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NADS AT THE UNIVERSITY OF IOWA: A TOOL FOR DRIVING SAFETY RESEARCH

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ABSTRACT

This paper presents an overview of the National Advanced Driving Simulator (NADS), its design, and core capabilities. The NADS is a high-fidelity driving simulator whose goal is to investigate human-centered issues as they relate to driving safety. Its primary mission is to investigate causes of accidents, with the goal of reducing fatalities on U.S. roadways. The NADS, whose construction has been funded primarily by the National Highway Traffic Safety Administration (NHTSA), is operated by The University of Iowa on a self-sustaining basis. A key component of the simulator's fidelity is the unique 9-degree-of-freedom motion system that reproduces normal driving accelerations to a degree never before possible. The simulator accommodates full-sized, fully instrumented vehicle cabs driven by research participants and utilizes a 24-foot projection dome, a motorized turntable that rotates ± 330°, a six-legged (hexapod) motion platform that moves about a 64-foot square bay, high-frequency actuators that accurately simulate road surfaces, fifteen high-resolution projectors that provide a 360° field of view with visual images updated 60 frames per second, and a surround sound system. User-friendly software tools enable users to quickly develop virtual environments and program scenarios necessary for research. In-house capabilities complement the NADS, providing a unique tool for highway safety research.

INTRODUCTION

Through a national competition administered by the National Science Foundation (NSF), the U.S. Department of Transportation in 1992 awarded the University of Iowa the host site of the NADS. The mission of the NADS project is to conduct research that will lead to a better understanding of the complex driver-vehicle-roadway interaction in critical driving situations and to a reduction in the number of traffic-related deaths and injuries on the nation's highways. NHTSA awarded design and construction contracts to TRW, Inc. The NADS design goals [1] were:

- State-of-the-art simulation fidelity
- Simulation of vehicle response to limit conditions
- User-friendly operation and user interface
- Flexibility and rapid configuration
- Maximum safety to participants and NADS staff
- Highly efficient two-shift operation
- Low-cost experiment rehearsal and debugging
- Minimized simulator-induced sickness

When it comes online, NADS will be a national shared-use research facility owned by NHTSA and operated by The University of Iowa. The NADS project delivers a high-fidelity simulator with a large motion envelope and fully immersed visual environment. A software library, a simulator development module (SDM) and four full-sized, fully instrumented vehicle cabs are also delivered. The NADS is housed in a 40,000-ft^2 facility that is designed and built for the NADS project and located on The University of Iowa Oakdale Campus. Figure 1 presents photographs of the NADS dome, the SDM, and the NADS building.

Figure 1 Photographs of the NADS dome (upper left), the SDM (upper right), and the NADS facility (lower).

The following sections provide overviews of the NADS system, including: scenario authoring tools and scenario control module, data reduction and verification tools, the NADSdyna vehicle dynamics software, and potential research areas.

NADS SYSTEM

As delivered, the NADS is comprised of eight modules that are integrated by TRW, Inc., the prime contractor for NADS development. These modules provide a high level of fidelity for driving simulation that will help researchers understand the complex driver, vehicle, and roadway interaction during critical maneuvers. Extensive enhancements to some of the NADS modules are currently underway at The University of Iowa. These enhancements are focused on the visual databases, scenario control tools, data reduction software and video recording and storage. Figure 2 illustrates a passenger sedan in the 7.3-m (24-ft) dome that is attached to a motorized turntable. The dome is mounted on a hexapod (six-legged) motion platform. This platform is mounted on a large track capable of reproducing extensive longitudinal and lateral motion cues to the driver. This configuration provides the substantial accelerations required for realistic passing and braking maneuvers, while high-frequency actuators attached to the vehicle cab accurately reproduce subtler sensations such as gravel, tar strips, potholes, etc. (see Figure 3). Fifteen LCD projectors and a surround sound system immerse the driver in a realistic visual and audio environment generated in real-time from programmable “virtual worlds” that provide detailed terrain and roadways, intelligent traffic, a variety of traffic signals and signs, pedestrians, weather conditions, and numerous other interactive features.

Figure 2 Computer-generated image of a NADS cab inside the NADS dome during a driving maneuver.

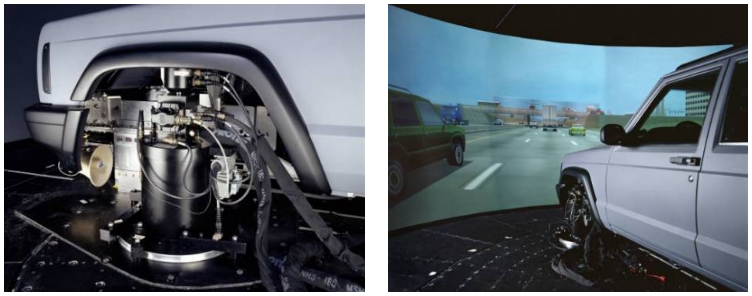


Figure 3. A close-up view of a high frequency actuator (left), and a photograph of a NADS cab inside the dome (right) during highway driving.

