N82-13681 D16

THE INFLUENCE OF MOTION CUES ON DRIVER-VEHICLE PERFORMANCE IN A SIMULATOR

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SUMMARY

Four different motion base configurations, ranging from no motion to a configuration consisting of roll plus yaw plus attenuated lateral translation, were studied on the Virginia Polytechnic Institute (VPI) driving simulator. The same trio of differently responding vehicles was simulated on each motion configuration; and the effects of the vehicle characteristics on driver-vehicle system performance, driver control activity, and driver opinion ratings of vehicle performance during driving were compared for the different motion configurations. Analysis of the data showed that:

1. The effects of changes in vehicle characteristics on the different objective and subjective measures of driver-vehicle performance were not disguised by the lack of physical motion.
2. Studies performed on a fixed-base simulator can thus be used to draw inferences despite the lack of motion.
3. The presence of motion tended to reduce path keeping errors and driver control activity.
4. If limited physical motions were to be added to a driving simulator, roll and yaw are recommended because of their marked influence on driver-vehicle performance and their relative ease of implementation.
5. The importance of motion increased as the driving maneuvers became more extreme.

INTRODUCTION

This research was undertaken to determine what influence motion cues have on the sensitivity of driver performance measures to changes in vehicle response characteristics. The findings were expected to be useful to researchers considering the inclusion of motion in their simulator facilities, in interpreting the results of research conducted in fixed-base facilities, and in improving our understanding of the cues that drivers use in controlling their cars. Most of the available information about the

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value of motion cues comes from research performed in aircraft simulators. A notable exception to this is the work performed by McLane and Wierwille (reference 1) which did show that driver performance is augmented by the addition of motion cues. However, they did not address the question of whether or not the same relative trends are observed with different motion systems but only that absolute measures of performance do differ.

Repa et al (reference 2) compared the performance of three research engineers in a fixed-base simulator and a Variable Response Vehicle under different vehicle response conditions and found very close correspondence between simulator and full-scale testing. However, it can be argued that these particular drivers were more skilled than the average driver and were able to adapt to the different vehicle configurations and to the laboratory simulator more effectively and more quickly than average drivers. Therefore, differences between the performance of the different vehicle configurations as well as between the full-scale and the simulator results may have been minimized because of the select group of drivers that was used.

The evidence currently available from aircraft simulator studies generally favors the presence of motion. According to Rolfe (reference 3), "... this conclusion is based upon findings such as:

(a) Experienced pilots perform better in a moving simulator than they do in a static simulator.
(b) The pattern of the pilot's contol activity in an aircraft is more closely approximated in a moving rather than a static simulator.
(c) Good motion systems are seen as increasing the 'realism' and acceptability of the simulation."

Additional points regarding the importance of motion are made by Staples (reference 4):

> "It is important where an unstable or near neutrally stable vehicle has to be controlled (e.g., a bicycle).
>
> It assists in control at high frequency, particularly where precision or high accuracy is desired (e.g., in tracking).
>
> It may be required because of its effect on visual acuity and visual judgment.
>
> It may degrade performance because of coupling either with a human control mode (pilot-induced oscillations), even on a vehicle with stable open-loop dynamics, or with the natural frequency of body components (vibratory responses).
>
> Finally, because motion provides direct information about the nature of the response to the pilot and because it cannot be ignored (in the short term), it serves as a powerful alerting input, directing attention to or eliciting an instinctive reaction to the response even though it was not the center of attention at that time."

In spite of the more or less general acceptance of the above statements, there is still considerable controversy concerning just how much motion is required under what vehicle conditions and for which tasks (reference 5). Unfortunately, there is no simple basic framework of human behavior which will allow us to identify in any given situation the elements of the total environment which contribute to the pattern of behavior (reference 4). As a result, the following research was undertaken to provide information of direct relevance to the cues drivers use during normal highway driving.

