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

DEVELOPMENT OF AN OFF-ROAD AGRICULTURAL VIRTUAL PROVING GROUND

Chris Schwarz, Samantha Hench, Brian Gilmore*, Bernie Romig*,
Ginger Watson, Jeff Dolan, Shawn Allen, Steve Cable
National Advanced Driving Simulator
University of Iowa
2401 Oakdale Blvd
Iowa City, IA 52241
319-335-4642 (phone)
319-335-4658 (fax)
cschwarz@nads-sc.uiowa.edu

Submitted July 7, 2003

ABSTRACT

A virtual proving ground (VPG) was developed for use in agricultural applications using the National Advanced Driving Simulator (NADS). The VPG environment consists of a real-time tractor dynamics model, visual and terrain databases with areas suitable for various types of driving tasks, a physical tractor cab equipped with instrumented controls providing a realistic interface between the operator and the simulated environment, and a set of audio cues which provide realistic tractor sounds. This project marks the first time that a cab other than one of the four standard NADS cabs was integrated into the simulator. A baseline experiment established that the VPG environment was realistic as measured by operator workload and realism assessments. This paper highlights some of the development tasks required to create the VPG and integrate the new cab, and summarizes some results of the baseline experiment.

INTRODUCTION

Advances in computer speed, image generation, and efficient mechanical modeling techniques over the last decade motivate the use of virtual proving ground (VPG) technologies for the design and analysis of ground-based vehicles [1-4]. VPG technologies, up to and including human-in-the-loop simulators, have been used in the commercial passenger vehicle, military, and agricultural sectors with great benefit, allowing manufacturers to operate their vehicles before building them. A virtual proving ground (VPG) refers to a completely simulated environment in which to test modeled vehicles. The VPG described in this paper consists of three main components: the vehicle, the environment (or test track), and the operator. Implicit in the inclusion of the operator in the loop, is the requirement that the VPG simulation be real-time. The National Advanced Driving Simulator (NADS) is capable of bringing these three components together very effectively. Simulator VPG studies similar to this one have been run at the IDS, and shown the efficacy of such efforts for military applications [1-4].

The NADS is a multi-million dollar research simulator that is available for use by industry, university, and government researchers. High Fidelity human-in-the-loop simulation is always an expensive proposition and the NADS even more so, since it was designed with the common operator in mind rather than the expert user, i.e. the scientist or engineer. Thus, every effort to immerse the operator into the simulation has been made. The standard NADS cabs are complete vehicle cabs with realistic interiors, dashboards, and controls [5]. Extraneous research equipment, such as cameras and communications systems, is generally unobtrusive or out-of-sight. The projected visual scene wraps a complete 360 degrees around the cab. Inside the dome, vibration actuators provide higher frequency road motion cues. Outside the dome, a nine degree-of-freedom (DOF), large excursion motion system takes care of all low frequency motion cues.

* Deere & Company
Moline Technology Center
One John Deere Place
Moline, IL 61254

This work has grown out of an NSF Industry/University Cooperative Research Center (I/UCRC) that was established between the University of Iowa and the University of Texas in Austin, and in which Deere & Company is an industry partner. The project described here has laid the groundwork for creating an off-road VPG for agricultural and, potentially, other off-road applications. This paper describes the development of the VPG, the design of the VPG validation experiment, and presents a sample of the results. The first section summarizes the modeling effort that went into creating a tractor model for real-time simulation. The vehicle dynamics, powertrain, steering, brakes, and tires are considered. The second section reviews the development of the VPG environment starting with the visual database. Then the cab hardware and instrumentation process is outlined; and the audio system is described. Finally, the driving scenarios and tasks that went into validating the VPG in the NADS are briefly described and some results are given.

VEHICLE MODELING

A John Deere 7810 MFWD tractor was modeled for use in the off-road, agricultural VPG. The 7810 is a 150 hp tractor with an 8.1-liter engine [6]. The vehicle that was modeled has a triple-link suspension (TLS) and a 19-speed PowerShift transmission. The TLS improves the off-road ride with hydraulic control cylinders and fore-aft suspension links that transfer longitudinal forces to the tractor's center of gravity. The PowerShift transmission provides 19 forward speeds and 7 reverse speeds. All shifts can be performed without the use of the clutch pedal with electronic control and hydraulic shift modulation. Moreover, controller logic allows skip-shifts and shuttle-shifts for smoother and more convenient shifting. The ComfortGard cab is equipped with an adjustable, air-damped seat and a digital display mounted on the steering column.

