Abstract

For several years the Federal Highway Administration (FHWA) Turner Fairbank Highway Research Center (TFHRC) has been conducting a research program on the effectiveness of roadway delineation for providing enhanced guidance to the driver negotiating curves on rural two-lane roads at night. The FHWA Highway Driving Simulator (HDS), located at the TFHRC, plays an important role in this research program. However, the results of such simulator research must be periodically validated by field testing in a more natural environment. For the first series of studies in this research program substantial simulator experiments were conducted first employing simplified roadway scenarios, and a modest field validation experiment was conducted later. Subsequent experiments represent a paradigm shift. The validation of simulator experiments employing more complex roadway scenarios requires finding a real rural two-lane roadway with a number of different curves in each direction. It is much easier to find such a natural roadway first and then simulate it later, than it is to devise a simulator scenario and then try to find a natural roadway which corresponds in most significant ways. Several advantages were realized from conducting the field experiment first. Most of these advantages derive from working with the intimate details of the real situation first and then identifying and transferring relevant aspects to the simulation. This paper describes some of these advantages and reveals some lessons learned.
Introduction

For several years the Federal Highway Administration (FHWA) Turner Fairbank Highway Research Center (TFHRC) has been conducting a research program on enhancing the effectiveness of roadway delineation (pavement markings and markers) for providing guidance to drivers at night. This research program has initially focused on helping drivers negotiate curves on rural two-lane roadways, since this condition produces a large number of fatal roadway crashes each year. The FHWA Highway Driving Simulator (HDS), located at the TFHRC, plays an important role in this research program. Testing roadway delineation in the field can be an expensive proposition. Applying experimental treatments to the surface of an operating road is an intricate and costly operation, not to mention the safety and ethical concerns of exposing the public to novel and untested delineation patterns. The HDS provides researchers a potential tool to easily test the effectiveness of a wide variety of conventional and novel pavement markers and markings without having to install and test them all in the field. The fundamental methodology is to test many combinations of pavement markers and markings in the less costly laboratory environment, and to validate only a small subset of these combinations in the more costly field testing environment.

First Series of Experiments – Simulate First

Initially, in order to take advantage of the efficiency afforded by the simulator, the first two human factors experiments in the FHWA visibility research program were conducted in the HDS. They were devised using simplified driving scenarios and a discrete response which is relatively easy to measure. The research participants drove at a constant speed down straight flat two-lane road segments with curves located some random distance down the road. The scenarios represented nighttime driving and there was no scenery. The task of the research participants was to identify the direction of the curve ahead in the road, and to push one of two buttons located on the steering wheel. As soon as they pushed one of the buttons identifying the direction of the perceived curve ahead, they were placed on a new segment of straight flat road. Each segment of road contained a different combination of pavement markings and markers. The first laboratory experiment concentrated on the effects of retroreflective raised pavement markers (RRPMs) (1). The second laboratory experiment concentrated on the effects of edge lines (2). In both experiments curve recognition distance was the dependent variable. The data from these two experiments afforded estimates of the relative effectiveness of various combinations of pavement markings and markers, and established the possible basis for quantitative trading relationships among these roadway delineation treatments.

Because driving in a simulator is not the same as driving in the real world, the results of such simulator research must be validated by field testing in a more natural environment. Consequently, the third experiment in the series was a field validation on a newly constructed roadway that was not yet open to the public (3). It was a straight flat segment of four-lane divided highway, only one side of which was used in the field validation experiment. This one side was delineated to look like a two-lane rural road with
alternating curves at the end. The research participants drove at a constant speed down the road segment, and responded to delineated curves ahead in the same manner as in the laboratory experiments. The results of the field validation experiment were used to develop conversion factors which might be applied to simulator data on curve recognition to make the simulator data more predictive of real world driving performance. The results also suggested special limitations and precautions which must be observed in simulator experiments employing RRPMs.

The particular sequence for the first series of FHWA experiments, earlier laboratory simulation experiments followed by a subsequent field validation experiment, was appropriate for the limited testing conditions assessed. These experiments used simplified driving scenarios and a response which does not require complex driving maneuvers. Consequently it was relatively easy to find a segment of real roadway which met most of the conditions of the earlier conceived laboratory experiment. Such a sequence of simulate first / validate later has been successfully applied in other simulator validation studies as well (4,5). However, it does lack some important secondary benefits which can be derived from working with the intimate details of the real situation before attempting to create a simulation, even when the conditions being simulated are relatively simple. This is one of the important lessons learned only in retrospect, after the first series of experiments had been completed.