METHOD

Driving Simulator

The facility that was used for this research was designed and built at Virginia Polytechnic Institute and State University under a General Motors grant. The simulator provides the driver with an unprogrammed* television-type display in coordination with the motions of yaw, roll, pitch, and lateral and longitudinal translation. Four channels of sound along with vibration are also provided. A brief description of the visual and motion systems follows. More complete descriptions are given in references 6 and 7.

Visual System - Generation of the simulated roadway image (figure 1) is accomplished by a special purpose computing system containing 37 integrated circuits. The generated signals are initially displayed on the face of a cathode ray tube. A TV camera scan converts this image and transmits it by cable to a TV monitor mounted above and behind the dash on the simulator buck. A Fresnel lens with an effective focal length of 50.8 cm (20.0 in), located between the monitor and the human operator, decreases the apparent roadway image proximity to the driver and enhances the illusion of distance [effective distance 10.1 m (33 ft)]. Additional realism is provided by a plexiglass windshield and a sheet metal mock-up representing a hood and fenders immediately in front of the dash. The field of view provided by the TV monitor and lens subtends 39° vertically and 48° horizontally. During simulation, all room lights are turned off so that only the roadway display and the illuminated speedometer are visible to the driver.

Motion System - The simulator is composed of an upper and lower platform, three main struts, and four motion servos (figure 2). The upper platform consists of a standard automotive configuration including bucket seat, dashboard (with speedometer), steering wheel, brake and accelerator pedal, and the visual display equipment described above. The upper platform is pivoted at each end which permits roll motion about an axis 33.0 cm (13.0 in) from the upper platform floor. The roll motion is accomplished by the roll servo which is attached between the upper and lower platforms. The lower platform, while providing support for the upper platform, is supported by nine precision rubber-wheeled casters which enable the platforms to rotate in yaw and to translate longitudinally and laterally on a

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* The visual display is a result of the actions of the driver and is not a pre-programmed scenario.

large lucite sheet. The platform motions are generated by the combined action of three servo-operated struts which have one end pivoted about a floor anchored support. Two of the servos are aligned with the longitudinal axis of the simulator and provide longitudinal translation and rotation in yaw. The third servo is oriented laterally and provides the lateral translation. Each motion servo is monitored by a feedback potentiometer and is controlled by its own electromechanical valve which receives signal inputs from the analog computer. A hydraulic pump, regulated at 10.4 MPa (1500 psi), provides fluid power to the motion system. Acoustical insulation of the pump unit controls the noise level in the simulator room. A 2.5 gallon accumulator and associated valving are used to maintain constant fluid pressure at any required flowrate. Fluid temperature is controlled by an integral refrigeration-type heat exchanger.

Vehicle Simulation - Simulation of vehicle dynamics is performed by an EAI TR-48 analog computer. Driver inputs to the steering wheel, accelerator, and brake pedals are sensed by potentiometers and converted to electrical signals. These signals are the inputs to the vehicle model simulated on the computer. Outputs of the model are analog voltages of vehicle velocity, roll, yaw, lateral position, and longitudinal acceleration, which form the signals applied to the motion servos. These signals are also applied to the driver's speedometer and to the image generation circuitry which continuously adjusts the visual display characteristics (position, perspective, velocity, etc.) to correspond to the simulated vehicle state.

The vehicle model used for the simulation allowed for rotations in roll, yaw, and pitch, as well as lateral and longitudinal translations. Three separate inputs were provided; namely, steering wheel displacement, accelerator/brake displacement, and aerodynamic force (wind gust). The model consisted of a set of transfer functions relating the three inputs to the vehicle motion components. This approach approximates the dynamic response of the vehicle and permits matching of the model responses to either measured full-scale responses or to responses generated by digital simulation codes.