The functionality of the model was limited in a few ways. The mechanical-front-wheel-drive (MFWD) was not engaged during normal forward motion. The split brake pedals were locked together for all drives. The differential lock mechanism was not used. Hydraulic systems, such as the brakes, steering, and TLS, were simplified for real time simulation. Thus, for example, hysteresis due to hydraulic leakage in the steering system was not modeled. Some parameters on the tractor are settable by the operator, and their values had to be adjusted in the model as well. First, no implement was hitched to the tractor and only single tires on the rear axle were used. The front and rear track widths were both set to 72", and the steering stop was set for a maximum tire steer angle of 52 degrees.

The NADS dynamics software is called NADSdyna and is based on the Real Time Recursive Dynamics (RTRD) developed at the University of Iowa [7-9]. The multi-body formulation enables precise modeling of linkages and joints, thereby capturing geometric nonlinearities. The recursive formulation allows fast, real-time simulation of complex dynamic systems. NADSdyna also includes several subsystems for the modeling of the powertrain, tires, brakes, steering, and aerodynamics. Each of these subsystems generates forces and moments, which are added into the core dynamic simulation. The aerodynamics subsystem was not considered in this effort due to the low speeds encountered in most tractor scenarios.

Powertrain

The 19-speed PowerShift transmission is an incredibly complex mechanism whose functionality was captured for use in the 7810 tractor model. It has four clutches, five brakes, a simple planetary gear, and two compound planetary gear sets. Some simplification was achieved by lumping component inertias together, representing the planetary gears with simple gear ratio maps, and not modeling the high frequency modulation control. The transmission is modeled in two parts. The first part consists of the inertias, gear ratios, and clutches, while the second consists of the controller logic. When the controller indicates a shift is to take place, it initiates the disengagement of a pair of clutches connecting the current gear and the engagement of a pair of clutches connecting the new gear. The controller has to recognize several different situations in order to function properly [6, pp. 35-6]. The driver may shift with or without the clutch pedal. If the clutch pedal is used, the transmission controller commands an up-shift directly to the target gear, or a down-shift to the groundspeed gear, followed by sequential shifting the rest of the way. If the clutch pedal is not used, the controller decides whether to shift directly to gear, sequentially shift gear-by-gear, or some combination of the two. Shifting does not begin until the shift lever movement stops, and unwanted shifts can be avoided by quickly shifting the lever again.

The NADSdyna powertrain model had to be extensively modified and enhanced because of the addition of the PowerShift transmission model. This subsystem is also home to the engine, differential, and MFWD models. The NADSdyna quasi-static engine model was adapted for use here [10]. The quasi-static approach uses a carpet plot to relate engine torque to speed and throttle. The engine torque is modified by friction and accessory losses, and drives a dynamic rotating inertia, which is linked to the rest of the powertrain. The operation of the governor below idle speed and above maximum speed was lumped into the torque carpet plot. The resulting engine model accurately predicts steady state engine speed, qualitatively captures transients in engine speed during gearshifts, and even reproduces engine stalls due to large shifts at low throttle.

The standard NADSdyna formulation for a limited-slip differential model is used [10]. This model accepts as inputs the drive shaft torque as well as the left and right axle speeds. The outputs are drive shaft speed as well as left and right axle torque. The differential action is modeled by a trigonometric blending curve as a function of the differential speed and parameter values. Isolation springs and dampers were modeled on the engine shaft and on both ends of the rear axle. The MFWD clutch and other clutches appear through the powertrain model as well. A general purpose clutch model was developed for use in the 7810 model. It accepts as inputs shaft speeds from both ends, and outputs equal and opposite shaft torque in each direction. The model switches between an ideal solid coupling with limited torque propagation, and a spring-damper model to represent clutch transients.

The use of spring-damper systems in the powertrain model results in a relatively stiff set of differential equations that requires smaller integration step sizes. The main NADSdyna integration method is a fixed step-size, 3rd order, Adams Bashforth method. The global step size was set to four milliseconds; however that is too large to maintain stability in the powertrain subsystem. Therefore, a multi-rate integration scheme was employed so that a smaller local integration step size could be used in the powertrain [11,12]. The local integration method is a 2nd order Adams Bashforth. The smaller order was chosen because of its larger stability region. The local step size was set to 0.2 ms. Powertrain outputs that are passed to other parts of the software are averaged over all the local steps in the previous global step before it is passed. Inputs to the powertrain are carried through the local steps with a zero-order hold, with the exception of wheel speed, which is incremented every local time step. The simplified PowerShift transmission model accurately mimics the functionality of the actual transmission and relatively rough gearshifts due to larger inertia intervals are faithfully reproduced.

