DSC North America 2003 Proceedings, Dearborn, Michigan, October 8-10, 2003 (ISSN 1546-5071).

Motion Cues for a 3-DOF Driving Simulator

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September 5, 2003

ABSTRACT

Few motion-capable driving simulators possess the ability to create the actual sustained forces felt by the human driver and/or occupants of a real automobile in accelerating, decelerating and turning. Instead various combinations of substitution, compromise, masking and subterfuge are employed to create the best illusion of driving motion for the given simulation environment. In implementing motion cues in driving simulation, efforts have tended to gravitate around two primary methods: 1) the vector substitution method and 2) the leaning vehicle method. The vector substitution method replaces the resultant vector of several forces with gravity when insufficient sustained forces are available. The leaning vehicle method follows the model of the bicycle or motorcycle, and leans the vehicle accordingly. Neither method is entirely adequate for simulating automobile driving. The vector substitution method tends to be employed in research laboratories equipped with high-fidelity driving simulators. The leaning vehicle method tends to be employed in video game parlors equipped with much less richly endowed driving simulators. As a result of their different application spheres, these two methods have been called the “engineering approach” and the “fun ride approach”. Each approach has its merits and its drawbacks, and these merits and drawbacks cut across application spheres. Nor are the differences in implementation of these two approaches trivial. If the driving scenario calls for the automobile to make a right-hand turn, for example, the simulator tilts to the left with the vector substitution method, whereas the simulator tilts to the right with the leaning vehicle method. In terms of simulation capabilities, the FHWA Highway Driving Simulator (HDS) falls somewhere between the high-fidelity research simulators and the lower fidelity gaming simulators. Is the vector substitution method or the leaning vehicle method best suited for this type of intermediate simulator? In order to answer this and other questions concerning simulating motion cues for driving scenarios, the FHWA is conducting a brief series of pilot studies investigating driver responses to various algorithms for implementing motion cues in the HDS. The first pilot study in the series compared the vector substitution method with the leaning vehicle method for 12 research participants. Driver responses to these two types of motion cues were measured under three different conditions: 1) steering the simulator vehicle while viewing the simulated roadway with the vehicle under cruise control, 2) passively riding while viewing the simulated roadway with the simulator vehicle under auto-pilot, 3) passively riding while blindfolded with the simulator vehicle under auto-pilot. The test for each condition consisted of 16 curves in different random orders. The results of the pilot study showed that participants generally expected that the motion of the simulator car cab would lean into curves as provided by the leaning vehicle method, instead of leaning out of curves as provided by the vector substitution method. The participants felt that the motion was more natural and judged curves more correctly when the vehicle leaned into the curve. Of the 36 blocks of trials that were run, 16 supported the leaning vehicle method, three supported the vector substitution method and 17 were inconclusive. Of the 12 research participants, five could be characterized as adhering strongly to the leaning vehicle motion algorithm, three could be characterized as occasionally adhering to the vector substitution algorithm and 17 were indeterminate. The overall results also indicate that research participants can judge the sharpness of the curves at a significantly better than chance level of performance. However, visual cues may play an important role in this ability. It is postulated that the results obtained with regard to leaning vehicle motion are the consequence of a strong expectation on the part of the research participants. The research participants behaved as if the simulated roadway had a relatively severe superelevation in the curves, even though no such superelevation was visually modeled. The preconception that such superelevation should be present overshadowed other sensory inputs. These conclusions need to be tempered by some important limitations in the implementation of the motion cues. For example, no compensatory tilting of the visual horizon was employed, no filtering was present for roll motions, the car cab roll may have been somewhat more than the participants expected, and the simulator scenes were relatively dark (nighttime driving).

INTRODUCTION

Background

The technical literature on the simulation of motion cues is extensive. Advani, Hosman, and Haeck (1) note that much of the literature centers around modeling motion cues for flight simulation. These authors acknowledge that modern civil aviation regulations require motion systems on high-end pilot training simulators, but that to date no standardized cuing methods exist. The local requirements of the simulator user often dictate the choice of a motion cueing algorithm.

Concerning driving simulators, Advani and Hosman (2) developed an integrated motion cueing algorithm. This algorithm offers a variety of choices in implementing motion cues. Advani and Hosman emphasize the necessity of identifying important portions of the driving task in selecting motion choices to be used in driving simulation. They identified two general driving tasks, tracking and disturbance rejection. Tracking tasks generally involve following a prescribed path, such as driving around an off ramp. Visual information is usually adequate for such tracking tasks. Disturbance rejection tasks generally involve perceiving perturbations and correcting for them, as when reacting to a sudden wind gust on the road. Non-visual motion cues play a much larger role in such disturbance rejection tasks. Even among these disturbance rejection tasks, it is necessary to isolate particular subtasks which are of special importance in supporting the driving behavior under investigation. There are cases where a vehicle could be placed in an unstable state while rounding a curve, as when encountering a patch of ice. The perception of incipient vehicle instability in such a situation, and correcting for that instability in time, is one such disturbance rejection subtask. If this subtask is important in the driving situation being researched, then the motion algorithm should be optimized to present the best possible cues for perceiving vehicle instability.