Experimental Design

The primary concern of this research was whether or not the addition or removal of motion cues would change the performance trends that are observed over different vehicle response configurations. The capability of the VPI simulator includes four separate motion cues — roll, yaw, lateral translation, and longitudinal translation -- and any of their combinations. At the outset, it was decided to focus only on the lateral motion information so the longitudinal cue was removed for all the tests. In the interest of experimental design simplicity, meainingfulness, and time, a total of four motion base configurations and three vehicle response configurations were chosen for study, resulting in twelve experimental conditions as shown in Table 1. While other combinations of motion cues would have been possible, this particular set of configurations (fixed-base, roll only, roll plus yaw, and roll plus yaw plus attenuated lateral translation) represents a natural progression in complexity and, from a hardware development point of view, a way to develop a motion platform over a period of time.

The "base" vehicle response configuration is that of a typical compact car and the "slow" and "fast" configurations were obtained by selecting tires with cornering stiffnesses that might be expected to lie at the extremes of the after market tire range. Slight adjustments in the cornering stiffnesses were made in order to keep the vehicle understeer and, hence, the control sensitivity* constant for all three vehicle configurations. As an added convenience, the aerodynamic center of pressure was assumed to be located at the front wheels, which is a much easier configuration to represent with the transfer function model of the vehicle used on the VPI simulator. The corresponding vehicle responses to control and disturbance inputs are shown in figure 3.

In the interest of obtaining unbiased driver performance in the various motion base configurations, the experiment was designed to provide each subject with only one motion base configuration. Thus, four different groups of six subjects were randomly assigned to each of the four motion configurations (for a total of twenty-four subjects). Half of the subjects in each group were female.

The schedule of events during the course of an experimental run is shown in figure 4. The first experimental run was used for practice.

Performance Measures

Random Wind Gus Disturbance Task - RMS measures of lateral position, yaw angle, and steering wheel angle were obtained on-line using hybrid circuitry for the last 2.5 minutes of the random wind gust task. The number of steering reversals greater than 3.4 deg were also obtained online over the same time period. RMS lateral position and yaw angle are direct measures of driver-vehicle lateral control performance. RMS steering wheel angle and steering reversals are interpreted as measures of the driver's steering control effort.

Step Wind Gust Disturbance Task - Maximum lane position deviation was used as the performance measure in this task. The maximum deviation was measured from the actual vehicle position prior to gust onset and not from the center of the lane.

Subjective Ratings - A 0-10 rating scale was used by the subjects at the completion of both the random and step wind gust disturbances to rate the performance of each vehicle with respect to the disturbances that were encountered. ("0" corresponded to no noticeable disturbance while "10" corresponded to an uncontrollable disturbance.)

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* A vehicle with greater control sensitivity, which is defined as the lateral acceleration produced by a steering wheel angle of 100 degrees, produces the same maneuver with a smaller steering wheel input.

RESULTS

Subjective Ratings

A highly significant difference in subjective ratings ($p < 0.0001$) occurred as a result of changes in vehicle response characteristics. No significant differences were noted as a function of motion base configuration. Figure 5 shows the mean ratings as a function of vehicle characteristics.

Random Wind Gust Disturbance Performance

Highly significant differences in performance for all four objective measures occurred as a result of changes in vehicle response characteristics ($p < 0.001$). No significant differences were observed as a function of motion base configuration for lateral position deviations and steering reversals. Figures 6 and 7 show the influence of vehicle configuration on these two measures.

For steering wheel deviations, a significant effect ($p < 0.02$) was also noted as a function of motion base configuration. Figure 8 shows the effects of both vehicle characteristics and motion base configuration on steering deviations.

For yaw angle deviations, significant effects due to motion configuration as well as to the interaction between motion configuration and vehicle characteristics were observed ($p < 0.01$). These effects are shown in figure 9.

Step Wind Gust Disturbance Performance

Significant effects due to vehicle configuration ($p < 0.0001$) and to motion base configurations ($p < 0.03$) were noted for the maximum lane position measure. Figure 10 shows these effects graphically.

DISCUSSION

We do not, in a strict sense, know which of the responses to changes in vehicle characteristics in the various motion cue configurations are most accurate because we have not compared the results with real driving. It is assumed, however, that the responses in the roll plus yaw plus attenuated lateral translation configuration come closest to those in the real driving environment.