Tires

The 7810 is capable of running on several different types of radial and bias tires; and the operator's manual lists recommended tire pressure as a function of the tire type and the supported mass [6, Section 60]. The range of tire model parameters is somewhat more limited by the extent of available tire data. For this reason, constant values for vertical stiffness were used rather than force-displacement curves. The front tires are modeled on the Firestone 16.9R28 radials, while the rear tires are based on the Firestone 18.4R42 radials. Equations for lateral and longitudinal tire forces, provided by Deere & Co., were implemented in the NADSdyna tire subsystem. The front and rear track widths were both set to 72", and toe-in angles were not modeled.

Brakes

The 7810 is equipped with hydraulic powered, wet-disk, self-adjusting/equalizing brakes. A split brake pedal enables the left and right brakes to be operated independently. The engagement of both brakes together activates the MFWD, which connects the front and rear axles. NADSdyna has several types of brake models including pneumatic and hydraulic. A manual hydraulic brake model was adapted for use with the tractor. The model maps brake pedal pressure to brake line pressure, and brake line pressure to braking torque. Since the brake pedal was not instrumented with a pressure transducer, the brake pedal pressure was estimated from the pedal position, based on a relationship that was measured in the actual tractor. The capability for differential braking is present in the model; however, it was not used in the first round of VPG experiments in order to minimize the complexity of the protocol and analysis.

Steering

The 7810 has a full-power hydraulic steering system, while NADSdyna has a range of steering system models, from kinematic to hydraulic assisted steering. Other NADS cabs use only a kinematic steering system because steering dynamics and transients tend to occur outside the bandwidth of interest. Effects such as hysteresis due to hydraulic leakage provide some motivation to add fidelity to the steering model; however the added fidelity would not be expected to impact the response of the driver in the baseline tasks. Therefore, the kinematic steering system was adapted for use here. The steering ratio was set to correlate the +/- 52 degree tire steering stops with the 3.75 turn lock-to-lock steering wheel range.

DATABASE DEVELOPMENT

An important part of the VPG is a representation of the driving environment, a virtual 'test track'. This component is comprised of the visual database, terrain base, and driving scenario files. A visual database was developed to accommodate various basic tractor tests that were done in the baseline experiment. The database included a long straight road with turnarounds at each end. As well, three walled out sections provided areas for specialized tasks. The entire database is 4000m by 4000m in size.

The database contains a single typical flat roadway with circular turnarounds at both ends. Various walled-in spaces are accessible from the road and provide small areas with higher feature density for isolated tasks. These include two off-road terrain features, an ISO rough track (see *FIGURE 1*) and a bump course. Data for the rough track was taken from ISO publications for rough track testing [13]. The bump course was created out of trapezoidal bumps to match wooden plank bumps that were constructed for the validation portion of the experiment. The virtual terrain is flat except for the rough course and the bumps. The goals of the visual database design were to create an environment that was both configurable and visually attractive. The boundaries of the visual database contain rolling hills to block the visual horizon; but these are not correlated with terrain.

FIGURE 1 Visual Database Rough Track Entry View.

The roadway has a dirt texture; and the areas outside of the road and walled-in areas have a grass texture. The textures used in the walled-in areas vary from monotone to a plowed field appearance. Simple models of a cone and a barrier were constructed to provide a configurable environment. Obstacle courses may be constructed by positioning cones, barriers or both in various configurations. Individual trees and structures were modeled to provide scenery. The driving scenarios were defined by specifying arrangements of cones and barriers on the road and defining initial tractor positions in the database.

SIMULATOR INTEGRATION

This project was significant because it was the first time that a cab other than the four main NADS cabs was installed in the simulator. The development required to integrate a new cab into the NADS was considerable in several respects. An aluminum frame was constructed to provide a mechanical interface between the tractor cab and the dome hardware. Instrumentation had to be added to the cab in order to provide real-time measurements of several controls to the other simulator sub-systems. Safety and communication infrastructure had to be adapted to the new cab. An audio system had to be installed; and new audio cues needed to be recorded. Each of these efforts is described in the following sections.