Von der Heyde and Riecke (3) present a detailed analysis of two prevalent approaches to applying motion cues in driving simulations. They identify the “engineering approach” used in high-end driving simulators and the “fun ride approach” used in video game driving simulators. In the current investigation these two approaches are renamed the vector substitution method and the leaning vehicle method. Von der Heyde and Riecke actually propose an experiment comparing these two methods similar in concept to the first pilot study described herein. However, the authors present no data from such an experiment. They point out the motion limitations of all driving simulators, over a wide range of simulation fidelity. Even the high-end research driving simulators cannot produce various kinds of sustained forces encountered in normal driving situations. The National Advanced Driving Simulator (NADS) can overcome some of these limitations, but not all (4). There is always a degree of compromise and artifice used to create simulated motion cues for driving tasks. In the case of high-end driving simulators like the NADS, the compromise and artifice are largely based upon a mathematical modeling of physical forces and accelerations. The gaming perspective can sometimes be quite different. Phillip Denne (5) espouses the primacy or artistry over mathematical rigor. From this perspective the goal becomes delivering an artificial reality which the public wants, and “they want reality as they think it ought to be.”

Application to FHWA Highway Driving Simulator

Thus there is no single method for achieving the illusion of driving motion. The FHWA Turner Fairbank Highway Research Center (TFHRC) is undertaking a series of pilot studies to investigate the most appropriate method for the FHWA Highway Driving Simulator (HDS). Several different motion cue methods are being tested in the proposed series of pilot studies. In the first pilot study of the series, two popular motion cue methods are compared and contrasted: 1) the vector substitution method and 2) the leaning vehicle method. The vector substitution method replaces the resultant vector of several forces with gravity when insufficient sustained forces are available. The leaning vehicle method follows the model of the bicycle or motorcycle, and in curves leans the vehicle accordingly. The vector substitution method tends to be employed in research laboratories equipped with high-fidelity driving simulators possessing motion capabilities in 6-degrees of freedom (DOF) and a viewing screen which moves with the simulator vehicle. These research applications often represent a relatively high degree of simulation immersion. The leaning vehicle method tends to be employed in video game parlors equipped with much less richly endowed driving simulators possessing motion capabilities in one or two degrees of freedom and a fixed viewing screen which does not move with the simulator vehicle. These amusement applications most often represent a lower degree of simulation immersion. These two methods for presenting motion cues have been called the “engineering approach” and the “fun ride approach” (3).

What then is the researcher having an intermediate simulation immersion environment to do? For example the FHWA HDS has a motion base capable of 3 degrees of freedom and a fixed viewing screen which does not move with the simulator vehicle. In terms of simulation capabilities, this simulator falls somewhere between the two application spheres. It is not clear what is the appropriate motion algorithm to apply to the FHWA HDS for the conduct of specific proposed experiments. It is also not clear which perspective to take with regard to the mathematical modeling of physical forces vs. delivering what research participants expect or want from a motion system.

Thus the FHWA HDS straddles two popular schools of thought for implementing motion cues in driving simulations. These two methods, the vector substitution method and the leaning vehicle method, are not the only methods, and perhaps not even the best candidate methods, to be evaluated as possible motion algorithms for the FHWA HDS. There are other possibilities. For example, in some cases the visual scene tilts or rotates to provide the primary cues, and the vehicle and driver remain relatively or completely stationary. In other cases, dynamic forces may be less prominent, and the vehicle motion basically follows the scene terrain.

Research Approach

The research approach for the proposed investigation employs a series of pilot studies and rapid prototype scenarios for testing various motion options for the HDS. The goal is not to execute a fully crossed experimental matrix of conditions, but to explore a number of options for motion implementation in the HDS, so as to develop the optimal algorithm, or algorithms, for future studies. The present investigation concentrates on the short-term experimental needs, rather than attempting to answer questions concerning the application of simulation motion algorithms in general. The investigation explores transitory rotational motion cues as well as the modeling of sustained forces and accelerations. The investigation explores the interaction of motion, auditory and visual cues. Highway conditions are not the main focus of the proposed series of pilot studies. There is no other traffic on the simulated roadway. Only traditional pavement markings and traffic controls devices are present in the simulated scenes.

The primary research question issues directly from the unique configuration of the HDS. How should motion cues be implemented in the HDS? What motion algorithm provides essential cues to support the driving task under study and promotes a general sense of realism and simulation immersion? Another important corollary to this basic question concerns simulator sickness. Which, if any, of the promising motion methods has a lower tendency to produce simulator sickness in our type of simulator? The answer to this corollary question will have an important bearing on which motion algorithm is ultimately selected to implement upcoming experiments. From a search of the scientific literature, to our knowledge no extensive prior experience base with this type of simulator has been systematically developed concerning the relationship between motion cues and either simulation realism or simulator sickness. The video gaming industry may have such an experience base, but these data are often not available in the scientific literature. The envisaged series of evolving pilot studies is directed toward improving simulator realism and reducing simulator sickness in this relatively unique type of research simulator.

Evaluation of Motion Algorithms

The first pilot study in the series addresses two primary methods of implementing motion cues in driving simulation: 1) the vector substitution method and 2) the leaning vehicle method. This first pilot study concentrates primarily on the problem of determining appropriate motion cues for turning in curves. The motion cues associated with accelerating and decelerating were not investigated in this first pilot study.

The vector substitution method is based upon calculating the resultant vector for a number of forces that may be acting upon a driver in a turning vehicle. The method replaces the resultant vector of several forces with gravity when insufficient real sustained forces are available.

The leaning vehicle method follows the model of the bicycle or motorcycle, and leans the vehicle accordingly. In the real world, in navigating curves while riding on a two-wheeled vehicle, the operator leans into the curve so that the resultant vector of acting forces tends to pass through the point where the wheel is in contact with the ground, thus making the slender vehicle and operator more stable. Although the case of a four-wheeled vehicle is not as simple, in the real world on a severe curve with little superelevation, the driver of an automobile also tends to lean into a curve to resolve acting forces.

