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A Demonstration of Motion Base Design Alternatives for the National Advanced Driving Simulator

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Summary

A demonstration of the capability of NASA's Vertical Motion Simulator to simulate two alternative motion base designs for the National Advanced Driving Simulator (NADS) is reported. The VMS is located at the Ames Research Center in Moffett Field, California. The motion base conditions used in this demonstration were (a) a large translational motion base and (b) a motion base design with limited translational capability. The latter had translational capability representative of a typical synergistic motion platform. These alternatives were selected to test the prediction that large amplitude translational motion would result in a lower incidence or severity of simulator induced sickness (SIS) than would a limited translational motion base. A total of 10 drivers performed two tasks, slaloms and quick-stops, using each of the motion bases. Physiological, objective, and subjective measures were collected. No reliable differences in SIS between the motion base conditions was found in this demonstration. However, in light of the cost considerations and engineering challenges associated with implementing a large translation motion base, performance of a formal study is recommended.

Background

Secretary of Transportation Skinner, in his national transportation policy statement, "Moving America—New Directions, New Opportunities" (Department of Transportation, 1989), has called for the development of a National Advanced Driving Simulator (NADS) as part of a collaborative effort between the government and the automotive industry. This driving simulator will enable researchers to conduct multidisciplinary investigations and analyses on a wide range of issues associated with driver, vehicle, and highway systems performance issues. Examples of research issues include highway safety, driver-vehicle interaction, human factors research, driver behavior, workload, stress, and performance; development of driver training and licensing; simulators, motor vehicle product development, highway engineering and design; military ground vehicle systems, and intelligent vehicle highway systems.

The NADS is conceived as having an advanced computer image generation system and the flexibility to simulate a variety of vehicle types. One important issue is the kinematic force cuing as would be provided by a motion base system. Possible designs of the motion base include a large amplitude translational acceleration system, or a synergistic hexapod system, which has a very limited translational amplitude.

A major driving research simulation facility has been operated since 1984 by Daimler-Benz AG in Germany (Drosdol and Panik, 1986). That simulator features a hexapod motion base and is designed to accommodate an actual automobile, with engine and drive train removed, secured inside a cylindrical structure (fig. 1). This lightweight projection dome, 7.4 m in diameter, provides the

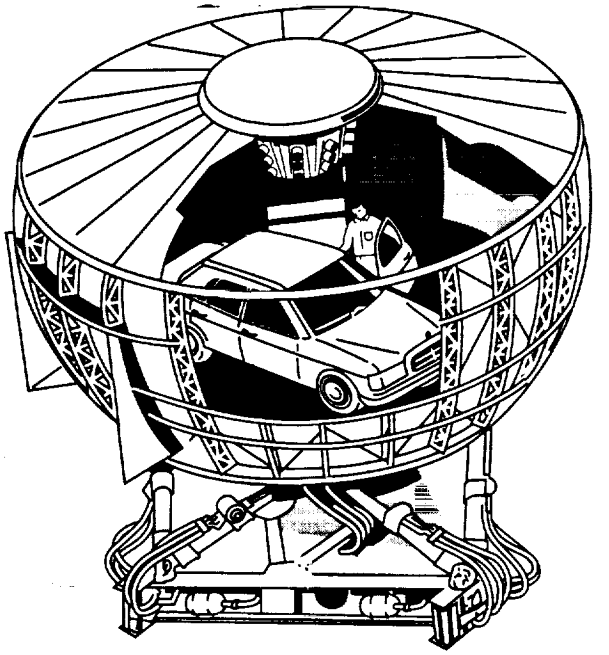

Figure 1. The Daimler-Benz simulator.

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capability for a wide-field-of-view display. The structure is mounted on a hexapod motion base, similar to those in many flight simulators. The limits of motion are approximately ±1.5 m in all translational axes and a maximum of ±33 deg in the rotational axes. The original design concept called for horizontal track(s) to provide translational acceleration cues to the driver. However, in an effort to limit cost, the tracks were not included when the facility was built (Hoffmeyer, personal communication, 1990).

A preliminary feasibility study for NADS, sponsored by the National Highway Traffic Safety Administration (NHTSA), has been completed (Haug, 1990). This study concluded that a synergistic motion base with limited translational capability would not be adequate to provide sustained longitudinal and lateral accelerations associated with vigorous vehicle maneuvers without inducing simulator sickness. The study recommended a motion base design capable of large amplitude translational accelerations in two horizontal axes (fig. 2), approximately ±15 m lateral and ±5 m longitudinal.

The primary argument for a large translational excursion motion system is to provide higher fidelity of the simulated vehicle dynamics. In an actual vehicle, motion is sensed by the driver through several senses, including visual, vestibular, and proprioceptive systems. Current simulation technology tends to provide highly realistic visual information but less realistic inertial information, thus inducing cuing mismatches across human sensory systems.

Current computer generated imagery (CGI) systems may cost upwards of $10 million and are capable of providing highly detailed visual scenes with a wide field-of-view. Thus, the driver's visual requirements for operating the vehicle are well served by current simulation technology.

Current motion systems, however, as exemplified by the hexapod provide very limited translational amplitudes, on the order of ±1 to 1.5 m.

Many driving maneuvers, such as vigorous braking, acceleration, or cornering, produce significant translational accelerations which are applied to the vehicle and driver for time periods on the order of 1-5 sec or more. A hexapod motion base simulates this type of maneuver by providing a momentary "onset" cue followed immediately by a rotation (tilt) that, once achieved, approximates the desired direction of acceleration by repositioning the driver's body axes relative to gravity. The hexapod uses "washout" (acceleration which is, ostensibly, below perceptible levels in the opposite direction) to keep the motion platform within the amplitude limits and to return the simulator cab to a neutral position. This washout acceleration can be in the opposite direction relative to a sustained acceleration applied to the actual vehicle.

In summary, a state-of-the-art visual system can provide high fidelity visual cues representing the accelerations being applied to the vehicle for virtually all driving conditions. A typical hexapod motion base can provide high fidelity cues only for limited maneuvers of low amplitude

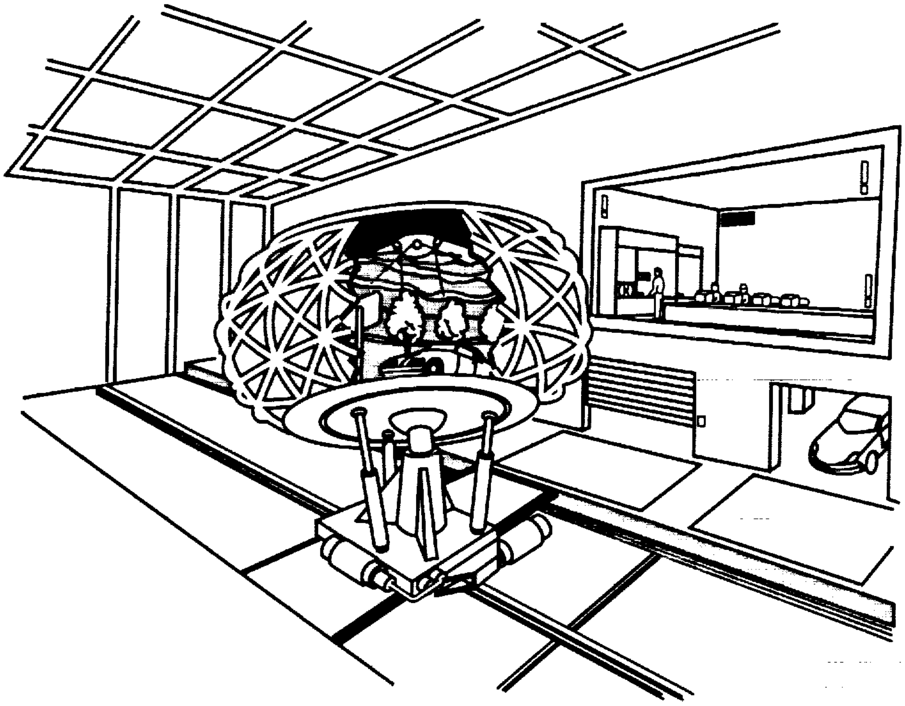

Figure 2. NADS preliminary design concept.

and duration. When the vehicle maneuvers become more vigorous, the translational force cues may be reproduced well but at the expense of false rotational cues. The discrepancy between the motion implied by the visual scene and the false cues provided by the motion base is thought to create a condition that has been called "cue conflict" or sensory conflict (Reason and Brand, 1975).