Second Series of Experiments – Validate First

The first series of three FHWA experiments showed the effects of enhanced pavement markings and markers on the ability of drivers to recognize curves from a distance. However, these experiments did not show the effects of these treatments on the performance of drivers actually negotiating curves. It is important that any quantitative relationships observed for recognizing curves from a distance be confirmed for negotiating the curves themselves before such relationships be proposed or implemented. Otherwise, what could be beneficial for recognizing curves from a distance might be detrimental for subsequently driving through them. Therefore a second series of experiments was designed with more complex roadway scenarios and with continuous driving responses that might be sensitive to many more contextual variables. This time the main dependent variables were driving speed, vehicle lane position and a subjective rating scale for the effectiveness of the pavement markings and markers present on any particular curve. The validation of such driver performance simulator experiments requires finding a real rural two-lane roadway with a number of different curves in each direction, all matched for the many contextual variables which are likely to influence the various response measures. Finding a natural roadway to later match an earlier conceived complex simulation of this sort would be extremely difficult, if not impossible. It is much easier to find such a natural roadway first and then simulate it later. Thus a validate first / simulate later approach was adopted.

For this second series of experiments a three-part study was conceived to investigate the effects of various safety treatments and enhancements for improving the driver’s ability to negotiate curves in the road at night. The study represents a cooperative effort between the FHWA and the Pennsylvania Department of Transportation (PennDOT). It also represents the first implementation of the FHWA paradigm shift to conduct field
validation experiments before conducting laboratory simulations. The first part of the study was a field validation experiment conducted on a real road employing a limited number of research participants and a limited number of roadway treatment conditions. This field validation experiment was conducted in the summer of 2004.

The second part of this cooperative study will be a series of two laboratory experiments conducted in the FHWA Highway Driving Simulator (HDS). The initial laboratory simulation will employ the same number of research participants and a similar number of treatment conditions as in the field experiment. It will be conducted in July 2005. This first laboratory experiment will serve as the basis for the validation of the simulator to conduct research on the effects of various roadway delineation and marking treatments on driving behavior on rural two-lane highways at night. If the results of the validation turn out favorably, the second laboratory simulation experiment will employ a larger number of research participants and a larger number of pavement marking conditions. In this second experiment the efficiency of the simulator will be employed to obtain answers concerning the effectiveness of novel combinations of pavement marking, marker and horizontal signage treatments not tested in the earlier field validation experiment. However, some of the exact original conditions of the Pennsylvania road evaluated in the initial field validation experiment will be included in second simulation experiment to serve as anchor points for comparison with actual driving results.

The particular sequence for the second series of FHWA experiments, an earlier field validation experiment followed by subsequent laboratory simulation experiments, was dictated by the complex testing conditions employed. These experiments used elaborate driving scenarios and a response which required involved driving maneuvers. Such a sequence of validate first / simulate later is not new. It has been successfully applied in other simulator validation studies (6,7). However, it is novel for the current FHWA visibility research program on enhancing the effectiveness of roadway delineation and represents a distinct change in approach. In the case of the FHWA research program, conducting the field experiment first did not render the subsequent laboratory experiment superfluous. The field experiment was designed to test only a small subset of the manifold combinations of pavement markers and markings of interest. The subsequent laboratory experiment could evaluate a much wider variety of roadway delineation treatments in a more cost effective manner.

**Method**

**Roadway**

The field validation portion of the cooperative FHWA/PennDOT study was conducted on a section of rural road in York County, Pennsylvania. A 6-mile (9.7-km) section of two-lane road with multiple combined horizontal and vertical curvature was selected. This section of roadway has a relatively high crash rate of about 16 crashes per year. PennDOT closed part of this road to through traffic during the nighttime testing. The entire 6-mile section of roadway was simulated in the FHWA HDS for the laboratory portion of the study. The simulated roadway scenario contains horizontal and vertical
roadway curvature, pavement markings, roadway signage, guardrails, foliage, terrain, representative buildings as they exist on the real road, and, most importantly, dynamic headlight illumination.

**Research Participants**

Sixteen research participants from rural Pennsylvania were recruited for the field experiment. Half were younger drivers (18-26 years old) and half were older drivers (61-79 years old). Half were males and half were females. A different sample of 16 research participants will be selected to take part in the laboratory simulation. This sample will have the same age and gender characteristics as the one selected in Pennsylvania, but will reside in the greater Washington, DC, area.