Cab frame

The structural frame serves several basic functions important to the NADS [5]. First, since many components of the vehicle are removed for integration into the dome, the frame serves to augment the frame structure and support the body of the cab. It can also serve as installation mounts for the computers, power supplies, HVAC, and other equipment stored under the hood and in the trunk. Second, The frame has mounting points for the vibration actuators and mobility casters. The mobility casters serve the dual purpose of enabling cab transport, and calibrating the cab resting height to center stroke on the vibration actuators. Third, the frame interfaces with the shear flexure assembly on the floor of the dome. The purpose of this assembly is to constrain the lateral, longitudinal, and yaw DOFs while allowing the vibration actuators to excite the vertical DOF. Finally, the frame stiffens the cab in order to reject cab torsional modes that might be excited by the vibration actuators. Aluminum 6061 was used to construct the frame because of its lightness and strength. *FIGURE 2* shows the motion platform interface that includes the vibration actuators. The figure indicates a lateral offset that is used to place the driver's eye point at the center of the dome when using a typical passenger vehicle cab. The tractor driver is in the lateral center of the cab, so a centered installation in the dome is required.

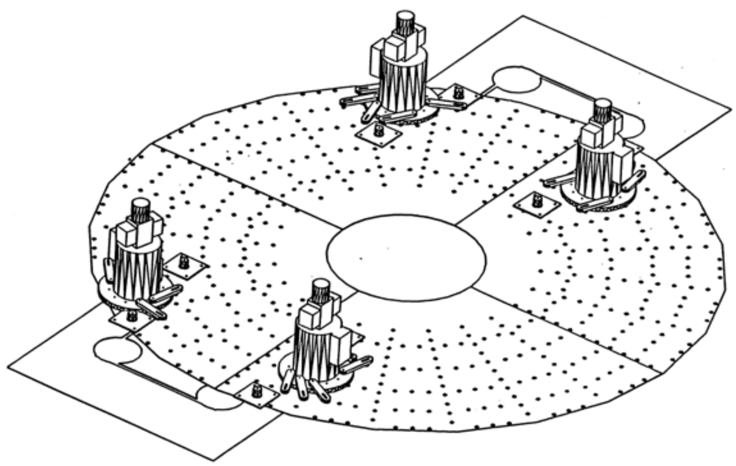

FIGURE 2 Motion Platform Interface.

Cab instrumentation

The cab used in the simulator was based on an 8000 series tractor cab with no enclosure that was provided by Deere & Co. The cab did have all the pedals, the steering column, and an OEM seat with seat arm instrument console, and provided a good base for the necessary instrumentation and enhancement that integration into the simulator required. The seat arm instrument console was removed and replaced with a plain armrest; and a standard 7810 instrument console, in a PowerShift configuration, was constructed to the right of the cab seat. Controls for the hitch and PTO were not included, as they would not be used in the experiment. Additionally, a standard 7810 digital dash was installed on the steering column, along with some plastic molding for aesthetic accuracy. The digital dash numerically and graphically displays various signals from the tractor such as engine RPM, gear selected, and tractor speed.

Major enhancements for the realism of the cab were an OEM hood that was mounted to the cab frame, and an ad hoc cab enclosure. A/B pillars and a roof were installed; but glass was not put in to completely enclose the cab. The hood was sanded to remove the glossy finish. All NADS cabs must have a dull finish so as not to reflect the beams from the projectors. The seat air cushion was made operational with the addition of a high current 13.8V power supply with the controls wired into the armrest switch. *FIGURE 3* shows the cab installed in the NADS dome. The hood, cab enclosure, and digital steering console are clearly visible; and the side instrument console is on the far side of the operator.

Instrumentation was installed to measure the driver's inputs and pass them to dynamics and the digital dash. A host PC that was installed behind the cab controlled this instrumentation. It contained a data acquisition (DAQ) card with 16-channels of 12-bit A/D, and 23 channels of digital I/O. The DAQ card was used to measure the brake, clutch, and foot throttle pedal positions, hand throttle position, gear shifter position, chassis 3-axis accelerometers, chassis 3-axis gyros, and a 3-axis accelerometer mounted to the seat. The steering wheel position was measured with a potentiometer connected to the steering shaft using a pulley. The position of the pedals was measured using potentiometers that were connected to the pedals through linkages and ball joints, which converted the linear motion to rotational. The same was done for the hand throttle and gear shifter. The gear shifting mechanism has detents, which allow only discrete positions. Therefore, the gear positions could be mapped to discrete potentiometer voltages. Additionally, a switch was installed to differentiate neutral from park. Cab rotation and vibration were measured using a standard motion reference pack (MRP) that is present in each NADS cab. It provides 3-axis acceleration and rotation measurements. Custom signal conditioning electronics were developed to convert the differential signals to single-ended ones for input into the DAQ card. Another 3-axis accelerometer was hard-mounted to the seat, above the air cushion, to measure vibration felt by the participant.