The consequences of sensory conflict in simulation range from being mildly unpleasant to temporarily debilitating (Kennedy, Hettinger, and Lilienthal, 1990; McCauley, 1984). The symptoms include nausea, vertigo, and emesis (vomiting). On rare occasions (less than 5%) delayed symptoms and other sensory aftereffects, such as dizziness may occur for up to 24 hr post exposure (Ungs, 1989). More commonly, slight nausea and discomfort are experienced and the driver (or pilot, in flight simulators) typically requests to terminate the simulation session. This syndrome, commonly called "simulator induced sickness," has been reported with increasing frequency over the past decade, as more wide field-of-view simulators have been put into operation (Kennedy et al., 1989).

In addition to the user's discomfort, other undesirable consequences of simulator sensory conflict may occur, such as degradation of driver/pilot performance during the simulation. This performance degradation may lead to variability or bias in simulation research data. Reduced user acceptance of the simulator facility is another potential outcome of a high incidence of simulator sickness. The extreme case, for a research simulation, is that simulator sickness could invalidate data obtained in the simulator, making it difficult to generalize the results to the real-world situation.

The large amplitude motion base suggested for NADS is predicated on sustaining accelerations longer, thus enlarging the envelope of driving maneuvers that can be accomplished in the simulator before entering the sensory conflict regime. The increased fidelity of motion cuing comes at a price, however. A large amplitude system would be more expensive to manufacture plus a larger building would be needed to house the simulation facility. The technology is available for the development of a large amplitude motion base; however, it is considered to be an engineering challenge. The decision about the motion base design, therefore, can be characterized as a critical cost-benefit tradeoff.

Objective of the NASA VMS Demonstration

The NADS Project Office of the Department of Transportation desired to obtain more information in support of a decision about the motion base design concept for NADS. This demonstration was done to provide experience with approximations of the two motion base design alternatives—a limited amplitude hexapod-type system and a large amplitude system.

It must be emphasized that this effort was a preliminary demonstration, not a full experiment.

Organizational Participants

In December 1990 the DOT sponsored an initial demonstration of the two motion base configurations at NASA Ames Research Center, Moffett Field, California. The organizations that participated in the NADS motion base demonstration are shown in table 1.

Table 1. Organizational participation in the demonstration

Organization	Role
DOT/NHTSA	Sponsor, observation and driving participation
NASA Ames Research Center, Code FS, Moffett Field, CA	Program Lead, VMS facility operations, modification, and preparation
SYRE, Moffett Field, CA	Motion base algorithms, CGI database software and digital data capture
NSI, Sunnyvale, CA	Motion base operation
J. B. Sinacori, Pebble Beach, CA	Motion equations, motion base drive logic
Monterey Technologies, Inc., Carmel, CA	Scenario design; Data collection schedule; Behavioral and physiological data collection and analysis
University of Iowa, Iowa City, IA	Observation and driving participation
Daimler-Benz, Germany	Observation and driving participation
Evans & Sutherland, Salt Lake City, UT	Observation and driving participation
Ford Motor Co., Dearborne, MI	Observation and driving participation
General Motors, Warren, MI	Observation and driving participation
Nissan, Japan	Observation and driving participation
Toyota, Japan	Observation and driving participation

Facility: Hardware and Software

NASA VMS

The NASA Vertical Motion Simulator (VMS) is the largest six degree-of-freedom motion-base flight simulator in the world (fig. 3).

The unique VMS motion base is capable of large amplitude translational motion.

The two horizontal axes can be implemented as either longitudinal or lateral depending on the physical orientation of the cab. Pitch, roll, and yaw are implemented via an uncoupled hydraulic-powered motion base that has rotational amplitude limits of approximately ±20 deg in each axis. A summary of the performance envelope of the VMS is given in table 2. The frequency response of the VMS motion system is summarized in table 3. A functional diagram of the VMS motion drive system is given in figure 4.

The VMS is normally used to support research on aerospace vehicles and systems. Reconfigurable cockpits enable simulation of a wide variety of crew station designs. Examples of vehicles that have been simulated are the space shuttle, tilt-rotor, rotorcraft, and fixed-wing military and civilian aircraft.

The VMS, a National Facility for R&D flight simulation, is used in support of many major national programs of aeronautical vehicle development. The Department of

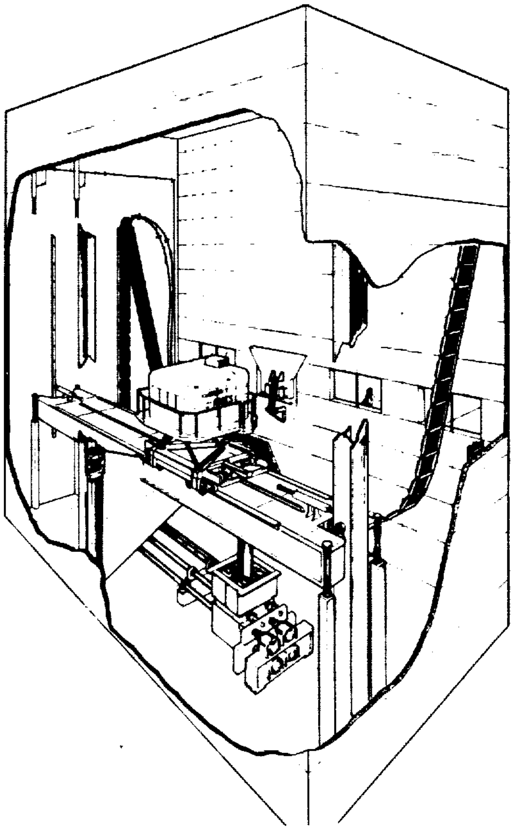

Figure 3. NASA vertical motion simulator.

Table 2. NASA VMS performance envelope

Axis	Position	Velocity	Acceleration
	Software limits		
Longitudinal	3.0 ft	4.0 ft/sec	10.0 ft/sec/sec
Lateral	15.0 ft	8.0 ft/sec	13.0 ft/sec/sec
Vertical	22.0 ft	15.0 ft/sec	22.0 ft/sec/sec
Roll	0.24 rad	0.7 rad/sec	2.0 rad/sec/sec
Pitch	0.24 rad	0.7 rad/sec	2.0 rad/sec/sec
Yaw	0.34 rad	0.8 rad/sec	2.0 rad/sec/sec
	Hardware limits		
Longitudinal	4.0 ft	4.0 ft/sec	10.0 ft/sec/sec
Lateral	17.5 ft	8.0 ft/sec	16.0 ft/sec/sec
Vertical	25.0 ft	16.0 ft/sec	24.0 ft/sec/sec
Roll	0.31 rad	0.7 rad/sec	2.0 rad/sec/sec
Pitch	0.31 rad	0.7 rad/sec	2.0 rad/sec/sec
Yaw	0.42 rad	0.8 rad/sec	2.0 rad/sec/sec

Table 3. NASA vertical motion simulator frequency response

Axis	Frequency	
	With feedforward	Without feedforward
Longitudinal	No feedforward used	0.8 Hz
Lateral	1.8 Hz	0.1 Hz
Vertical	1.2 Hz	0.2 Hz
Roll	2.1 Hz	1.0 Hz
Pitch	1.9 Hz	0.8 Hz
Yaw	3.0 Hz	0.9 Hz**

**This data point extrapolated. Lag at 2.08 Hz is 32.7 deg.

Transportation identified the NASA VMS as a potential tool for executing a preliminary comparison of the two possible motion base design concepts for NADS because of its long (12 m) horizontal linear track.