While it is clear that some measures of driver performance in a simulator are significantly influenced by the combination of motion cues that are presented, it is equally clear that meaningful results can still be obtained with a fixed base facility. Several important aspects of driver-vehicle performance -- namely, subjective opinion ratings, RMS lane deviations, and steering reversals -- were not affected by the different motion configurations. Others, i.e., steering wheel deviations for the random disturbance task and maximum lane deviations for the step disturbance task, were affected by motion; but the relative ranking of the different responding vehicles remained the same for all motion configurations. Only yaw angle deviations for the random disturbance task showed some divergence between the different vehicle configurations as motion cues were eliminated. For this measure, "slow" responding vehicles had disproportionately higher deviations in the no motion configuration. This would be a far more serious concern if the absence of motion tended to disguise rather than exaggerate an effect that was observed when motion was present. Previous studies have shown that yaw angle deviations are one of the most sensitive measures to changes in experimental conditions (reference 7), so the present results are not surprising. Also, aircraft simulator studies have shown that motion cues become more important when the task becomes more demanding (reference 4) - which corresponds, in this case, to the control of the "slow" responding vehicles. Table 2 summarizes the high degree of transferability of results that exists across the different motion configurations.

The reductions in lane tracking deviations and driver control activity that did occur when motion was added can be attributed to the alerting effect provided by the motion. This effect is most clearly illustrated by the marked reduction in maximum lane deviations that took place when yaw motion was added in the step disturbance regulation task (Fig. 10). The same effect is well known in the field of aircraft simulation where the presence of motion in a wind gust regulation task leads not only to earlier recognition and reaction to the gust, thus reducing the initial excursion, but also results in more accurate control of the motion (reference 8). In the absence of motion, the human operator must obtain the information on the vehicle's response to the disturbance primarily from the visual display. Some alerting effect is possible from auditory cues, but the direction for the required correction must still come from the visual display.

The transient response characteristics of the vehicle which were varied to provide the different responding vehicles for the present study are subtle vehicle characteristics to examine on a fixed base simulator. If control sensitivity were the characteristic being varied, it would automatically produce changes in driver performance whether or not motion cues were present. As a result, the present study was expected to be particularly effective in revealing the limitations of a fixed base facility. The fact that the fixed-base configuration provided results close to those of the moving base configuration indicates that at least for normal highway driving meaneuvers, motion cues may provide information that is in many ways redundant to that provided by visual cues.

The lack of statistically significant differences in summary performance measures with such a small subject pool (six subjects per motion configuration) must be viewed with some caution. Had more subjects been used or a more detailed analysis of the data been performed, more of the differences may have become significant. The attenuated lateral motion is also best thought of as only a partial cue because of the attenuation that is required to keep lateral excursions within a limited physical range [i.e., ± .5 m (20 in)]. If a larger throw had been used, it is possible that significant changes would have been observed with the addition of lateral motion. However, even with nonsignificant differences in performance across motion configurations, there is no denying that the presence of motion does result in a more realistic driving simulation.

The marked reduction in maximum lane excursions following a step wind gust that occurred when yaw motion was introduced does suggest that as the driving maneuvers become more severe, certain motion cues may become more important. For example, in a skid control maneuver, the absence of a yaw motion cue might very well lead to a delayed driver response and subsequent loss of control with a vehicle configuration that would otherwise be well within the control capabilities of the driver. The high degree of transferability of results from a fixed base configuration to moving base configurations that was obtained in the present study thus applies to normal highway driving maneuvers only.