FIGURE 3 Tractor Cab in NADS Dome.

Force feedback was not implemented on any of the instrumentation. Fortunately, this did not affect the gear shifter or hand throttle controls, as the feel was dictated by the controls themselves and not the underlying mechanisms. In other cases, passive stiffness or damping was added to estimate the correct feel. An anchored nylon strap was attached to the steering shaft to enforce the 3.75 turn lock-to-lock "hard" stops. A simple spring was attached to the clutch pedal and rubber cylinders were used on the brake pedals, providing a degree of passive stiffness. Steering wheel damping was realized with a 19:1 gear reducer box.

Four small (1" square) cameras were mounted in the cab to provide views of the driver's face, driver's posture, over-the-shoulder forward view, and of the feet. These views were broadcast in the control room and recorded as part of the data collection. Communication requirements were fulfilled by the installation of two intercom channels in the cab, the driver's channel being recorded as part of the experiment. E-stop (emergency) and F-stop (fire) switches were added to the cab as part of the NADS safety requirement. Both switches immediately shut down all motion systems. Additionally, the F-stop switch shuts down power to the simulator and all supporting computers. An E-stop switch was placed on the shift panel within reach of the driver; and both E-stop and F-stop switches were placed within reach of the research assistant staff (RAS).

There are several layers of data communication in the simulator dome and between the dome and control room. A host PC located in the dome collects all signals measured in the cab and passes signals to the digital console. Communication with the console takes place via the vehicle data bus using the CCD protocol. An RS-232 to CCD converter was used to connect the digital console to the host PC. The previously mentioned DAQ samples measurements of the cab instrumentation. Communication between the cab and the control room takes place via optical fiber over a shared memory communications network (SCRAMNet). The SCRAMNet is a low latency reflective memory ring and is necessary to maintain real-time operation while passing simulation data between subsystems. An Ethernet network handles passing of error messages from remote systems to the control room. The NTSC video output from the four cameras is routed through converters to transmit the video over fiber optic cables to the control room. Once in the control room, the signals are then converted back to standard NTSC and run to a video switch matrix. Power for the cameras, as well as the fiber converters, CCD protocol converter and digital dash, are supplied by an external 12-V power supply. A simplified network and wiring diagram for the off-road VPG simulator configuration is shown in *FIGURE 4*.