The safety of the user is of paramount importance in VMS operations. The VMS is human operator rated and all users must receive a thorough safety briefing before flying (or driving) the simulator. There are four separate safety systems used in the VMS. Further information about the VMS safety systems is given in appendix A.

Simulator Cab Modifications

The VMS has several interchangeable cabs, usually used to simulate different classes of aircraft. One of these (R Cab) was modified to represent a generic automobile. The "out-the window" visual scene was provided by three beam-splitter, collimated CRT displays arranged to provide a field-of-view of approximately 30 deg vertical by 150 deg horizontal. A McFadden wheel and column assembly, usually used for an aircraft yoke, was modified by the installation of an automobile steering wheel. A McFadden aircraft pedal assembly was modified to simulate the automobile brake. An automobile-type accelerator pedal was fabricated especially for use in this project. A CRT normally used to simulate "glass cockpit" instruments was used to represent an analog speedometer. Music was played through speakers located in the cockpit. No modifications were made to the aircraft-type seat and safety harness.

Automobile Dynamic Model

A rudimentary automobile model was developed by John B. Sinacori Associates. The body axis accelerations were determined by the following driver inputs: throttle position, brake position, and steering wheel position.

The throttle and brake positions were run through a second order low-pass filter to obtain positive and negative longitudinal acceleration components. Drag proportional to velocity was included in the longitudinal calculations.

The steering wheel rotational angle was used as the input to a seventh order low-pass filter. The output of this filter was the vehicle yaw rate. The filter transfer function was obtained from a DOT/NHTSA report on vehicle handling models, prepared by Systems Technology, Inc. (Allen, Rosenthal and Szostak, 1988). The transfer function contained a throughput gain that was determined by the vehicle speed. Thus, the yaw rate was determined by the steering wheel position and the vehicle speed.

The necessary lateral acceleration to maintain a no-slip condition was calculated from the vehicle speed and yaw rate.Roll and pitch angles were calculated from the lateral and longitudinal accelerations via a second order low-pass filter. The steady state roll and pitch gains were ten and five deg per G, respectively.

No vertical accelerations were calculated or used in the model.

This simple model provided a rudimentary vehicle with overall performance and fidelity that could be characterized as fair to good. The vehicle's least realistic feature was the response to a steering input. By simply setting the lateral acceleration to that required by the centripetal calculations, the driver had the sensation of steering with both the front and rear wheels. The overall effect, as perceived by the driver, was between that of driving a car and driving a fork lift.

The time constraints of this program prevented the development of a sophisticated automobile model for implementation on the NASA VMS. However, the handling qualities were considered adequate to achieve the objective of comparing the two motion base configurations.

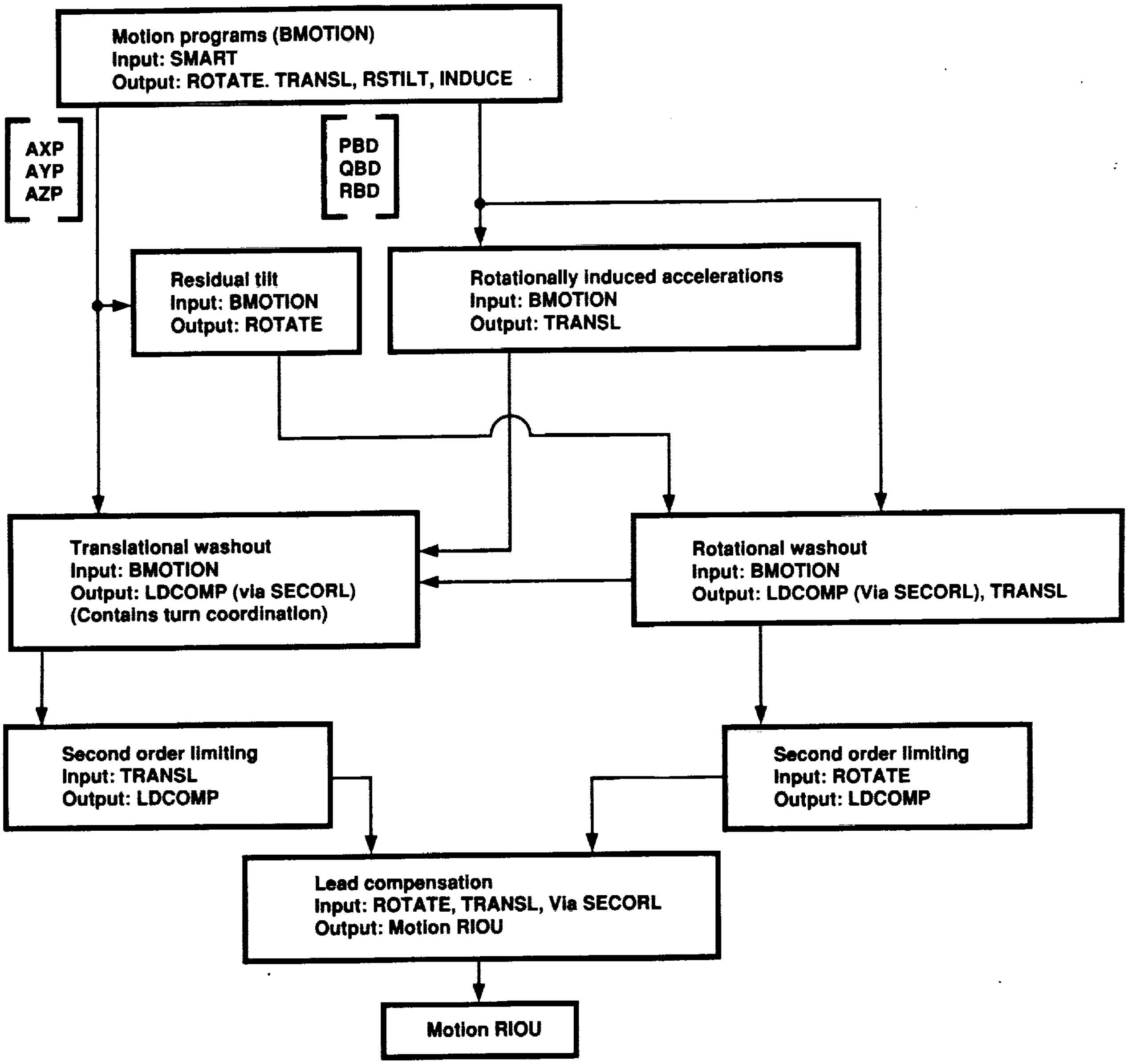

Figure 4. NASA vertical motion simulator motion drive system.

Visual System

An Evans & Sutherland CT5A computer image generation system was used to generate the visual imagery for this simulation. The imagery consisted of two primary scenes, as follows.

Slalom scene– A full size airport runway was implemented for the slalom task that included vertical and horizontal cement lines, runway edge lines, tire marks, and some linear color blending. Four alternative linear slalom courses were built, differing in the spacing of the traffic cones, which were spaced at 100, 150, 200, and 250 ft apart. Only the 150 ft spacing was used during this demonstration. Two adjustable side lines were implemented parallel to the line of cones. These side lines provided turn amplitude guidance cues for the drivers. Buildings lined both sides of the runway for its entire length. The buildings provided enhanced visual flow in the drivers' peripheral visual field.

Braking scene– The braking task was performed in a straight, narrow city street. The street was lined on either side with four-story buildings. Trees and a few pedestrians also populated the street, providing drivers with a strong sense of visual flow.

Motion Base Emulations

Low frequency accelerations in the horizontal degrees of freedom are simulated in the VMS by pitching or rolling the cab to introduce a gravitational component into the desired axis. The major difference between the two motion conditions used in this demonstration was the amount of translational motion used in concert with the cab rotation.