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TABLE 1
EXPERIMENTAL CONDITIONS

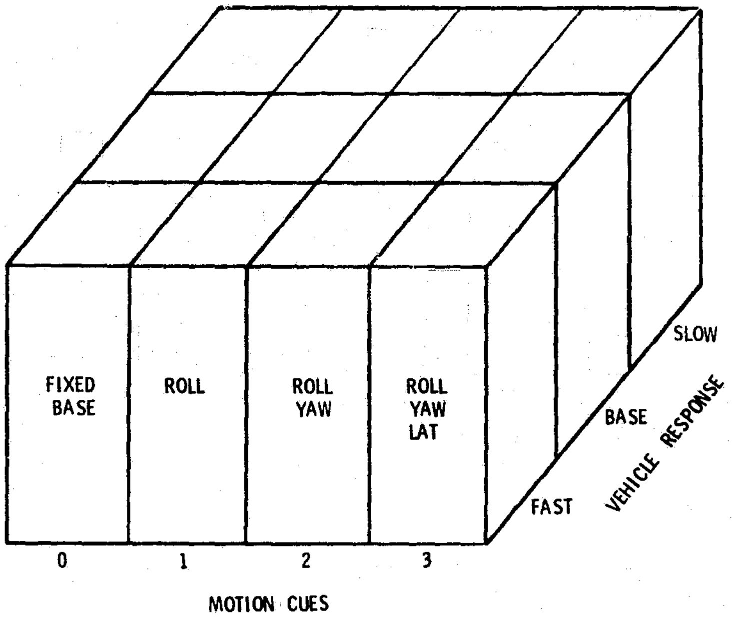

TABLE 2
TRANSFERABILITY OF RESULTS SUMMARY

Dependent Variable	Transferability of Results Across Motion Configurations
Subjective Ratings	Transferable on an Absolute Basis
Lane Deviations (Random Gusts)	Transferable on an Absolute Basis
Steering Reversals (Random Gusts)	Transferable on an Absolute Basis
Maximum Lane Deviations (Step Gusts)	Transferable on a Relative Basis
Steering Wheel Deviations (Random Gusts)	Transferable on a Relative Basis
Yaw Angle Deviations (Random Gusts)	Not Directly Transferable