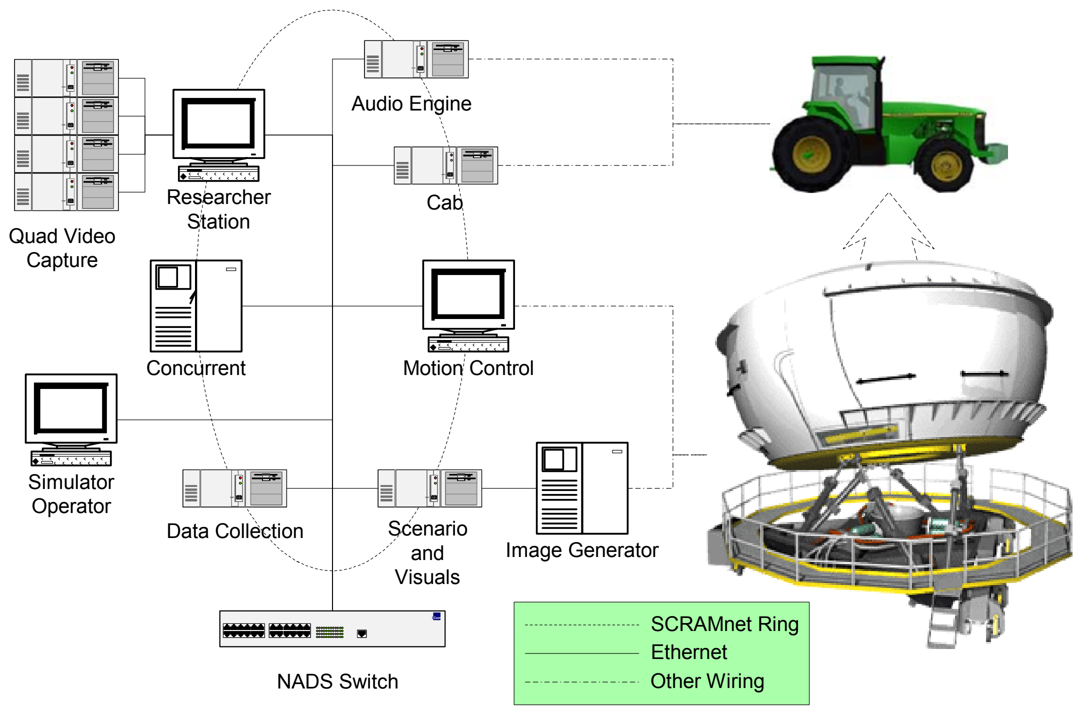

FIGURE 4 Simulator Network and Wiring Diagram.

Audio System

The audio engine was the only hardware component that could be borrowed without modification from an existing NADS cab. It was designed to be modular; as there are only two audio engines to be shared between all the cabs. It is a custom built PC solution that communicates with other simulator subsystems through a SCRAMNet card. The audio signals are produced through four SimPhonics C30 DSP cards, a Midiman DMAN 2044 audio card, and a Turtle Beach Daytona audio card, all routed through a custom-built mixer to six Stewart Electronics PA-200B audio amplifiers, which distribute amplified signals to up to six speakers in the cab. The audio software accepts information from dynamics and generates cues to be sent to the DSP and analog cards for playback. Environmental sounds can be strictly sample based or a combination of sample-based and interpolated.

The engine audio cues were reproduced for the initial baseline VPG experiment. Samples from an actual 7810 tractor were made using a Nagra DII digital reel-to-reel recorder with two externally-placed microphones; and engine samples were taken at 1000, 1500, and 2000 RPM (both idle and in motion). Each microphone was given it's own discrete track, linked by SMPTE timecode, and recorded at a 48 kHz sampling rate with 24-bit resolution. As a result, each RPM recording consisted of four tracks of audio.

The recorded samples were then moved onto a digital audio workstation and processed for use in the simulation. The four tracks for each RPM level were mixed to establish a realistic recreation of the isolated engine noise, and resampled to 16-bit, 16 kHz signals. The signals sent to the audio cards are interpolated between the discrete RPM samples that were recorded. Since the microphones were placed in close proximity to the engine, and since there was no direct barrier between the speakers and the driver, it was necessary to engineer the engine sound to take into account the soundproofing of the cab. After doing some sound pressure level meter readings with the actual tractor, low-frequency shelf equalization with a cutoff frequency of 650 Hz and a transition width of 1 octave was applied to each sample. This provided a sample that would better estimate the sound one would hear in the driver's seat of an actual 7810.

Two speakers were installed to handle the engine audio cues. A Clark synthesis TST 329F tactile transducer was attached at the bottom of the steering column to facilitate steering wheel rumble as well as some audio. A Polk Audio DB12, 4 ohm subwoofer speaker and enclosure was mounted behind the cab seat to recreate the large majority of engine noise. This combination not only gave the low-end growl of the diesel engine, but also allowed a small amount of high-end ambience that enhanced the life-like feel of simulation.

BASELINE EXPERIMENT AND RESULTS

A baseline experiment was designed and carried out to technically compare ride, handling, control, and feel of the 7810 tractor in the NADS virtual proving ground (VPG) environment to an actual 7810 John Deere tractor. The major goal of the VPG validation was to demonstrate functional correspondence between the simulated and actual 7810 tractor in a reasonable set of operating tasks [10]. The effectiveness of the simulator in providing a realistic driving environment was studied by comparing workload, performance, and perceptions of realism. Eight operators completed baseline, shifting, bump, lane change, and acceleration/braking tasks in the simulator and on the test course. Comparisons were made using a tractor experience survey, a vehicle response survey, workload measures, a perceived realism survey, a simulator sickness questionnaire, a structured interview, and driving performance data.

The baseline drive was for familiarization and consisted of driving straight and doing some simple gear shifting. The shifting task was longer, and included a more comprehensive series of sequential and skip shifts, all done without the clutch pedal. The bump task was performed in one of the walled-off areas of the visual database. The operator drove over three bumps, one on just the left side, one on just the right side, and one on both sides simultaneously. The lane change task involved performing a double lane change at a fairly slow speed by maneuvering through narrowly spaced cones. The acceleration/braking tasks involved driving straight on the road, first accelerating to maximum speed, then braking to a complete stop. Cones were placed along the road to serve as markers for the driver to throttle up or decelerate. The same set of tasks was performed in the 7810 tractor on a real test track; but details pertaining to that aspect of the validation are not discussed in this paper, apart from some final results.