**Procedure**

The field experiment was conducted during August 2004. Tests were conducted from about 9 PM each night until about 5 AM the next morning. During the field experiment, each night each research participant drove an instrumented FHWA vehicle along the designated test roadway section, once in each direction, for 9 nights. Various roadway delineation treatments were applied to each of the curves and tangents on different nights. The main body of experimental drives in the simulator will represent an accurate replication in order of the visibility enhancement treatments applied to the test roadway in Pennsylvania. The only major difference will be a number of initial training drives to acquaint the research participants with the simulator before the main body of the experiment.

**Equipment**

In the field the FHWA instrumented test vehicle was a 1999 Saturn SL-1 four-door sedan. The instrumentation aboard the vehicle recorded speed, lane position and accelerations throughout each test drive. The FHWA HDS employs an almost identical 1998 Saturn SL-1 four-door sedan. The vehicle cab rests on an electro-dynamic actuator giving it limited motion in three dimensions: roll, pitch and heave. The simulation visual display is projected on a 180-degree wrap-around screen which does not move. In addition, the FHWA Digital Highway Measurement (DHM) van was used to take measurements of the actual roadway geometrics in the field. The DHM measurements included distance, width of each lane, heading, point of curvature, point of tangency, and many other geometric details about the test roadway. These DHM data were employed to model the roadway geometry in the simulator.

**Experimental Roadway Treatments**

Different pavement marking and marker treatments were present on the test roadway during each day of the main part of the field experiment. The first experimental day represented the baseline or existing conditions (faded pavement markings). For the next five days the roadway delineation changed on the various curves and tangents comprising the test roadway segment. These changes included brighter center lines, brighter edge lines, wider edge lines, the addition of RRPMs, and the inclusion of horizontal signing warning of approaching curves. The laboratory simulation experiment will accurately portray these changes to the markings along each segment of the simulated roadway on each successive day of experimentation.
Calibrations

Careful photometric calibrations were conducted to facilitate accurate simulation of the brightness of the roadway delineation treatments in the laboratory. In the field the brightness of the pavement markings was varied by altering the proportion of glass beads mixed into the marking paint, and the resulting retroreflectivity was measured by means of a portable retroreflectometer. The brightness of the raised pavement markers was varied in the field by applying neutral density optical filters over the lens surfaces of brand new markers, and the resulting retroreflectivity was measured by means of a laboratory goniometer after completion of the field experiment. The average retroreflectivity of the real roadway surface was also measured for the purpose of computing contrast ratios. In the laboratory simulation, the luminance of the pavement markings, raised pavement markers and roadway surface will be measured by means of a spot photometer. It is anticipated that the luminance of the actual pavement markings in the field, as well as the luminance of the roadway surface, can be adequately recreated in the laboratory simulation. However, the luminance of simulated brand new unfiltered raised pavement markers in the laboratory will probably fall far short of the luminous intensity of similar real markers in the field. Most driving simulators cannot produce the extremely high contrast ratios afforded by brand new raised pavement markers applied to a real roadway in the field.

Conclusions and Discussion

The experience gained to date from this ongoing cooperative FHWA/PennDOT study points toward the efficacy of the validate-first approach for this type of experimentation. The field experiment was successfully accomplished and formed a sound basis for creating the subsequent laboratory simulation. An example of the visual fidelity of the laboratory simulation is shown in Figure 1, which compares a photograph of one of the curves along the test roadway (left) with an image of the same curve as it appeared in the simulation (right). The lack of background trees and the differences in the color of the roadway and of the center line are the result of optimization of the scenario for nighttime viewing. For example it was discovered as a part of the initial field testing that a worn

Figure 1. Photograph (left) and simulation (right) of Curve No. 2.
yellow center line which appears extremely faded during the day may retain a sufficient number of glass beads to appear relatively distinct and visible at night. It was also learned later in the laboratory that a given roadway scene may not be capable of optimization under both day and night illumination conditions. These two lessons proved important in refining the nighttime simulation for the first laboratory experiment.