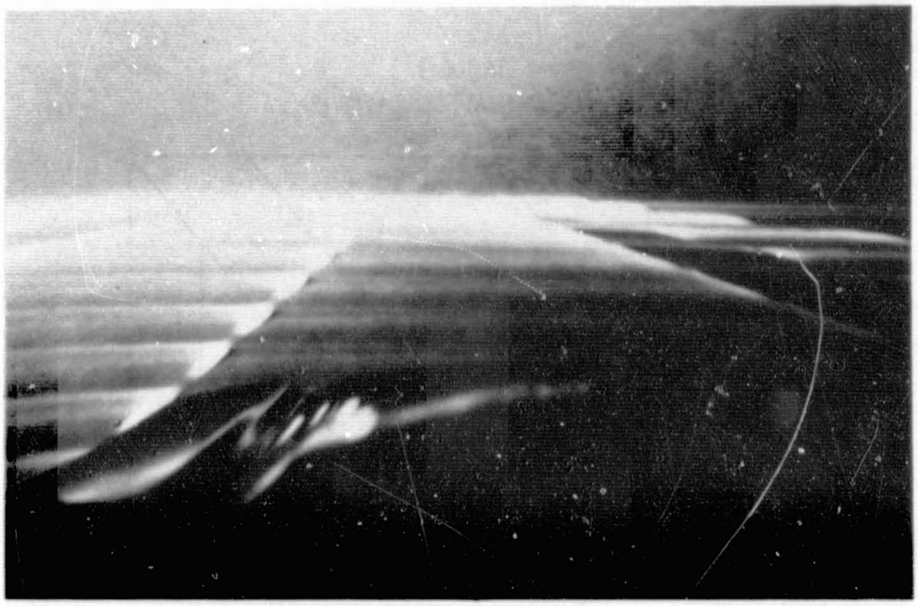

FIG. 1 PHOTOGRAPH OF ROADWAY IMAGE

FIG. 2 DRIVING SIMULATOR MOTION PLATFORM

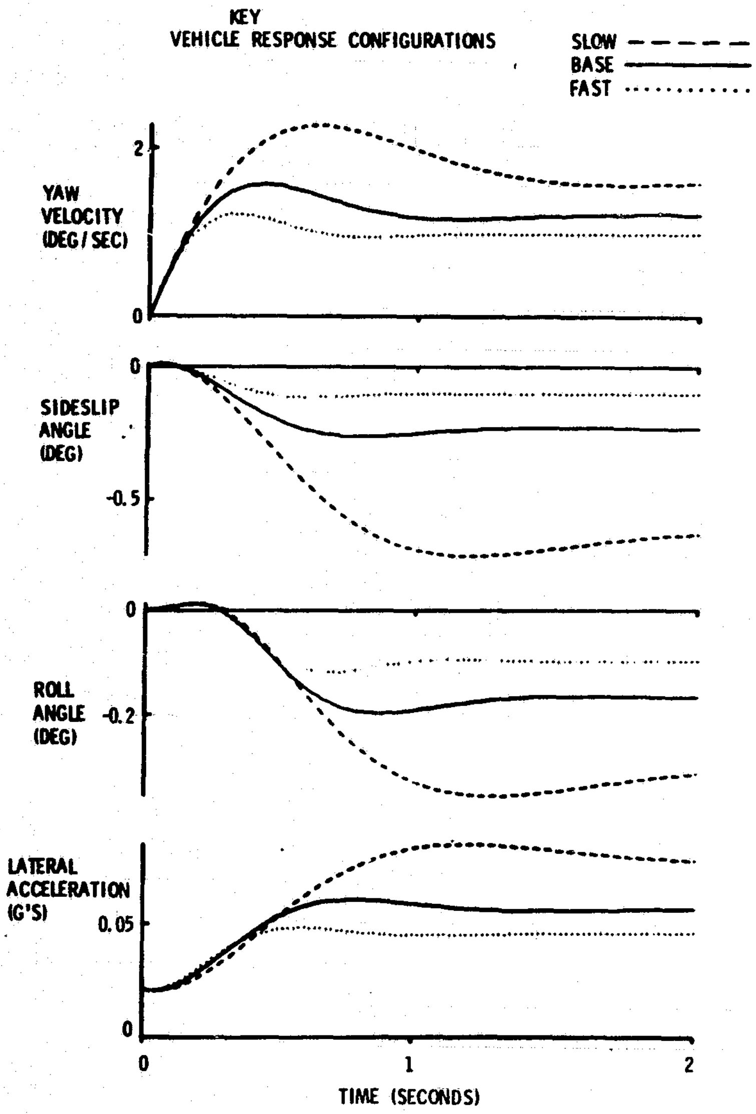

FIG. 3B VEHICLE RESPONSES TO DISTURBANCE INPUTS

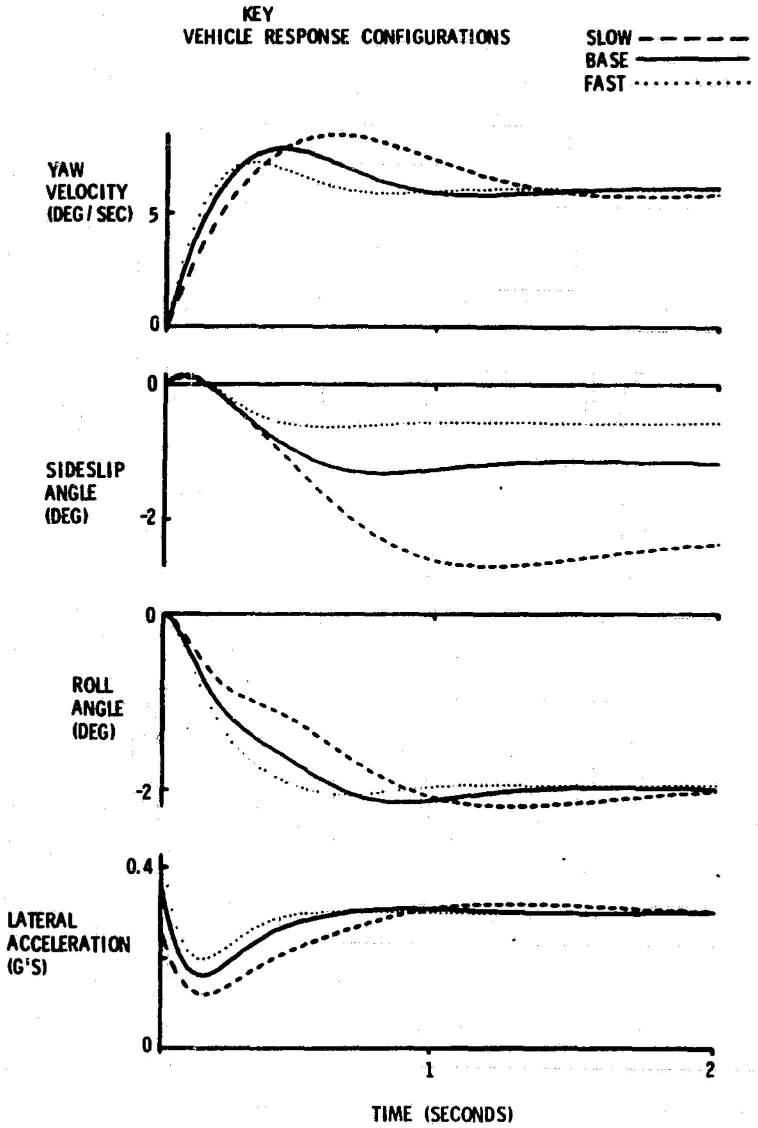

FIG. 3A VEHICLE RESPONSES TO CONTROL INPUTS

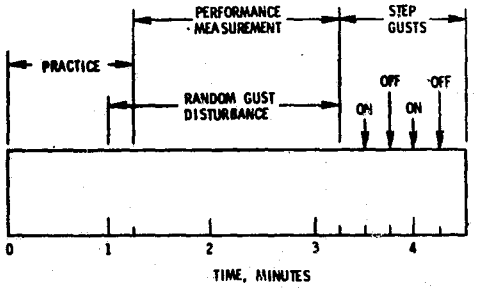

FIG. 4 SCHEDULE OF EVENTS

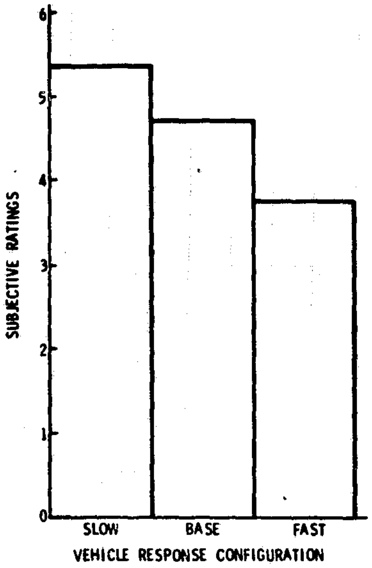