The Overall Workload scale showed a very strong positive correlation between perceived workload in the simulator and on the test track (mean r=0.97, median r=0.93). This showed that operators rated their workload approximately the same in the real and virtual environments. The greatest discrepancies were noted during the lane change exercise. The Perceived Realism Survey also indicated high marks for certain aspects of the VPG. The survey indicated that the braking was the least realistic simulator feature and that the 7810 cab itself was most realistic. In this survey, braking referred to the feel of the brake pedal rather than the motion perception of deceleration during braking. See *FIGURE 5* for realism survey results. There was little to no simulator sickness during the study.

Comments collected from the drivers revealed a picture of what was good and bad in the VPG. The use of an actual, albeit converted, Deere cab in the simulator resulted in high marks for cab realism, indicating a high degree of physical correspondence in the simulator. Operators commented that the feel of the shifts, going up through the gears, was very realistic. The lane change task was difficult for drivers because of field-of-view limitations. There were no front tires in the simulator to judge position in the lane. Moreover, cones were not visible once they dropped off the bottom of the front screens. Thus, it was difficult to simulate such a precision maneuver. Finally, the lack of control feel systems was noticed on the brake pedal. Nevertheless, the high workload correlation indicates a level of functional correspondence in the simulated VPG that would be needed to pursue applied VPG experiments.

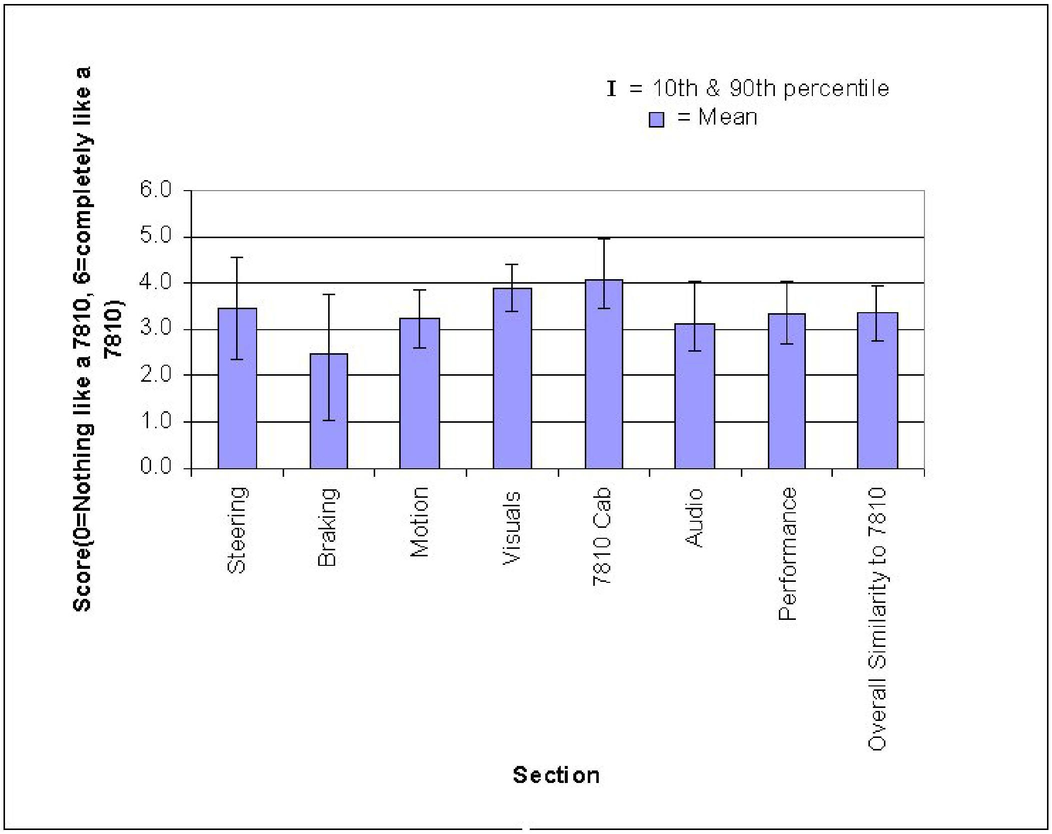

FIGURE 5 Simulator Realism Survey Results.