Thus, for many different real curves, at least from the driver's perspective, the body orientation may be similar. However, the implementation of appropriate motion cues in a driving simulator may be different depending upon which motion algorithm is selected. Although not the focus of the first pilot study, a similar rationale holds for acceleration and deceleration, with various motion methods resulting in different behaviors for the simulator vehicle. In practical driving simulator implementation, the precise motion algorithm employed is often the result of a priori modeling of physical forces and accelerations, as well as practical adjustments for the particular type of motion capabilities available.

Determination of Factors Affecting Motion Perception

Besides the various relevant motion models, the current series of pilot studies will investigate other important factors affecting motion perception in a driving simulator. The overall perception of realism or simulation fidelity is a complex sensory fusion of many cross modal inputs. Not the least of these inputs are visual cues. The realism of the visual scenario can have a powerful effect on overriding subtleties or contradictions in motion cues. For this reason, in the proposed series of pilot studies, under one condition research participants drive the scenarios in an active manner with full visual inputs. In other conditions the participants are either passively driven through the scenario with full visual inputs, or blindfolded, where the motion and gravitational cues are likely be more prominent.

Other factors affecting the relative perception cues for motion include vehicle speed and the time of day. Because higher speeds tend to make motion cues more pronounced, the proposed series of pilot studies will employ a variety of vehicle speeds, ranging from fast (about 65 mph) to slow (about 25 mph). The brightness (daylight) or darkness (twilight or night) of the visual driving scene is also likely to have an effect on the interpretation of motion cues. In the particular simulator configuration of the HDS, the visual driving scene is presented on a projection screen which does not move with the motion of the vehicle. This type of screen arrangement can produce more conflicting visual cues than a viewing screen which moves with the simulator vehicle. These contradictory visual cues could result from the perception of the edge of the projector screen, or the perception of the motion of the A-post of the car relative to some fixed feature of the screen surface. A darker environment, like driving in a nighttime scenario, is likely to mask some of these possible contradictory visual motion cues. In a simulated daylight environment the vehicle cab and surrounding laboratory space are bathed in light, making it easier to perceive contradictions between motion cues. The first pilot study reported herein was run in a dark environment, i.e. a simulated nighttime driving scene, in order to minimize extraneous cues.

Development of an Appropriate Motion Algorithm

The primary research goal of the current investigation is to develop a motion model, or combination of motion models, most appropriate for the upcoming experiments in the HDS. One such planned experiment is in the Intersections Research Program Area. This experiment involves driving through signal controlled intersections on rural/suburban roadways. Thus one of the scenarios will be driving along a straight roadway with a series of signalized intersections. Research participants will decelerate and stop on yellow and red traffic signal lights, and accelerate and maintain speed on green signals. As a result of preprogrammed timing cycles, research participants will likely experience differing severities of decelerations.

Another planned experiment is in the Visibility Program Area. This experiment involves driving through curves on rural two-lane highways. In this case the scenario to be tested will consist of driving along relatively long tangent segments of roadway that ultimately end in a turn either to the right or to the left. The curves will be of differing degrees of curvature (sharpness), differing deflection angles (length of curve), and differing degrees of superelevation (roadway bank). The first pilot study reported herein is concerned with the most appropriate motion model for the situation of driving through curves on rural two-lane roadways at night.

It would be convenient if one motion model proved superior to the others for all of the driving circumstances of interest in the next few experiments to be conducted in the HDS. If that motion model also tended to produce the least motion sickness, the outcome would be better still. Then, at least in the short term, the development of an appropriate motion algorithm for the HDS would be relatively simple. However, no one set of motion parameters may prove adequate for all driving scenarios, in which case some scale factors and adjustments may be needed. Certain adjustments to the model may prove superior for curves and others for acceleration and deceleration at intersections.

METHOD

Research Participants

The research participants were 14 employees from the FHWA TFHRC located in McLean, Virginia. Each research participant possessed a valid U.S. driver's license. Limited demographic information (e.g., age, gender, city of residence, driving experience, health, etc.) was collected. The sample of drivers included 7 males and 7 females and ranged in age from 21 to 62 years. The investigation took about one hour for each research participant to complete, all in one session. Employees of the TFHRC were asked to volunteer to participate in the investigation. They were not paid separately for their services, although they were allowed to include the time spent in their normal Pay Period. Of the 14 research participants, two were eliminated. One female participant (Number 3) developed symptoms of simulator sickness and could not complete all three blocks of trials. Details of this case may be found in a different paper delivered at the present Conference. One other male participant (Number 10) was eliminated at random because of an error in counterbalancing the blindfolded condition. Thus the data reported in the present paper are for 12 research participants, 6 males and 6 females. The average age was 32.6 years old.

Experimental Conditions and Variables

The stimulus conditions and independent variables employed in the first pilot study are given below. Some of the FIXED stimulus conditions listed below will become independent VARIABLE conditions in subsequent pilot studies.

1. Roadway scenario, FIXED: straight-segments followed by curves
2. Lighting condition, FIXED: nighttime
3. Driving speed; FIXED: computer (cruise) control always set to 45 mph
4. Driving/viewing condition, VARIABLE: three conditions: 1) steering and viewing, 2) passive riding and viewing, 3) passive riding while blindfolded
5. Motion algorithm, VARIABLE: vector substitution vs. leaning vehicle
6. Length of the tangent approach segment before a simulated curve, VARIABLE: 4 different distances ranging from 406 to 806 feet
7. Length of the tangent trailing segment after a simulated curve, FIXED: 492 feet
8. Degree of curvature of a simulated curve, VARIABLE: 10 degrees or 30 degrees per 100 feet, randomly assigned
9. Deflection angle of a simulated curve; FIXED: 90 degrees
10. Direction of simulated curve: VARIABLE: right or left, randomly assigned.
11. Superelevation of simulated curve, FIXED no superelevation (0 percent)
12. Entry and exit spiral of simulated curves, VARIABLE: two values, correlated with degree of curvature
13. Auditory driving cues, VARIABLE: engine noise correlated with vehicle speed.

