptic modality was the least annoying and created the least interference to the driving task. The combined modality, while not supporting the safest lane recovery behavior, was the most preferred and most likely to be purchased.

Formative Evaluation of a Cooperative Advanced Warning System

The Design Problem. Roadway obstructions, stalled vehicles, foreign objects, pedestrians and animals in the roadway or about to enter the roadway create a significant safety hazard. Driving in the rural environment has been described, in psychological terms, as automated behavior in which the driver pays only minimal attention to the roadway, and response time to hazards may be measured in seconds rather than milliseconds. The surprise appearance of a roadway hazard may result in a collision with the object or a hazardous swerve to avoid the collision. It would enhance safety if drivers could receive an advance alert to such hazards to improve their alertness and response times. In the urban environment, drivers maintain a higher level of alertness but, because of visual barriers such as buildings, vegetation, or other vehicles, they may have difficulty seeing hazards in time to avoid a collision. In particular, pedestrians walking in or crossing roadways become a problem. One common scenario involves pedestrians crossing a multilane roadway but being visually screened from the driver by a large vehicle in the adjacent lane.

Preventive Safety Research, Inc., has designed and developed a prototype Cooperative Advance Warning System (CAWS) to allow drivers who detect a hazard to send an advanced alert to other drivers. The warning is in the form of a bright pink strobe light at the front and rear of vehicles that may be triggered by the driver. The flash frequency is coded to indicate the urgency of the alert.

A formal independent human factors evaluation of this system was requested by investors to assure its effectiveness. Such an evaluation could have been conducted during field trials on the roadways, but such a trial would have significant limitations because of the infrequency of hazardous events and the risks in staging such events in real-world traffic. In addition, it was important to identify any negative aspects of the system before it reached the streets.

Methods. Using specifications from the system designer, DriveSafety, Inc., developed a special simulation entity, a flashing pink strobe light that could be attached to the front and back of ambient vehicles in the simulation. A pink button on the steering wheel simulated the CAWS activation button in a CAWS-equipped car. The flash frequency could be controlled by the experimenter. A series of traffic scenarios was developed in which hazardous situations that might be noted by other motorists occurred. These included obstructions in the roadway, traffic accidents, pedestrians crossing the rural highway, animals in the roadway, and pedestrians in a crosswalk. Scenarios were in a combination of nighttime and daytime lighting conditions.

Thirty licensed drivers (mean age = 34 years) drove a set of four scenarios (daytime rural and urban, nighttime rural and urban) lasting five to ten minutes. Half of the drivers first viewed a 5-minute video describing the CAWS warning system, while the other half viewed an American Automobile Association video promoting safe driving. At some point in each video, a vehicle displaying a flashing CAWS light appeared. A minute or less later, a road hazard appeared in the driver's path. Measures of driver response and collision avoidance were recorded. All participants completed a user survey about the CAWS system.

Results. Results showed significant differences between drivers who had received the CAWS training and those who hadn't. A detailed examination of data from one scenario will provide an example. In this scenario, the participant is driving on a rural two-lane highway at night. A vehicle with a rapidly flashing CAWS light appears and a few seconds later a deer herd crosses the highway. In this scenario, 64% of control group drivers collided with the deer compared to 20% of CAWS-trained drivers. The mean approach distance for control group cars was 5.6 m compared to 24.1 m for CAWS-trained drivers. Much of this difference was because the CAWS drivers immediately began slowing after observing the warning (Figure 5).

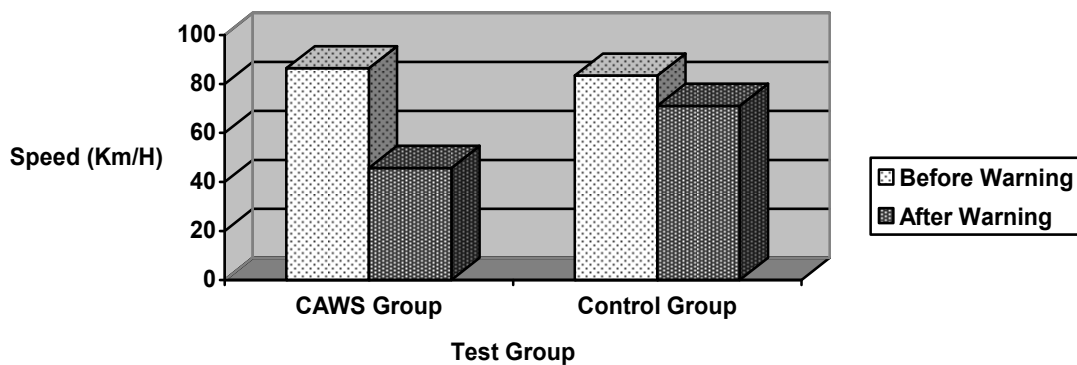


Figure 5. Driving speeds in response to CAWS imminent warning

CONCLUSIONS

Immersive simulation is becoming a valuable tool for formative evaluation in the surface transportation environment, as it has been for aerospace environments. Evaluation and refinement of highway design features using visualization and immersive simulation is effective in numerous environments such as planning and contextual design, design of structures, design of alternative geometries such as roundabouts, and design of driver information and support systems. Emerging simulation technologies allow simulation of real-world roadway sections on which proposed new geometries and infrastructure-based safety countermeasures can be evaluated. High-fidelity simulation allows conceptual and engineering evaluation of innovations in a safe and controlled environment in which participants can have controlled levels of training. The Transportation Research Board (Hughes, Manore, and Pain, 2005) has published a research plan on immersive simulation that explores many remaining issues in promoting its use.

ACKNOWLEDGMENTS

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