FIG. 5 SUBJECTIVE RATINGS FOR THE THREE VEHICLE RESPONSE CONFIGURATIONS

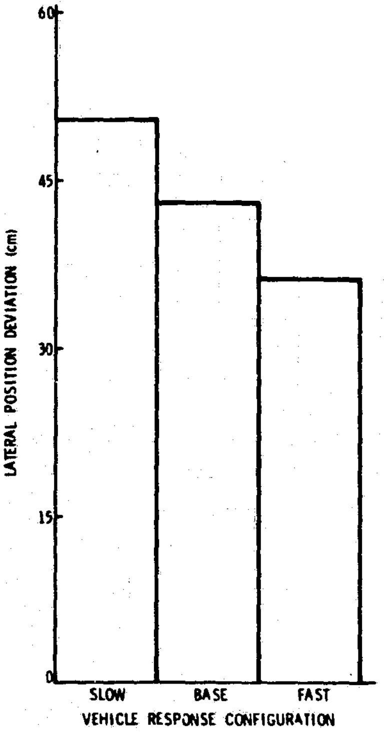

FIG. 6 LATERAL DEVIATIONS DURING RANDOM DISTURBANCES FOR THREE VEHICLE RESPONSE CONFIGURATIONS

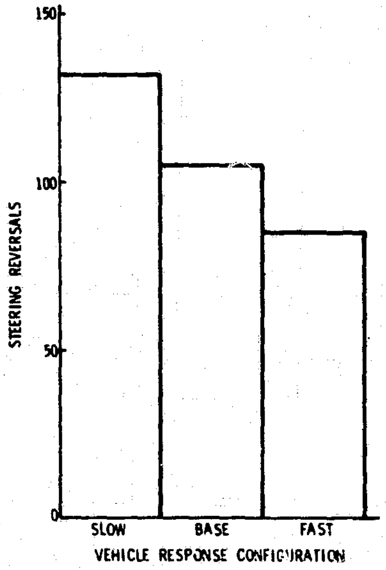

FIG. 7 STEERING REVERSALS DURING RANDOM DISTURBANCES FOR THREE VEHICLE RESPONSE CONFIGURATIONS

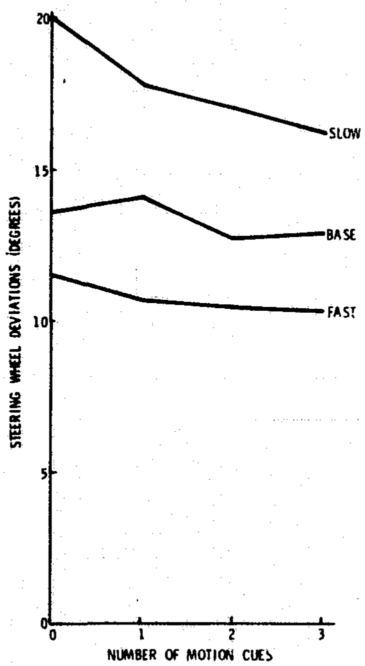