Both the Hexapod and the NADS motion base algorithms provided approximately the same translational acceleration recovery. In both cases, the steady state translational acceleration was recovered with residual tilt, and the maximum recoverable acceleration is determined by the available roll and pitch angles. The NADS algorithm used low tilt rates and large horizontal excursions. The Hexapod algorithm used high tilt rates and small horizontal excursions.

The differences between the NADS and the Hexapod algorithms becomes apparent primarily during transient response. The "Hexapod" algorithm is appropriate for a short travel motion system. The residual tilt, used to substitute gravity for translational acceleration, must develop much faster than is necessary with a large translational motion system. The high rotation rates necessary to accomplish this rapid residual tilt cause a significant false cue to the driver.

Another feature implemented in the motion drive software was the ability to modify the effective center of rotation for the pitch and roll axes. This is necessary because the cab floor is approximately 5 ft above the gimbals center. Therefore, pure roll and pitch accelerations would have produced significant anomalous translational accelerations at the driver's position. A motion drive algorithm calculated the appropriate accelerations and applied commands to the longitudinal and lateral servos to effectively cancel the unwanted translational acceleration at the driver's location. This was done for both motion base drive algorithms.

Lead compensation routines were implemented to improve the bandwidth of all degrees of freedom except longitudinal.

The NADS demonstration used the VMS without the vertical axis. All other axes were used.

It should be noted that both of these motion algorithms were simplified approximations. The Hexapod algorithm was not a full high-fidelity emulation of a synergistic hexapod motion base. The NADS algorithm only approximated the characteristics of the conceptual design for the motion base that has been proposed for the NADS research facility (Haug, 1990).

The VMS motion system usually requires tuning for each simulation. The magnitude of the accelerations is tuned to different simulated vehicles and task profiles. The tuning process involves providing the largest possible motion envelope for the specific vehicle and task while avoiding the software safety limits. Some simulations, particularly those with a single dominant frequency of operation, may also require phase tuning. The phase tuning attempts to maintain near zero phase lag between the aircraft (or automobile) and simulator accelerations. The time available for motion system tuning was limited.

Method

Drivers

The drivers in this demonstration were 10 adult males selected by the DOT sponsor of the demonstration. Similarly, the order in which these men drove the simulator also was determined by the sponsor.

Procedure

At the initial briefing, the tasks and procedures were described to the drivers and other observers.

Prior to driving the simulator for the first time, each driver read the facility safety procedures and received a walk-around briefing during which emergency procedures and features were described and/or demonstrated.

Before each session, the driver was taken to a preparation room where he completed the Symptom Checklist (appendix B) and was fitted with the physiological data collection sensor system.

The physiological data collection sensor system consisted of six electrodes attached to the chest and abdomen, two electrodes attached to the left wrist, a stretchable band worn around the lower chest, and a semicircular sensor taped to the little finger of the left hand. All electrodes were pre-gelled silver/silver-chloride. This sensor package collected a battery of psychophysiological measures which will be described fully in a subsequent section of the report. The drivers wore the electrodes throughout the day. The wiring harness itself was connected to the electrodes prior to driving and removed after each drive.

After being fitted with the sensor system the driver performed the pretests of the Walk-on-line eyes closed (WOLEC) and Stand-on-leg eyes closed (SOLEC) tests of postural equilibrium.

The driver was then escorted to the simulator. The driver was strapped into the seat using an aircraft-type shoulder and lap harness. The seat was adjusted to the driver's satisfaction. The physiological sensor package was connected to the data acquisition system and baseline physiological data collection was initiated.

After driving instructions were given and questions answered, the simulator was moved to its center (starting) position and the task initiated. The task sequence for each driver is shown in table 4.

Although this project was a demonstration rather than an experiment, an attempt was made to counterbalance the order of presentation of tasks and motion base conditions, as shown in the table. Switching between tasks (braking and slalom) required a 30-min delay to physically remount the cab after rotating it 90 deg. Therefore, each driver experienced both motion conditions while the cab was mounted for either the Braking or the Slalom Task. Switching between motion conditions was very rapid (approximately 30 sec). Half the drivers experienced the NADS motion base first and half the Hex. Because the ill effects of sensory conflict usually are slow to develop, accurate attribution of the effects to motion base condition was not possible with the given schedule. The driving task schedule reflected an attempt to enable all drivers to experience all four conditions (2 tasks × 2 motion bases). That objective was incompatible with an experimental design that might otherwise have been implemented to eliminate carryover (sequence) effects.

After the driving task was completed, or at the driver's request, the simulator was returned to the "dock" position where the data collection was terminated, the driver unbuckled and allowed to leave the cab. The driver was then escorted to the lounge where he completed the post-run postural equilibrium tests and the symptom checklist. If the driver was through for the day, the electrodes were removed, otherwise only the wiring harness was removed and the electrodes remained attached for use on his next drive.

Tasks

Braking task– The driver drove his vehicle down a 15-ft-wide street at approximately 35 mph (fig. 5). Sidewalks 10 ft wide bordered the roadway on either side. Each 300 ft block contained an identical four story building. At the end of each block there was an intersection with another 15 ft roadway (along with sidewalks). At one of these intersections an obstacle, an automobile or pedestrian, could enter the roadway. The exact corner at which the obstacle entered the roadway was varied on each run to reduce the predictability of the task. The obstacle would enter the roadway when the driver's car was 160 ft from the selected intersection. The obstacle moved at 7 ft/sec. When the obstacle entered the roadway, the driver's task was to apply the brakes aggressively to avoid a collision. Once the obstacle had cleared the roadway, the driver was to continue down the road.

Each driver performed the task several times in one motion condition, and then performed the task several times with the other motion condition. Driver 1 performed the braking task 10 times in each motion condition. All of the other drivers were limited to 5 trials in each condition due to time constraints. The entire session required about 40 min for all of the drivers except Driver 1.

Table 4. Task sequence

B-HEX = braking task – hexapod motion algorithm
B-NADS = braking task – NADS motion algorithm
S-HEX = slalom task – hexapod motion algorithm
S-NADS = slalom task – NADS motion algorithm

Driver	Morning		Afternoon	
1	B-HEX	B-NADS	S-NADS	S-HEX
2	B-NADS	B-HEX	S-HEX	S-NADS
3	B-HEX	B-NADS	S-NADS	S-HEX
4	B-NADS	B-HEX	S-HEX	S-NADS
5	S-HEX	S-NADS	B-NADS	B-HEX
6	S-NADS	S-HEX	B-HEX	B-NADS
7	S-HEX	S-NADS	B-NADS	B-HEX
8	S-NADS	S-HEX	B-HEX	B-NADS
9	B-HEX	B-NADS	S-NADS	S-HEX
10	B-NADS	B-HEX	S-HEX	S-NADS

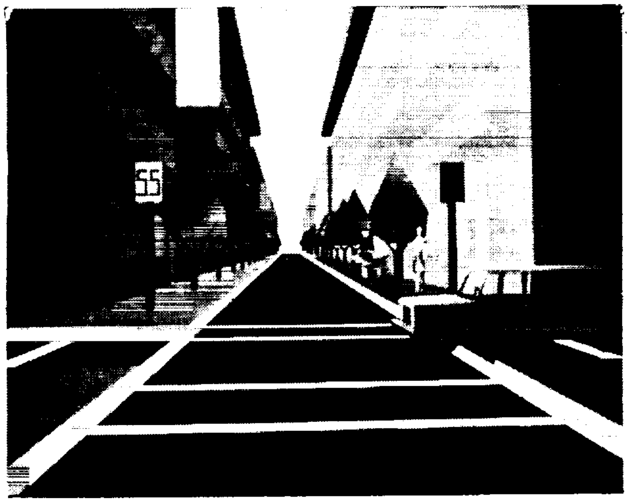

Figure 5. Braking task scene.