CONCLUSIONS

This work developed an off-road agricultural virtual proving ground using the National Advanced Driving Simulator. The VPG includes the real time tractor dynamics models, visual database, terrain model, instrumented cab, audio cues, specific tractor scenarios, and a human operator. To demonstrate that the VPG is realistic, a baseline test was conducted both in the simulator and on a physical test track. The perceived realism and workload as assessed by experienced operators showed that the VPG has a high degree of realism and functional correspondence with the actual tractor. As a result, off-road equipment manufacturers could be expected to simulate many types of operator tasks in the NADS VPG, and learn more about how operators interact with their equipment, even before it has been built.

Several things can be done, with relatively small effort, to improve the realism even further. With the addition of front wheels that turn, the field-of-view problem during the lane change would be mitigated a great deal. Creating audio cues for other tractor noises may improve the aural realism of the VPG to the point that the operator could throttle and shift based on sound alone, something that is done quite often during normal tractor operation. The addition of some force feedback would be expected to give the brake pedal a more accurate feel.

The example of industrial research described in this paper shows some of the benefits of a shared-use facility like the NADS. Proof-of-concept work can be commissioned in the simulator without a company having to commit the large amount of money required to build a NADS-like device.

ACKNOWLEDGEMENTS

This project was funded, in part, by Deere & Co. through an NSF Industry/University Cooperative Research Center. The authors which to acknowledge the expert advice of Dr. Christina Hollis, formerly of John Deere Construction Equipment Div., and Dr. Nohoon Ki, of the John Deere Product Engineering Center.

REFERENCES

1. Kuhl, J., Haug, E.J., Stoner, J. Operator-in-the-Loop Simulation for Virtual Prototyping of Ground Vehicles. Proceedings of Summer Computer Simulation Conference (SCSC'93), Boston, MA., July 1993, pp. 919-924.

2. Haug, E.J., Choi, K.K., Kuhl, J., and Wargo, J.D. Virtual Prototyping Simulation for Design of Mechanical Systems. Journal of Mechanical Design, Transactions of the ASME, Vol. 117B, Jun 1995, pp. 63-70.

3. Kuhl, J. et al. The Iowa Driving Simulator: An Immersive Research Environment. Computer, Vol. 28, No. 7, 1995, pp. 35-41.

4. Freeman, J.S., et al. The Iowa Driving Simulator: An Implementation and Application Overview. International Congress and Exposition, Detroit, MI, 1995, SAE #950174.

5. Bourne, S. and Lenkeit, J. The Development and Features of NADS Cabs. Human-Centered Transportation Simulation Conference, Iowa City, IA 2001.

6. 7610, 7710, and 7810 Tractors – Operator's Manual. OMAR162168 Issue F9, John Deere Waterloo Works, Deere & Company, 1999.

7. Bae, D.S., and Haug, E.J. A Recursive Formulation for Constrained Mechanical Systems, Part I – Open Loop. Mechanics of Structures and Machines, Vol. 15, No. 3, 1987, pp. 359-382.

8. Bae, D.S., and Haug, E.J. A Recursive Formulation for Constrained Mechanical Systems, Part II – Closed Loop. Mechanics of Structures and Machines, Vol. 15, No. 4, 1987.

9. Bae, D.S., Hwang, R.S., and Haug, E.J. A Recursive Formulation for Real Time Dynamic Simulation. Proceedings of the ASME Design Automation Conference, 1988, pp. 499-508.

10. Salaani, M.K., Guenther, D.A., and Heydinger, G.J. Vehicle Dynamics Modeling for the National Advanced Driving Simulator of a 1997 Jeep Cherokee. SAE International Congress & Exposition, Session: Vehicle Dynamics & Simulation (Part A&B), Detroit, MI, March 1999, SAE #1999-01-0121.

11. Solis, D. and Schwarz, C. Multirate Integration in Hybrid Electric Vehicle Virtual Proving Grounds. Proceedings of DETC'98 Design Automation Conference, Atlanta, 1998.

12. Haug, E.J., Negrut, D., Serban, R., and Solis, D. Numerical Methods for High-Speed Vehicle Dynamic Simulation. Mechanics of Structures and Machines, Vol. 27, No. 4, Nov 1999, pp. 507-533.

13. Agricultural Wheeled Tractors and Field Machinery – Measurement of Whole-Body Vibration of the Operator. ISO 5008:2002(E), 2002.

14. Moraal, J. Evaluating Simulator Validity. NATO Conference Series (Series) 3: Human Factors, Vol. 17, 1981, pp. 449-463.