A sample of some of the possible dependent variables which may be used in the proposed series of pilot studies follows:

1. Vehicle speed during the entire driving segment of each scenario, in kilometers per hour
2. Vehicle lateral lane position during the entire driving segment of each scenario, in meters from the center of the roadway
3. Individual participant ratings and responses to questions concerning motion perception, curve perception, quality of simulation, and simulator sickness throughout the driving segment of each scenario

4. Individual participant responses to questions on a Background Survey administered before the beginning of practice trials
5. Individual participant responses to questions on a Post-Experiment Questionnaire administered after the completion of the experimental trials.

The most important dependent variables for the first pilot study are contained in the third item. During all of the driving scenarios, an experimenter rode in the simulator vehicle cab with the participant. This experimenter recorded participant perceptions of motion and curvature for each curve in the driving scenario. The experimenter also regularly asked about the presence of any symptoms of simulator sickness.

Stimulus Generation

The experiment was conducted in the FHWA fully interactive HDS located at the TFHRC. The simulator consisted of a 1998 Saturn SL sedan car cab mounted on a motion base. A loudspeaker system provided engine and roadway noise. A curved projection screen in front of the car cab provided an 88-degree field of view of the simulated roadway environment, with a vertical field of view that covered the entire windshield. Scene elements were generated by both the Multigen Creator real time modeling package and through dynamic scene graphics programming. The computer graphics were rendered in real time by an SGI ONYX2 computer with Infinite Reality Engine graphics, running SGI OpenGL Performer software. The visual scenes were projected by an Electrohome 9500 video projector with a visible resolution of 1920 X 960 pixels refreshed at a nominal 60-Hertz frame rate. The visual horizon did not rotate on the screen. All motion cues came from motions of the car cab. The simulator car cab had limited motion consisting of three degrees of freedom: two rotational modes, pitch and roll, and one translational mode, heave (vertical motion). These movements were imparted to the simulator car cab by an electro-mechanical motion base controlled by appropriate vehicle dynamics software. The vehicle motion system employed both software and hardware safety clamps and interlocks to protect research staff and participants from harm due to the motion of the car cab.

Motion Algorithms

The two motion algorithms, the vector substitution and leaning vehicle method, use the same Vehicle Dynamics Model (VDM). The VDM for the current pilot study is based on the VDM provided by Illusion Technologies International (ITI), Inc. It is comprised of five major components: engine, transmission, steering, suspension and brakes. The engine model uses an ideal air cycle with throttle-limited airflow to determine the engine torque output for a given throttle and engine rotation velocity. The transmission model inputs engine torque and transforms the torque based on the selected gear. The torque is proportioned from the transmission to the drive wheels using differential gearing. The steering model calculates the tire slip angles, lateral acceleration, longitudinal acceleration, yaw rate, etc. for a vehicle in steady state cornering. The suspension model uses simple damped linear spring equations to determine suspension roll and pitch due to vehicle accelerations. The brake model generates wheel torques as a function of driver brake pedal force and brake controller commands.

The FHWA HDS has a 3-DOF (pitch, roll and heave) vehicle motion base to implement the commands from the VDM. The motion platform control model receives these commands as vehicle accelerations and random noise from a noise generator. Only one difference distinguishes the two motion algorithms serving as the independent variable for the current pilot study. The roll angle is calculated as it normally would be for the vector substitution method, so as to lean the vehicle outward from the center of the curve. For the leaning vehicle method the roll angle is reversed to lean the vehicle inward toward the center of the curve. The rotation angles are also scaled to adjust for optimal motion perception. Since the experiment was designed for zero superelevation and a flat roadway, the amount of roll of the vehicle cab was directly related to the angular change of the vehicle's direction of motion over time, or centripetal acceleration. The non-real centrifugal force referred to elsewhere in relation to the perceptions of the research participants is assumed to be inversely proportional to this centripetal acceleration.

The characteristics of the vehicle motion during this first pilot study are shown in Table 1. The Table gives the maximum roll angle in degrees, as well as the increase in roll angle at the beginning of the curve, and the decrease in roll angle at the end of the curve. The vehicle motion varied somewhat from trial to trial depending upon whether the curve turned to the right or left, and whether the car cab leaned in or out of the curve. Therefore, all of the values are given as the maximum, mean and minimum measurement of motion for each condition. The maximum roll angle was calibrated with an inclinometer. The increase and decrease in roll angle was computed by measuring the time that it took to move from level to the maximum roll angle at the beginning of the curve, and the time that it took to move from the maximum roll angle to level at the end of the curve. For the 30-degree curve condition, the maximum roll angle was at the limit of motion for the simulator.

TABLE 1 Simulator Roll Motion

Roadway Curvature	Statistic	Increase in Roll Angle, degrees/sec	Maximum Roll Angle, degrees	Decrease in Roll Angle, degrees/sec
10 degrees per 100 feet	Maximum	1.3	6.0	1.4
	Mean	1.0	5.4	1.3
	Minimum	0.78	5.0	1.1
30 degrees per 100 feet	Maximum	2.6	8.5	3.0
	Mean	2.4	8.5	2.6
	Minimum	2.1	8.5	1.9

Experimental Design

The first pilot study consisted of three driving sessions for each research participant. In one driving session (steering condition) the participant steered the simulator vehicle through a series of 16 curves in a random order, but vehicle speed remained steady at 45 miles per hour (cruise control). In another driving session (riding condition) the simulator vehicle drove itself through the same series of 16 curves in a different random order, and the research participant sat passively in the driver's seat and viewed the simulated roadway scene out the windshield. In a third driving session (blindfolded condition) the simulator vehicle drove itself through the same series of 16 curves in a different random order, and the research participant sat passively in the driver's seat wearing a blindfold. For both the riding and blindfolded conditions, the vehicle speed remained steady at 45 miles per hour, as in the steering condition. There were 4 different types of curves in each driving scenario: 1) right hand– 30 degrees of curvature; 2) left hand – 30 degrees; 3) right – 10 degrees; and 4) left – 10 degrees. All curves had a 90-degree deflection angle, a 0 percent superelevation, and high luminance pavement markings. Thus all the curves were very clearly marked, but had no superelevation or bank to them.