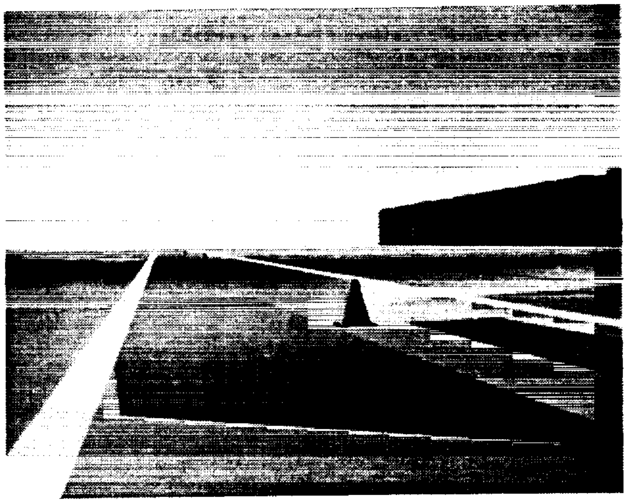

Figure 6. Slalom task scene.

The session for Driver 1 required approximately 1 hr 40 min because he performed a greater number of stops and because final tuning of the motion algorithms was being completed.

Slalom task– The slalom task was performed on a runway approximately 300 ft wide (fig. 6). A series of 15-in. tall traffic cones were spaced in a line every 150 ft for 5000 ft. Two lines parallel to the line of the traffic cones were located on the ground 9 ft from the line of the cones. These lines provided peak lateral excursion cues. The driver's task was to perform a slalom through the cones at about 20 mph. He was to drive from side to side so that the lines on the ground appeared to be straight in front of him when his vehicle was alongside of each cone.

Each driver performed three passes through the cones with one motion algorithm, and then three passes using the other motion algorithm.

Data Collected

Several categories of data were collected in the demonstration, specifically:

- Simulated vehicle dynamics
- Simulator dynamics
- Subjective ratings
- Symptom checklist
- Postural equilibrium measures
- Physiological measures

In addition, there was a final debriefing discussion in which the participants voiced their opinions about all aspects of the demonstration. This type of anecdotal "qualitative" data is considered important, particularly for preliminary studies.

The categories of measures listed above will be described briefly followed by summaries of the data for each.

Auto and Simulator Dynamics

A list of the digital data that were captured and archived is given in table 5. These data were collected at 10 Hz.

In addition to the digital data, the control inputs and the motion base response were plotted on chart recorders.

Subjective Ratings

A 7-point rating scale previously used in studies of simulator sickness at NASA Ames was used in this demonstration. The scale ranges from 1 = "I feel normal" to 7 = "extreme nausea, stop immediately." The drivers were asked to provide a verbal response on the subjective rating scale after each set of maneuvers in the simulator. The interval between these responses was approximately 2-5 min.

Symptom Checklist

A symptom checklist was filled out by each driver before and after each session in the simulator. This was the same checklist as used in previous studies of simulator sickness at NASA and in the large Navy Simulator Sickness database (Kennedy et al., 1989).

Table 5. Listing of data variables

- Driver input variables
  - Brake position (in.)
  - Brake force (lbs)
  - Steering wheel position (deg)
  - Throttle position (in.)
- Vehicle variables
  - Position, north (ft)
  - Position, east (ft)
  - Forward velocity (ft/sec)
  - Lateral velocity (ft/sec)
  - Forward acceleration (ft/sec^2)
  - Lateral acceleration (ft/sec^2)
  - Roll (rad)
  - Pitch (rad)
  - Yaw (rad)
  - Roll rotation rate (rad/sec)
  - Pitch rotation rate (rad/sec)
  - Yaw rotation rate (rad/sec)
  - Roll acceleration (rad/sec^2)
  - Pitch acceleration (rad/sec^2)
  - Yaw acceleration (rad/sec^2)
- Driver station variables
  - X acceleration (ft/sec^2)
  - Y acceleration (ft/sec^2)
  - Z acceleration (ft/sec^2)
  - Roll angle (rad)
  - Pitch angle (rad)
  - Roll rotation rate (rad/sec)
  - Pitch rotation rate (rad/sec)
  - Yaw rotation rate (rad/sec)
  - Roll acceleration (rad/sec^2)
  - Pitch acceleration (rad/sec^2)
  - Yaw acceleration (rad/sec^2)
  - X position (ft)
  - Y position (ft)
  - X velocity (ft/sec)
  - Y velocity (ft/sec)
  - X acceleration (ft/sec^2)
  - Y acceleration (ft/sec^2)

Postural Equilibrium

Two tests of postural equilibrium were administered as part of the Pre-Post test battery—the Stand on Leg Eyes Closed (SOLEC) and the Walk on Floor Eyes Closed (WOFEC). Both tests are done with arms folded, eyes closed. Three trials of each test were given on each administration. The SOLEC score is based on the time (sec) standing on one leg; maximum performance is 30 sec. The WOFEC score is based on the number of steps, heel-to-toe, successfully completed; maximum performance is 12 steps.

Physiological Test Battery

The physiological measurement battery developed by Monterey Technologies, Inc. was used for each driver. The battery consists of the following measures:

- Electrocardiogram (ECG)
- Electrogastrogram (EGG)
- Ventilation rate
- Skin conductance level (SCL)
- Blood volume pulse
- Skin temperature

Measurement/Analysis Methods

The analog physiological data were sampled at 100 samples/sec, then reduced in the following manner. The heart rate (f_h) and the skin conductance level (SCL) were summarized as mean values for 30-sec epochs. The variance in cardiac interbeat interval was partitioned such that variance in the frequency band, 0.12 to 0.40 Hz, was reported each 30 sec as vagal tone (VT; Porges et al., 1982; Vagal Tone Monitor, Delta-Biometrics, Inc., Bethesda, MD). The vagal tone metric provides good estimates of activity in the vagus (10th cranial) nerve, the principal component of the parasympathetic branch of the autonomic nervous system (ANS). This is the branch which, in a simplistic view, mediates relaxation. The sympathetic branch of the ANS mediates the "fight or flight" response. We monitored sympathetic activity through the SCL metric. The heart rate is slowed by parasympathetic activity and increased by sympathetic activity, as well as being affected by other factors.

The digitized EGG data collected during one minute (6000 samples) were shifted to zero mean, tapered at both ends (Bingham et al., 1967), and subjected to a discrete Fourier transform (MATLAB, The Math Works, Inc., South Natick, MA). The output of the transform included raw energy estimates and phase estimates in each frequency bin from 1 through 9 cycles/min. The energy estimates were summed into indices of normal gastroenteric activity (1 though 3 cycles/min) and of hypergastria (4 through 9 cycles/min; Stern et al., 1990). The occurrence of hypergastria provides an objective indication of the prelude to overt nausea.

Results and Observations

Auto and Simulator Dynamics

At the present time, the computer data on vehicle and motion base dynamics have not been analyzed. A sample of the acceleration and position time-histories in the NADS and the hexapod motion conditions are contained in appendices C and D, respectively. As shown in these appendices, good acceleration-following was achieved with both the NADS and the Hexapod motion algorithms. The NADS condition provided more translational motion (lateral in the Slalom task and longitudinal in the Braking task) than the Hexapod condition.

Subjective Ratings

The subjective ratings on the seven-point scale of motion discomfort are summarized in table 6, where the maximum rating by each driver is given for each task and motion base condition.

Table 6. Maximum subjective ratings by task and motion base condition.[a]

	Braking		Slalom	
Driver	NADS	HEX	NADS	HEX
01	–	–	1	7
02	1	2	1	1
03	1	3	2	3
04	3	2	1	1
05	2	1	1	1
06	1	1	1	1
07	2	3	3	2
08	3	2	2	1
09	2	2	3	7
10	1	1	2	3
Mean =	1.8	1.9	1.7	2.7

[a] The report from Driver 1 in the braking task was not used because he was driving the simulator during preliminary motion base tuning.