FIG. 8 STEERING DEVIATIONS DURING RANDOM DISTURBANCES FOR FOUR MOTION CUE CONDITIONS AND THREE VEHICLE RESPONSE CONFIGURATIONS

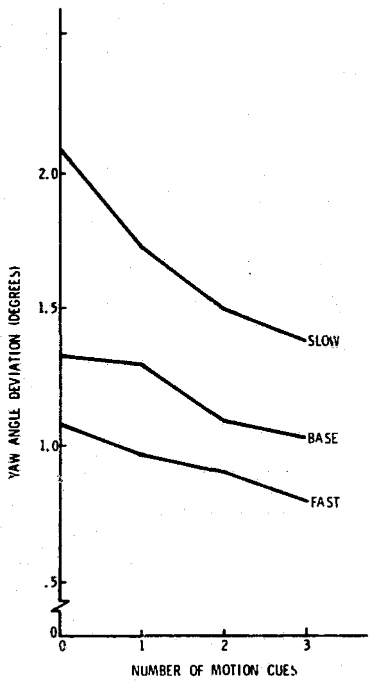

FIG. 9 YAW DEVIATIONS DURING RANDOM DISTURBANCES FOR FOUR MOTION CUE CONDITIONS AND THREE VEHICLE RESPONSE CONFIGURATIONS

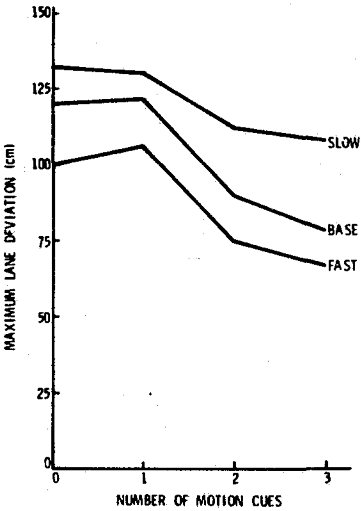

FIG. 10 MAXIMUM LANE DEVIATIONS DURING STEP DISTURBANCES FOR FOUR MOTION CUE CONDITIONS AND THREE VEHICLE RESPONSE CONFIGURATIONS