The scene recreated a nighttime drive over flat land (no vertical curvature) in a relatively dark environment. The 4 different curve types were randomized over each block of 16 trials in a different order each time. There were two different motion cueing algorithms: one where the where the car cab leans into the curve (leaning vehicle method) and the other where car cab leans out of the curve (vector substitution method). These two motion algorithms were randomized over each block of 16 trials in a different order. Thus in any one driving session, there were 4 different curve types paired with two different motion algorithms, or 8 combinations, and one replication, to make a total of 16 trials per block. Each trial consisted of a tangent roadway segment (between 406 and 806 feet in length), followed by a curve, followed by another tangent segment of 492 feet in length. Each trial took about 25 seconds to complete at a fixed speed of about 45 miles per hour. After each driving session of 16 trials (7 minutes), there was a short break of about one minute. There were three groups of 4 research participants in each group. One group of research participants completed the steering condition first, another group completed the riding condition first, and the third group completed the blindfolded condition first. An experimenter rode in the passenger seat for all trials. All data collection was by means of paper forms on a clipboard carried by the experimenter. The experiment took about 60 minutes per research participant, including completing all forms, tests and questionnaires.

Procedure

Each research participant read and signed an Informed Consent form and provided information on a brief Background Survey. Then the participant completed a pre-experiment baseline procedure for possible symptoms of simulator sickness. Details of the simulator sickness management procedure used at the TFHRC are the subject of a different paper delivered at the present Conference. Next each research participant read the following verbatim instructions:

"This experiment is designed to assess your perception of going around curves in a driving simulator. The experimenter will help you to enter and exit the simulator, will instruct you what to do, and will ride with you at all times in the passenger seat. The speed of the simulator vehicle will mainly be controlled by the computer, just as if you had placed the vehicle in cruise control. Therefore, most of the time you will not need to operate the accelerator or brake pedals.

"There will be three parts to the experiment. Each part consists of a driving scenario with a series of 16 curves in the road, with straight stretches of roadway in between. Some of the curves will be sharp, and some will be shallow. These curves will be in a different random order for each part of the experiment.

"Two different systems will be employed to convey to you a feeling of motion while in the simulator. One important purpose of the experiment is to determine which of these two motion systems feels the most natural while going through the curves. Sometimes the motion will feel natural and sometimes it will feel unnatural.

"In the first part of the experiment, you will steer the simulator vehicle through the series of 16 curves. Your task is to stay in the center of your lane on the road, even though you will not be controlling the speed of the simulator vehicle. In this part, you will rate each curve as to whether the feeling of motion was natural or unnatural. You will also rate whether each curve was perceived as sharp or shallow.

"In the second part of the experiment, the simulator vehicle will steer itself. In this part you will ride in the driver's seat and watch the scenario through the windshield. You will rate the same two qualities concerning each curve. Was the feeling of motion natural or unnatural, and was the curve perceived as sharp or shallow?

"In the third part of the experiment, the simulator vehicle will steer itself, like in the second part. However, this time you will be asked to wear a blindfold covering your eyes. Even though you will not be able to see anything, the motion cues conveyed by the simulator will give you sensations of going around curves. This time you will rate each curve as to whether it was perceived as turning to the left or to the right, and whether the curve was perceived as sharp or shallow.

"The order in which you will complete each part of the experiment will be different for different research participants. Thus you may begin with any one of the three parts of the experiment and transition to any other part. The experimenter will tell you which part is coming up, and what to do, before each part begins. Each part of the experiment will take about 7 minutes, with a brief pause of about one minute between parts. All three parts, including pauses, should take about 25 minutes. Do you have any questions?"

After completing the third block of trials, each participant filled out a brief Post-Experiment Questionnaire and was administered a post-experiment test to ensure the absence of any significant symptoms of simulator sickness. One female participant did not complete the experiment. She displayed mild symptoms of simulator sickness at the conclusion of the first block of 16 trials in the steering condition. With a single instance, it is impossible to ascertain which driving condition or which motion model, if any, might be more prone to simulator sickness.

RESULTS

The preliminary results of the first pilot study appear to support the leaning vehicle method as meeting the expectations of the research participants better than the vector substitution method. The participants felt that the motion was more natural and judged curves more correctly when the vehicle "leaned into" the curve (leaning vehicle method) than when the vehicle "leaned out" of the curve (vector substitution method). For curves with the sharpness, superelevation and speed used in the current pilot study, the vector substitution method always rotated the car cab outward from the center of the curve. However, this relationship is not true in general. For a sharp curve with a high percent of superelevation driven at a very slow speed, the vector substitution method would lean the vehicle into the curve center. Thus, while the leaning vehicle method always leans the vehicle into the curve, the vehicle substitution method does not always do the reverse. Consequently, the vector substitution method cannot in general be defined as an outward leaning vehicle model.