Symptom Checklist

The symptom checklist, sometimes called the Simulator Side Effects Questionnaire (SSEQ), was scored according to the Lane and Kennedy (1988) method. Scores on the SSEQ were subjected to a 2 × 2 × 4 Analysis of Variance (ANOVA). The factors were Task (Slalom versus Braking), Order of motion condition (Hex first versus NADS first) and Time of Test Administration (Pre-1, Post-1, Pre-2, and Post-2). Time of administration was significant at the $p < .01$ level. The outcome of the ANOVA indicated that both Task and the Order of Motion Conditions were significant between the 0.05 and 0.10 level. People who drove the NADS motion algorithm before the hexapod motion algorithm did not experience as severe symptoms as those who drove the hexapod prior to the NADS. This could indicate that drivers were able to adapt to the simulation when the NADS condition occurred first, but were unable to adapt when the hexapod condition occurred first. The mean SSEQ scores are shown in figure 7.

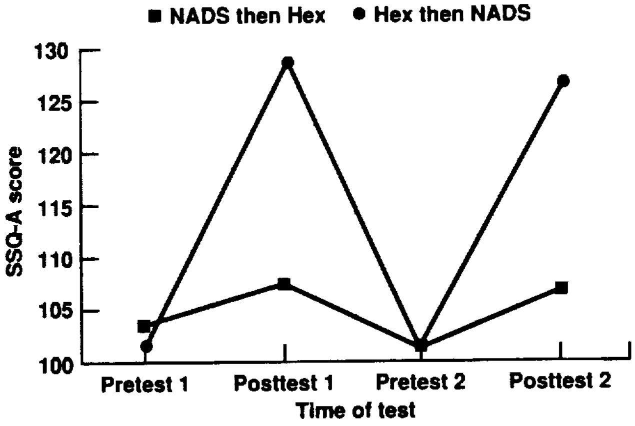

Figure 7. Mean SSEQ scores.

Postural Equilibrium Tests

The SOLEC and WOFEC test data were subjected to a three factor ANOVA (2 × 2 × 4) mixed design with repeated measures on the last factor. The first factor was task order, the second was motion base condition (Hex versus Nads), and the third was time of test administration (Pre-Post, etc.). No significant differences were found in either the SOLEC or WOFEC tests. This was not unexpected because of the relatively short exposure times.

Physiological Measures

No statistical analyses of the physiological data were attempted; the reduced records were reviewed in graphic form. Few data were lost. However, in several cases, the SCL signal appeared intermittent, and, in one case (subject 9), the EGG signal was lost due to a connection failure at one electrode.

The absence of signs of overt motion or simulator-induced sickness was confirmed by the covert physiological measures. With one exception, we saw no physiological patterns suggesting more than slight discomfort with either motion base condition.

The one exception was subject 9 in the hexapod-slalom condition. To put that occurrence in perspective, we have shown the heart rate and vagal tone of subject 9 throughout the braking motion condition (fig. 8) and the slalom motion condition (fig. 9).

We have observed in other simulator investigations that vagal tone increases gradually and heart rate decreases gradually, as a subject relaxes and becomes familiar with the simulator environment and with the visual and motion cues. This pattern can be seen in the data of subject 9 within both the Hex and NADS portions of the braking

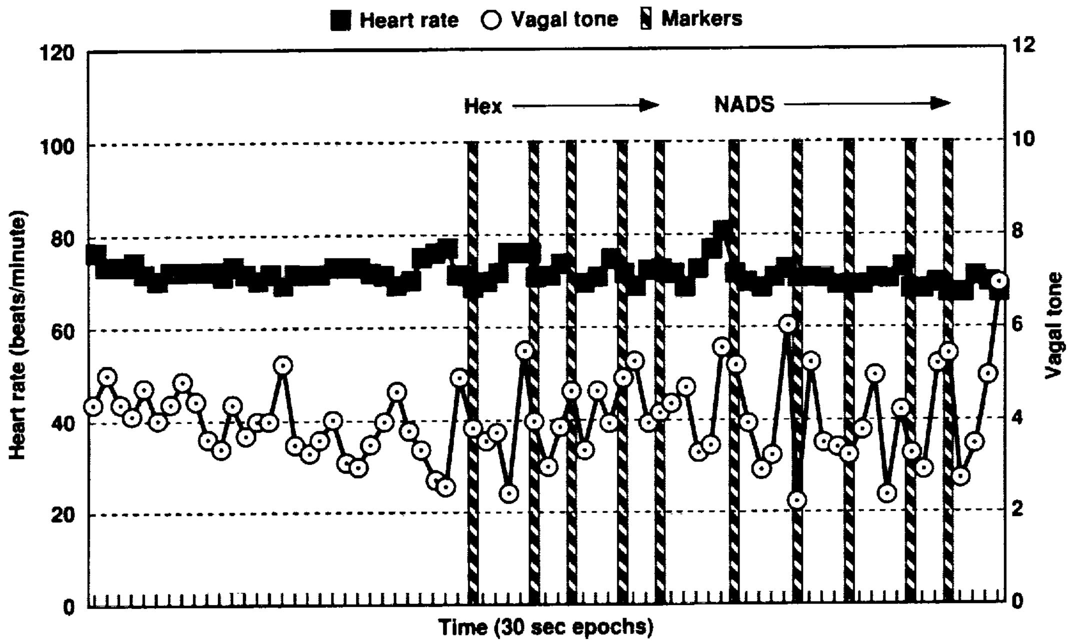

Figure 8. Heart rate and vagal tone during braking task.

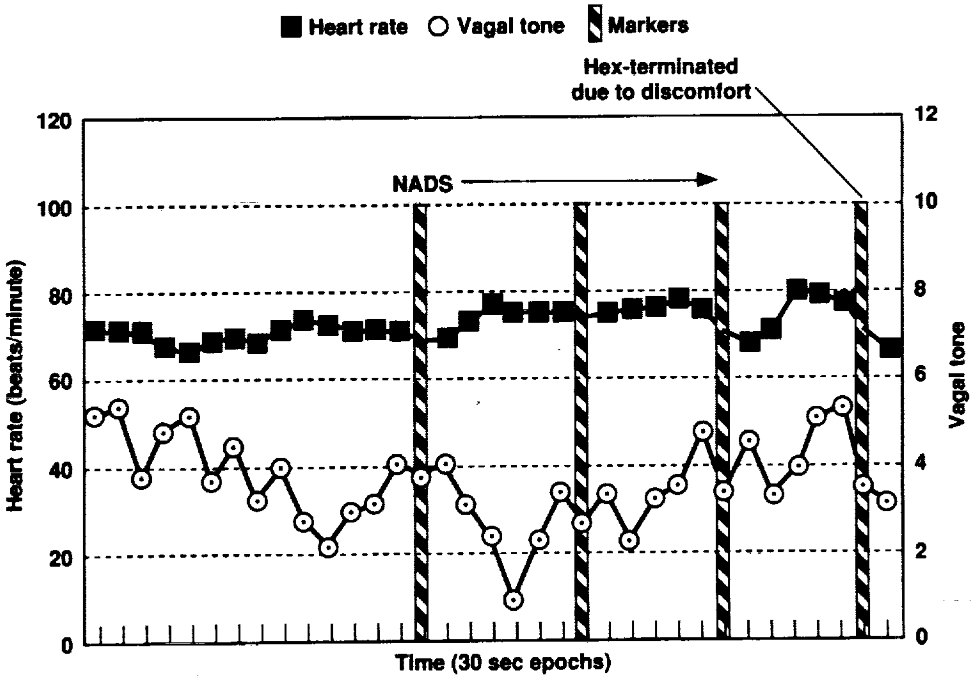

Figure 9. Heart rate and vagal tone during slalom task.

motion condition (fig. 8) and the NADS portion of the slalom (fig. 9). Concomitantly, SCL voltage decreased within the same time segments, reflecting decreasing sympathetic tone.