Several other advantages were realized from conducting the field experiment first. From the outset the researchers considered important practical implementation variables by interacting with highway and traffic engineers in the field. For example, intricate installation and maintenance factors must be taken into account before certain patterns and orientations of RRPMs should be proposed for implementation on curvy rural roads, especially in states with harsh winters. Furthermore, the current technology on board paint striping trucks has distinct limitations which render it impossible to apply certain geometric patterns and certain bead densities to the roadway delineation lines. Riding on the truck with the line painting crew provided a much needed dimension of realism and utility, leading to the elimination of impossible or impractical alternatives which had been originally proposed in the experimental design. By working extensively in the field first researchers are less likely to devise abstract simulator experiments which do not adequately answer the concerns of practicing engineers, who are the ultimate users of the research results. The validate first paradigm allows practicing engineers in the field to help design concrete laboratory experiments, inserting their inputs early in the research process, and thereby facilitating the relevance and applicability of any positive results obtained.

Another advantage of the validate-first approach is in the creation of appropriately modeled driving scenarios for laboratory simulation. Salient scene elements which govern nighttime driving response can be readily identified in the field and later captured in the simulation, while less important scene elements can be de-emphasized or ignored. Over 120 drives down the same road over the course of several nights with 16 different research participants behind the wheel each night can create vivid impressions of what visual, auditory, and motion stimuli are regularly encountered, and which ones are important to simulate. These impressions are gathered both from multiple first hand observations and from the spontaneous verbal comments and conversation of the research participants. As would have been expected, any retroreflective material stood out in the nighttime scene, whether that material was applied to the roadway surface (pavement markings and markers) or was found along the side of the road (regulatory, warning and guide signs). Therefore, in addition to devoting careful attention to modeling the pavement markings and markers which formed the focus of the study, over 120 roadside signs were modeled and placed in their proper places along the 6 miles (9.7 kms) of simulated roadway. The importance of guardrails was also readily apparent, not only the reflectors on the rails, but the image of the continuous guardrails themselves and their periodic posts. A less obvious but extremely important visual cue turned out to be the continuous clumps of grass that lined the edges of the roadway in many places. Near to the vehicle the rapidly passing individual blades of grass provided important speed cues, and further away from the vehicle these grassy embankments gave indications of the sharpness of upcoming curves. The role of such grassy embankments was not
anticipated, but experience in the field indicated their importance. So, despite considerable difficulty in modeling them, these grassy embankments became a prominent feature of the subsequent simulation.

The advantages of the validate-first approach are not limited to the appropriate modeling of visual stimuli for the laboratory simulation. Unique vehicle dynamics situations specific to the particular test roadway can be identified, and later modeled in the simulator to the best degree considering the limitations of the motion generating equipment. Over 120 nighttime drives down the same road with 16 different research participants conditioned the body of experimenter to a variety of relevant motion cues. One important cue was the sensation that the road is inclined either downward or upward along certain roadway segments. Another important cue was the sensation of traversing the crest of certain hills. A less obvious cue was the unique vehicle dynamics associated with one of the high crash rate curves. A moderate right-hand curve was followed by an immediate dip in the road and then a sharp left-hand curve. This situation produced un-sprung vehicle weight at a critical moment in the turning maneuver, setting up the circumstance for a possible loss of vehicle control. The vehicle dynamics model in the HDS was adjusted to render an approximation to such important motion cues. Even if the HDS could not adequately simulate a number of the important motion cues, at least the validate-first approach established the goal for motion cue modeling.

In summary the main advantages of the validate-first approach are not intrinsic to the validation process itself. In the present context, validation consists of the comparison of experimental data collected on a real road with similar experimental data collected in a driving simulator. The validation process is insensitive to time. It is immaterial whether the field experiment on the real road was conducted before or after the laboratory experiment in the driving simulator. What counts is whether the two collections of driver performance data are the same or different. Thus the advantages of the validate-first approach are primarily methodological. A simulation is an abstraction from reality. It incorporates certain aspects of reality and ignores others. The validate-first approach follows the logical progression of the abstraction process. It begins with the more varied natural world and proceeds to the more sparse simulation of that world. Of course, if it were just for the selection of the appropriate road to simulate, one might select the road first, simulate that road, conduct the laboratory simulation next and then return to collect the field data. But this arrangement ignores the deeper benefit of conducting the field portion of the study first. This deeper benefit allows the experimenter to gain better orientation, insight and direction early in the study. In these crucial formative stages, this deeper benefit allows the experimenter to become immersed in the richer and ultimately more relevant real world, rather than in the relatively impoverished and unnatural world of simulation. In short, if simulation is an abstraction of reality, it is better to let nature be the first instructor.

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