To assess the results of the pilot study, in the steering and riding conditions, the "natural" response was correlated with the expected response if the leaning vehicle method alone completely determined the response. The proportion of curves that were judged as "natural" based on an assumed perfect "leaning in" criterion was computed for each research participant. This proportion was called the Leaning In Quotient (LIQ), and indicated perfect adherence to the leaning vehicle algorithm when LIQ = 1, and perfect adherence to the vector substitution algorithm when LIQ = 0. An LIQ = 0.5 would indicate random guessing. The LIQ for each research participant and for each testing condition is shown in Table 2. In the blindfolded condition, where the motion cues were expected to have the major influence, the right vs. left curve response was likewise correlated with the expected response given an assumed perfect "leaning in" criterion. A proportion was computed for curves that were correctly judged as to direction based on this criterion. This proportion was similarly converted into an LIQ, which had the same implications for adherence to a strict motion algorithm as the previous LIQ, even though this latter LIQ was based on a different underlying metric. Thus the two kinds of LIQ metrics are presented together in Table 2. A statistically significant deviation from an LIQ = 0.5 would indicate an adherence to the vector substitution method for LIQ < 0.5 and an adherence to the leaning vehicle method for LIQ > 0.5.

TABLE 2 Leaning In Quotient (LIQ)

Participant Number	Condition			Average
	Blindfolded	Riding	Steering	
1	0.00	0.69	0.50	0.40
2	0.13	0.81	0.56	0.50
4	0.50	0.75	0.38	0.54
5	1.00	0.75	0.44	0.73
6	0.75	0.50	0.50	0.58
7	0.56	0.50	0.25	0.44
8	0.44	0.88	0.38	0.56
9	0.81	1.00	0.69	0.83
11	0.44	0.69	0.44	0.52
12	1.00	1.00	0.88	0.96
13	1.00	1.00	0.94	0.98
14	1.00	0.94	0.44	0.79
Average	0.64	0.79	0.53	0.65

Examination of the LIQ data portrayed in Table 2shows a preponderance of LIQ scores greater than 0.5, with a grand average LIQ of 0.65 for the entire matrix. If this grand average is considered as the overall proportion of leaning in responses, then for a sample size of 576, an LIQ = 0.65 is statistically significantly different from the chance proportion of LIQ = 0.50 at the alpha = 0.05 level. Therefore, in a gross analysis, the results of the study favored an hypothesis that the operative motion model was the leaning vehicle method.

In a more detailed analysis, for each individual participant in any given condition the LIQ can be tested against statistical expectation to determine whether for that block of 16 trials the participant favored the vector substitution algorithm or the leaning vehicle algorithm. With the small number of only 16 trials per condition, exact probabilities of the binomial distribution for small samples were used to construct a confidence interval, rather than the normal distribution approximation to the binomial. A confidence interval was constructed for the null hypothesis that the responses of the given participant were purely the result of chance, and that the participant exhibited no statistically significant adherence to either motion algorithm. For a sample size of 16 and a two-tailed alpha level of 0.05 an LIQ of 0.25 or less would result in rejecting the null hypothesis in favor of the vector substitution method (leaning out). Similarly an LIQ of 0.75 or more would result in rejecting the null hypothesis in favor of the leaning vehicle method (leaning in).

The confidence interval defined above was used to convert the data in Table 2 into categories to characterize the results of running a given block of trials with a given research participant. In Table 3 the cells in Table 2 have been replaced with an "I" if the participant adhered to a leaning in criterion (LIQ = 0.75 or more) or an "O" if the participant adhered to a leaning out criterion (LIQ = 0.25 or less). Blank cells represent indeterminate outcomes where the null or chance hypothesis cannot be rejected. The totals of the "I" participant blocks are shown in the marginals. As can be seen in Table 3, of the 36 blocks of trials, 16 supported the leaning vehicle method ("I"), three supported the vector substitution method ("O") and 17 were indeterminate (blank). The most "I" participant blocks are shown in the riding condition, the next most in the blindfolded condition and the least in the steering condition. Of the 3 "O" participant blocks, two were in the blindfolded condition and one was in the steering condition. No single participant exhibited a tendency to adhere to the leaning out algorithm ("O") on more than one block of trials. Thus, out of the 12 research participants, 3 participants can be characterized as having a weak tendency to on occasion follow the vector substitution method. These three participants cannot be characterized, however, as having a tendency to follow the vector substitution method in any consistent way.

TABLE 3 Leaning In ("I") and Leaning Out ("O") Blocks of Trials

Participant Number	**Condition**			**Total "I"**
	Blindfolded	**Riding**	**Steering**	
1	O			0
2	O	I		1
4		I		1
5	I	I		2
6	I			1
7			O	0
8		I		1
9	I	I		2
11				0
12	I	I	I	3
13	I	I	I	3
14	I	I		2
Total "I"	6	8	2	16

By contrast, as concerns the "I" participant blocks, two participants exhibited a tendency to adhere to the "I" algorithm on all three blocks of trials, and three participants exhibited a tendency to adhere to the "I" algorithm on two blocks of trials. If these two categories are combined, out of the 12 research participants, 5 participants can be characterized as having a strong tendency to generally follow the leaning vehicle method. In the blindfolded condition, where motion cues are the only indicators of curve direction, 6 of the 12 research participant blocks can be characterized as "I" blocks and two as "O" blocks. In the steering condition the proportion of "I" participant blocks was much smaller. However, these blocks of trials were possibly contaminated by driver performance issues. Since the research participants had to drive these scenarios, they tended to rate as "unnatural" any extreme motion cues which they may have caused due to their own poor performance in negotiating a given curve, irrespective of which way the vehicle leaned on that particular curve. Furthermore, it is the blindfolded condition where the participant's response is most influenced by purely motion cues, and this condition showed a good number of "I" participant blocks.