Occasionally, we have observed that a subject's vagal tone and heart rate increase together. This is counterintuitive, since vagal activity is supposed to lower the heart rate. However, the vagus nerve also carries the signals which induce hypergastria. Thus, this dual increase, observed in the simulator and motion environments, appears to signal motion discomfort: increased sympathetic activity has triggered the elevated heart rate, while increased parasympathetic activity has triggered hypergastria. This is the pattern one sees in the data of subject 9 just prior to the termination of the HEX slalom run, when the subject reported overt illness and requested that the session be stopped.

Concomitantly, SCL voltage increased, signalling increased sympathetic tone. Three physiological occurrences provided objective evidence corroborating the one self-reported occurrence of simulator sickness.

Debrief/Discussion

Those drivers who were at the VMS simulation facility on the final day of the demonstration met for a discussion and debrief. Mr. Sinacori described the motion base "tuning" that was done early in the demonstration period. The gain was reduced to approximately 0.5 to avoid "ringing" and to avoid hitting the safety limits (see appendix A).

The discussion enabled each of the drivers who attended the debrief to express his views of driving the two tasks in the two motion base conditions. The following is a summary of those comments.

Mr. Benedict, Toyota, said that the demonstration was very helpful in evaluating the difference between the two motion base concepts. The Hexapod condition did not feel like a car. This was true in both maneuvers, but especially in the slalom. The motion was not as smooth in the Hex condition, i.e., the car seemed to "nose-dive" upon braking. The perceived eye height seemed high—more like a van than a car. Also, the simulated velocity seemed faster than indicated by the speedometer.

Mr. Morasaka, Toyota, noticed a distinct difference between the two motion base conditions when driving the braking task. The Hexapod responded oddly (too much tilt) when accelerating or braking. He reported feeling slightly queasy in the Hexapod condition, but it passed when he tried to be very smooth with the controls.

Mr. Komoda of Toyota commented that the seat was too high, and when he adjusted it down and leaned it back, it felt more like a sports car. The Hexapod motion did not feel correct to him. Specifically, it made him feel as though he were on top of a pendulum. He would have preferred to perform the braking task with stronger brakes. In the slalom task, the NADS motion was much better than the Hexapod. Mr. Komoda stated that the handling qualities were like a large, soft-sprung American car. (Mr. Sinacori confirmed this perception, by noting that the time constant was 0.2 sec and the yaw rate approximately 0.27 radians/sec). Mr. Komoda commented that sometimes it was difficult to give the 1-7 subjective rating of motion discomfort independently from rating the vehicle handling quality and motion base response.

Mr. Aoyagi, Evans & Sutherland, who acted as translator, commented that, as a passenger in the simulator cab rather than as a driver, he felt that he was actually in a moving car.

Mr. Hoffmeyer, Daimler-Benz, stated that the NADS algorithm was better than the Hex in both maneuvers. This was not surprising because lower tilt rates always perform better. When driving faster and reaching the motion limits, the NADS felt almost as bad as the Hex. The NADS only expanded the envelope of acceptable performance. [Mr. Sinacori noted that the threshold for tilt (pitch) rate is about 4 deg/sec in aircraft simulators. Mr. Hoffmeyer, responded that up to about 10 deg/sec seems acceptable based on informal studies at Daimler-Benz]. Also, lack of smoothness of actuation can be as much of a problem as the rotational rates. He mentioned that when the brakes were applied then released, an inappropriate bump occurred. Further development of the washout algorithms would be needed to minimize such effects.

Mr. Welles, Evans & Sutherland, congratulated the facility personnel (Mr. B. Swift and Mr. J. Zampathas) who developed the visual data base on the CT5A in only three weeks. He found the collimated CRTs to be somewhat bothersome, especially for closer objects. He commented that the perceived eye height was high, approximating a van, and that distance perception was difficult. The auto model felt a bit like a boat, rather than a car. Mr. Welles noticed a distinct difference between the motion base conditions. He felt considerably more at ease driving in the NADS motion base condition.

Other comments from the general discussion included:

- More dead-band in the steering wheel is needed
- The music helped mask the audio cues of the motion base, but it is not a complete solution

- The NADS was more "realistic" than the Hexapod motion base condition

- Overall, the participants felt that it was an excellent simulation, especially considering the time constraints for modifying the aircraft simulator to represent an automobile

Conclusion

1. The VMS adequately supported an initial demonstration of ground vehicle dynamics and alternative motion base configurations. (The limited data from the present demonstration were never intended to provide a basis for NADS design decisions).

2. Cases of simulator sickness were rare. Longer exposure times and more aggressive maneuvering, however, would be expected to increase the incidence of the problem.

3. Overall, the driver/participants preferred the NADS motion base configuration to the Hexapod configuration.

4. The subjective ratings of motion discomfort and the postural equilibrium tests were not informative because of the low rate of simulator sickness experienced by the drivers in this demonstration.

5. The general lack of overt symptoms of simulator sickness was supported by the physiological data analysis. In the single incident of overt sickness, indices of sympathetic and parasympathetic tone provided objective evidence of the self-reported subjective states.

Recommendations

A full empirical study of alternative motion base design concepts for the NADS program should be performed with the NASA VMS, particularly in light of the costs inherent in the implementation of a large linear excursion motion system.

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Appendix A

NASA VMS Safety Systems

The VMS incorporates a comprehensive and complex set of safety features and devices to protect both the machinery and its occupants from injury. The system is fully man-rated in accordance with NASA policies and procedures. One of the requirements for users is a safety briefing and demonstration before flying or driving the simulator.

Each of the six degrees of freedom has built-in acceleration, velocity and displacement limiters to assure that the motions stay within safe operating ranges under all conditions. Also, there is an integral safety interlock system that continuously monitors the status of a number of critical parameters and, if a parameter is out of tolerance, can disallow start-up or automatically execute an orderly shutdown.

Displacement limiters of various types and implementations are incorporated to provide fail-safe operation even for multiple-failure conditions. Limiters come into effect only when the situation is outside the realm of normal operations. Limiting represents an abnormal condition (or possibly even an emergency); and anomalous cues will be experienced by the pilot under these conditions. The displacement limiters are designed to act progressively, so as to provide the smoothest and least disruptive interruption of normal operations. There are five stages of limiters for each degree of freedom arranged in ascending order as follows:

1. Software Parabolic Limits. The motion drive algorithm includes second order limiting routines (hence the term parabolic) that restrict commanded acceleration if the simulator is too close to a physical limit. The consequence of hitting a parabolic limit is a temporary disruption of normal motion resulting in a minor false cuing. The experiment may either be terminated or allowed to continue at the user's discretion.

2. Software Stops. The motion drive algorithm also includes limiters which restrict the displacement commands to appropriate maximum values. The consequence of hitting a software limiter is similar to that for hitting a software parabolic limit.

3. Hardware Parabolic Limits. Parabolic limits are also implemented independently in the servo drive electronics. The consequence of hitting a hardware parabolic limit is similar to that for hitting a software parabolic limit; however, the anomalous accelerations are likely to be greater in magnitude.

4. Limit Switches. Limit switches are installed at the positive and negative end-of-travel points. These can only be activated if the corresponding software parabolic limit, software limiter, and hardware parabolic limit fail to halt the motion. When a limit switch is activated, the motion system automatically shuts down.

5. Snubbers. The snubbers are large shock absorbers and may be considered "last resort" safety stops. They are designed to safely arrest motions in the event of a runaway under worst case conditions. A snubber impact also results in shutting down the motion system.