The above conclusions do not support a bimodal distribution of participant expectations concerning simulator motion cues. Figure 1 shows a frequency distribution of the LIQ scores obtained in this first pilot study. Although there may be a bimodal distribution of participant expectations in the population, the small sample of 12 research participants yields the skewed frequency distribution depicted in Figure 1. There is little indication of bimodality, but a strong bias toward high LIQ scores emerges clearly. Thus the present results indicate that on the average the leaning vehicle method seems to meet the motion cue expectations of the research participants better than the vector substitution method.

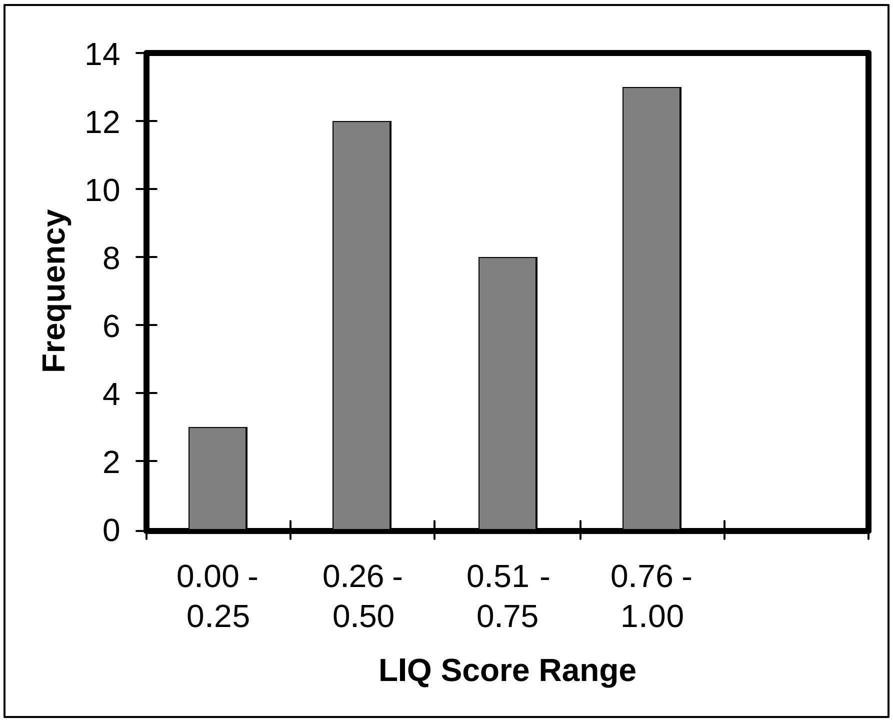

FIGURE 1 Frequency Distribution of LIQ scores

A parallel analysis was conducted for the data on curve sharpness judgments. All curve sharpness judgments were analyzed independent of judgments concerning the motion of the car cab. On each trial the participant judged whether the curve was sharp or shallow. The proportion of times each participant judged the curves correctly was computed for each driving condition, irrespective of motion cue. This proportion was called the Curve Sharpness Quotient (CSQ), and indicated a perfect score of correctly judging all 16 curves when CSQ = 1, and random guessing when CSQ = 0.5. The CSQ for each research participant and for each testing condition is shown in Table 4. Once again the exact binomial was used to calculate a statistical expectation for the CSQ, only this time a one-tailed test was employed. For a sample size of 16 and an alpha level of 0.05 a CSQ of 0.69 or more would result in rejecting the null hypothesis of random guessing in favor of a demonstrated ability to accurately judge the sharpness of the curves in the simulated scenario.

TABLE 4 Curve Sharpness Quotient (CSQ)

Participant Number	Condition			Average
	Blindfolded	Riding	Steering	
1	0.81	0.81	0.81	0.81
2	0.63	0.88	0.63	0.71
4	0.38	0.75	0.38	0.50
5	0.75	0.75	0.75	0.75
6	0.56	0.81	0.69	0.69
7	0.44	0.81	0.75	0.67
8	0.44	0.56	0.75	0.58
9	0.75	1.00	0.94	0.90
11	0.75	0.88	0.88	0.83
12	0.63	0.75	0.69	0.69
13	0.69	1.00	0.81	0.83
14	0.88	0.88	1.00	0.92
Average	0.64	0.82	0.76	0.74

As was done for the LIQ, this criterion CSQ value of 0.69 defined above was used to convert the data in Table 4 into categories to characterize the results in terms of ability to judge curve sharpness. In Table 5 the cells in Table 4 have been replaced with a "C" if the participant judged curve sharpness at or better than the criterion CSQ = 0.69. Blank cells represent indeterminate outcomes where the null hypothesis of chance guessing cannot be rejected. The totals of the "C" participants blocks are shown in the marginals. As can be seen in Table 5, of the 36 blocks of trials, 27 indicated a tendency for the participant to correctly judge the sharpness of the curves, and 9 were indeterminate (blank). The most "C" participant blocks are shown in the riding condition, the next most in the steering condition and the least in the blindfolded condition. In general, most of the research participants could correctly judge the sharpness of the curves for most of the blocks of trials, except possibly in the blindfolded condition.

The grand average of the matrix in Table 4 can be regarded as the proportion of correct sharpness judgments collapsed over all participants and conditions. From the normal approximation to the binomial, for a sample size of 576, an overall proportion of 0.74 is statistically significantly different from the chance proportion of 0.50 at the alpha = 0.05 level. Thus overall the results indicate that research participants can judge the sharpness of the curves at a significantly better than chance level of performance. However, in the blindfolded condition, where no visual cues were present to assist in the judgments, the number of "C" cases was somewhat lower, indicating that visual cues may play an important role in determining curve sharpness judgments.

TABLE 5 Correct ("C") Blocks of Trials

Participant Number	Condition			Total "C"
	Blindfolded	Riding	Steering	
1	C	C	C	3
2		C		1
4		C		1
5	C	C	C	3
6		C	C	2
7		C	C	2
8			C	1
9	C	C	C	3
11	C	C	C	3
12		C	C	2
13	C	C	C	3
14	C	C	C	3
Total "C"	6	11	10	27

DISCUSSION

The results presented above indicate that research participants generally have an expectation that a driving simulator will follow a leaning vehicle motion model instead of a vector substitution motion model. However, the physics of the situation would indicate that the vector substitution model is the more veridical for the particular simulation. For the degree of curvature represented, the speed of the vehicle and the lack of superelevation in the curve depictions, the physics would indicate that the body of the driver would be pulled toward the outside of the curve, not toward the inside. Of course the actual pull would be the result of a lateral centrifugal force trying to translate the body sideways along the seat. Unfortunately, it is difficult to create such sustained translational forces in a driving simulator. Consequently, according to the vector substitution method, a rotational roll movement is substituted. In any case, the research participants seemed to disregard this interpretation of motion, and to believe instead that some sort of severe superelevation was present on the curves, even though none was modeled. For some reason the participants expected sufficient superelevation on a curve to offset any centrifugal force and result in the sensation that the vehicle was leaning into the curve. This result indicates the strong effect that people's expectations can have on how they will experience a given situation, irrespective of what their senses may be receiving. It also indicates that superelevation cues can be extremely important and delicate variables in crafting driving simulations. The vendors active in the video gaming industry are apparently aware of this public expectation for vehicles to lean into curves (3). The gaming industry employs the artificial reality which the public wants, and "they want reality as they think it ought to be" (5).

To confirm the hypothesis that motion expectations could be based on curve superelevation, one additional block of 16 blindfolded trials was run with the last research participant (Number 14) after the experiment was over. On this occasion the experimenter requested that the participant imagine that he was driving on a huge flat parking lot, where the curves were merely painted lines on the smooth surface, with no superelevation anywhere. This particular participant had rendered a perfect LIQ of 1.00 in his original blindfolded session, strongly supporting the leaning vehicle method. In this last supplemental session with the modified verbal instructions, this same participant made a complete and perfect reversal on all 16 trials, returning an LIQ of 0., strongly supporting the vector substitution method.

The present results represent the outcome of only the first in a series of planned pilot studies directed at ascertaining the most appropriate motion cues to use in the FHWA HDS facility. This particular pilot study concentrated on the reactions of research participants to two clearly different motion cue algorithms. With the vector substitution method the simulator car cab leaned out from the center of the curve, whereas with the leaning vehicle method, the simulator car cab leaned in toward the center of the curve. These two kinds of motion produced distinctly different sensations. Being the first, the present pilot study was directed at eliciting some of the more salient aspects of the driver's response to motion cues in the simulator, like overall direction of roll. Many subtle features of the simulation could not be incorporated into this initial pilot study, but will be investigated later. Thus the present pilot study has a number of limitations, some of which could possibly have a significant effect upon changing the results obtained. Some of these limitations are listed below:

1. The VDM used in the HDS had not been validated against actual performance of a similar automobile on a real road.
2. No compensatory tilting of the visual horizon was employed in the computer graphics for the vector substitution method.
3. The onset and offset of the roll motions may have been more abrupt than would be expected, since no filters employed.
4. The leaning vehicle method was simply the reverse of the VDM, instead of a separate calculation algorithm derived from a bicycle or motorcycle model.
5. The simulator scenes were relatively dark overall, making it less easy to ascertain whether the curves had superelevation or not.
6. The amount of car cab roll may have been somewhat more than expected by the research participants.
7. The sample of research participants was small, and a high proportion of the participants were familiar with highway design practices.

These are some of the possible limitations inherent in this initial pilot study. Despite these limitations this first pilot study yielded useful results and helped to point the direction for future studies. After all, the reality of simulation is its unreality. Since all simulation is an abstraction of experience, even in its most elaborate implementation, simulation shares an essential ingredient with theatre, the suspension of disbelief. No simulator can fully realize a veridical physical model of reality, neither in the visual, auditory or motion modality. There will always be a strong element of theatre. Various combinations of substitution, compromise, masking and subterfuge are employed to create the best illusion. In the realm of theatre, does it matter what brand of illusion the simulation purveys, one rooted in the physics of the situation or one directed toward the expectations of the public? One artifice can just as readily be substituted for another. For research and training simulators, it is important to choose an unreality which supports the subtask components essential to the behaviors being measured or trained.

ACKNOWLEDGEMENTS

The work reported herein was conducted for the Federal Highway Administration (FHWA) under two separate contracts. One contract was with Science Applications International Corporation (SAIC), and the other was with AAI / Engineering Support, Inc. Many individuals from these three entities, as well as from other FHWA contracting organizations, helped to make this research possible. Teamwork was at the core of the effort. The authors wish to express special appreciation for guidance and direction to Thomas M. Granda and M. Joseph Moyer of the FHWA Human Centered Systems Team, and to Stephen A. Fleger of SAIC and Barry Wallick of AAI/ESI. Kenneth S. Opiela of the FHWA Roadway Team assisted in sponsoring the work. Ronald B. Hoffman engineered and managed efforts to minimize simulator sickness. Stephen D. Greene recruited and managed the research participants. Vladislav Popov reduced and analyzed the data. The authors are grateful to all who helped to make this endeavor a success.

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