Appendix B

Symptom Checklist

NADS
DECEMBER, 1990

DTS______________
RUN#______________

SYMPTOM CHECKLIST

PILOT NAME or SUBJECT NO.____________________ DATE:________ TIME:________

Please circle: **BEFORE**

AFTER

Instructions: For each symptom, circle the rating that applies to you **RIGHT NOW.**

	SYMPTOM	RATING			
1.	General Discomfort	None	Slight	Moderate	Severe
2.	Fatigue	None	Slight	Moderate	Severe
3.	Boredom	None	Slight	Moderate	Severe
4.	Drowsiness	None	Slight	Moderate	Severe
5.	Headache	None	Slight	Moderate	Severe
6.	Eye Strain	None	Slight	Moderate	Severe
7.	Difficulty Focusing	None	Slight	Moderate	Severe
8a.	Salivation Increased	None	Slight	Moderate	Severe
8b.	Salivation Decreased	None	Slight	Moderate	Severe
9.	Sweating*	None	Slight	Moderate	Severe
10.	Nausea	None	Slight	Moderate	Severe
11.	Difficulty Concentrating	None	Slight	Moderate	Severe
12.	Mental Depression	No	Yes		
13.	"Fullness of the Head"	No	Yes		
14.	Blurred Vision	No	Yes		
15.	Dizziness	No	Yes		
16.	Vertigo	No	Yes		
17.	Visual Flashbacks**	No	Yes		
18.	Faintness	No	Yes		
19.	Aware of Breathing	No	Yes		
20.	Stomach Awareness***	No	Yes		
21.	Loss of Appetite	No	Yes		
22.	Increased Appetite	No	Yes		
23.	Desire to Move Bowels	No	Yes		
24.	Confusion	No	Yes		
25.	Burping	No	Yes		
26.	Vomiting	No	Yes	No. of times____	
27.	Other: Please describe____________________				

____

(continue on back)

28. Compared to symptoms experienced under the same conditions during flight in an actual aircraft, would you describe the above symptoms that you just experienced during the simulator flight as being: (please circle)

LESS THAN **SAME AS** **WORSE THAN**

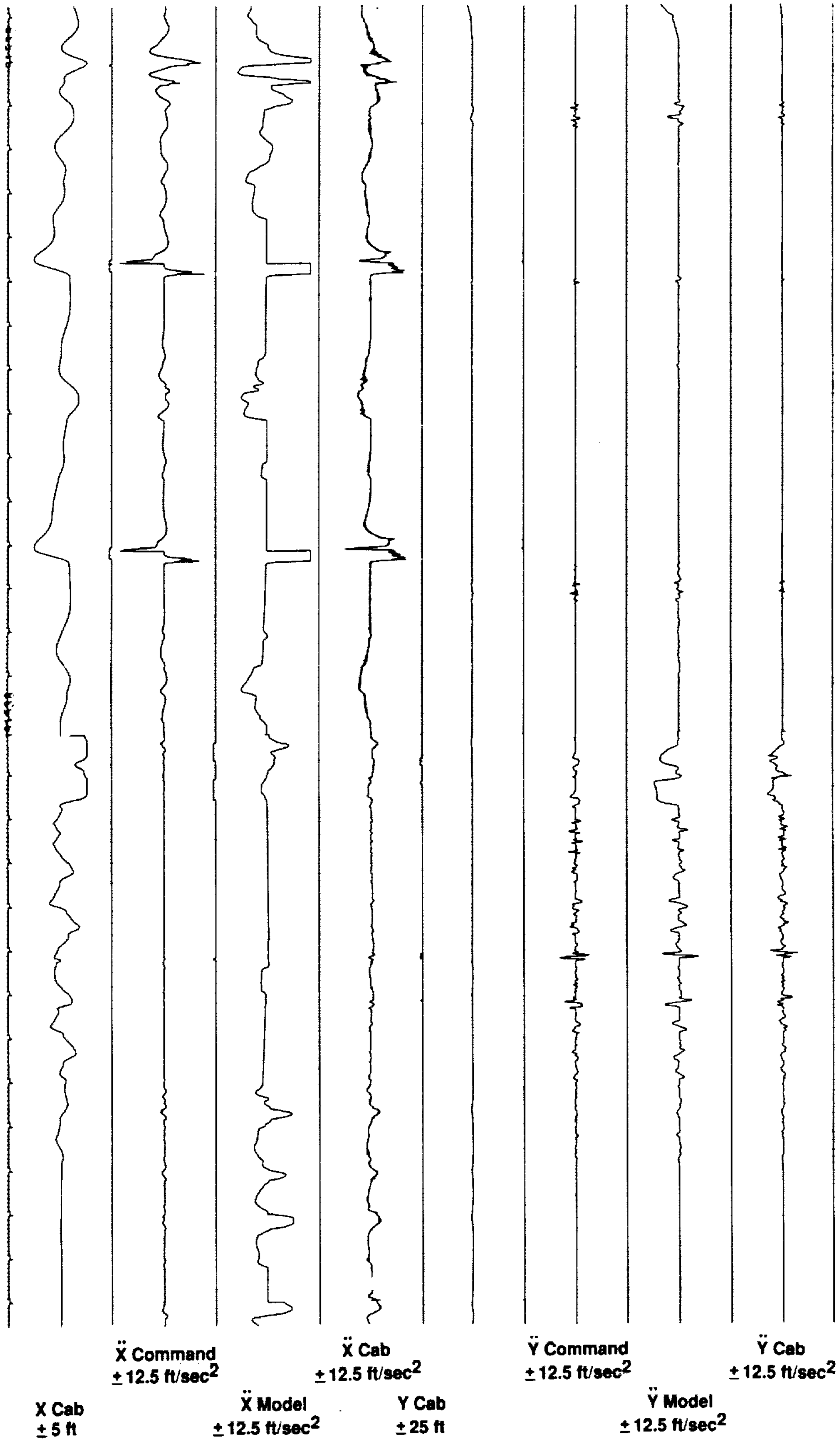
* "Cold sweating" due to discomfort, not due to physical exertion.

** "Visual Flashback" is a visual illusion of movement or false sensations similar to aircraft dynamics when NOT in the simulator or aircraft.

*** "Stomach Awareness" is usually used to indicate a feeling of discomfort just short of nausea.

Appendix C

Time History of Cockpit Motion NADS Motion Condition



$\ddot{X}$ Command
± 12.5 ft/sec^2
$\ddot{X}$ Cab
± 12.5 ft/sec^2
$\ddot{Y}$ Command
± 12.5 ft/sec^2
$\ddot{Y}$ Cab
± 12.5 ft/sec^2
X Cab
± 5 ft
$\ddot{X}$ Model
± 12.5 ft/sec^2
Y Cab
± 25 ft
$\ddot{Y}$ Model
± 12.5 ft/sec^2

Appendix D

Time History of Cockpit Motion Hexapod Motion Condition


Ẍ Command
± 12.5 ft/sec²
Ẍ Cab
± 12.5 ft/sec²
Ÿ Command
± 12.5 ft/sec²
Ÿ Cab
± 12.5 ft/sec²
X Cab
± 5 ft
Ẍ Model
± 12.5 ft/sec²
Y Cab
± 25 ft
Ÿ Model
± 12.5 ft/sec²

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13. ABSTRACT ***(Maximum 200 words)***

A demonstration of the capability of NASA's Vertical Motion Simulator to simulate two alternative motion base designs for the National Advanced Driving simulator (NADS) is reported. The VMS is located at the Ames Research Center in Moffett Field, California. The motion base conditions used in this demonstration were (a) a large translational motion base and (b) a motion base design with limited translational capability. The latter had translational capability representative of a typical synergistic motion platform. These alternatives were selected to test the prediction that large amplitude translational motion would result in a lower incidence or severity of simulator induced sickness (SIS) than would a limited translational motion base. A total of 10 drivers performed two tasks, slaloms and quick-stops, using each of the motion bases. Physiological, objective, and subjective measures were collected. No reliable differences in SIS between the motion base conditions was found in this demonstration. However, in light of the cost considerations and engineering challenges associated with implementing a large translation motion base, performance of a formal study is recommended.

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