A brief description of the eight NADS modules follows. Technical specifications of NADS visual, motion, vibration and auditory modules are summarized in Table 1.

1. Visual System-- The NADS uses the Evans & Sutherland Harmony Image Generator (IG) to display the imagery on the 7.3-m (24-ft) dome. The IG consists of seven Advanced Graphics Engines (AGEs), each containing four Graphics Processors (GPs). One of the AGEs contains four Render Processors (RPs), and each of the remaining AGEs contains three RPs. The RPs feed fifteen output channels of imagery, each driving one view port. Each view port corresponds to a single Barco LCD projector with a maximum resolution of 1024 x 768. Three view ports are used for the high-resolution (1.1 arc minutes per optical line) inset, and the remaining

12 view ports cover 30 degrees of horizontal field of view each. The NADS visual system has a sustained polygon throughput of 21,000 polygons per frame, at 60 Hz update rate (see Table 1). The NADS visual system will provide the driver with realistic fields of view, including rearview images which are viewed through the actual vehicle mirrors.

2. Motion System-- The motion system was developed by MTS Systems and provides the largest translational motion envelope ever developed for a driving simulator, 64x64 feet. It also provides a continuous 330-degree turning yaw angle in both clockwise and counter-clockwise directions, pitch and roll, and high-frequency cues that duplicate motion over the full range of driving maneuvers. The NADS motion system provides a sustained acceleration of +/- 0.6-g in translational directions and +/- 1-g in the vertical direction. The maximum speed of the NADS dome is 6.1 m (20 ft)/s (see Table 1). The maximum frequency and displacement of the high-frequency actuators is 20 Hz and +/- 0.5 cm (0.2 in).

3. Control Feel System-- Control feel systems were developed by DRI Inc. for steering, brakes, clutch, transmission, and throttle to provide the driver with a realistic feel of the road and vehicle system response to driver inputs, over the full vehicle maneuvering and operating range. The control feel system is capable of representing automatic and manual control characteristics such as power steering, existing and experimental drive trains, anti-lock braking systems, and cruise control.

4. Auditory System-- The audio system was developed by I*SIM Inc. and provides three-dimensional sound sources and are coordinated with other sensory systems. The auditory system has a bandwidth from 15Hz to 20 kHz and a signal-to-noise ratio of 95dB (see Table 1). The audio database includes sounds emanating from highway surfaces, from high-density multiple-lane traffic, from the vehicle during operation (engine, brake, and wind noise), and from the roadway due to changes in the synthetic weather conditions.

5. Vehicle Cab System-- Vehicle cabs were developed by DRI Inc. and consist of actual vehicle cabs configured to fit within the dome mounted on the motion platform to provide the driver with realistic vehicle driving experiences. Video cameras in the cab can be used to capture simultaneous images of the driver, foot and hand positions, and other configurable views. The cabs have a full range of vehicle instrumentation interfaces. Four vehicle cabs are provided: a Chevy Malibu, a Ford Taurus, a DaimlerChrysler Cherokee and a Freightliner Century truck. Cabs are designed and constructed to allow rapid interchangeability, with a typical cab exchange time of eight hours.

6. Simulator Development Module (SDM)-- The SDM is a NADS-like simulator for off-line development of experiments and virtual environments. The SDM contains all the basic elements of the NADS, except motion, and uses only three projectors. Duplicate hardware resources make it possible to operate both the NADS and SDM simultaneously, which enables experimenters to cost-effectively preview scenarios and drive through scenes to assure themselves that the experiment is well structured before carrying out experiments on the full NADS system. Depending on study requirements, the SDM can be used as a fixed base simulator for data collection as well.

7. NADS Software Library-- The NADS software library has a high-fidelity vehicle dynamics software, NADSdyna, that was originally provided by The University of Iowa and has been updated by VRTC. The NADSdyna accurately represents vehicle motions and control feel conditions in response to driver control actions, road surface conditions, and aerodynamic disturbances. Vehicle dynamics models simulate light passenger cars and trucks, heavy trucks, and buses. The models will encompass normal driving conditions and maneuvers encountered during crash avoidance situations, including spinout and incipient rollover.

   The NADS software library includes the baseline visual system database. A full range of highway traffic control devices (signs and signals), three-dimensional objects that vehicles encounter, high-density multiple-lane traffic interacting with driver's vehicle, common intersection types (railroad crossings, overpasses, bridge structures, tunnels), and roadway weather environments are available. The NADS software library also includes user-friendly tools for scenario authoring and control. A more in-depth discussion of scenario authoring and control tools and NADSdyna will be given in later sections of this paper.

8. Computer System - A system of dozens of computers that control all aspects of NADS operation is integrated by TRW, Inc. Databases defining vehicle characteristics, the visual driving environment, environmental audio

characteristics, and roadway characteristics that influence performance of the vehicle are integrated to enable the researcher to create and supervise controlled experiments.

In addition to the delivered components, the UI has been working with TRW to enhance various simulator subsystems and upgrade critical hardware components. These enhancements and upgrades are designed to a) better integrate the NADS and SDM with the software engineering environment of the U of I NADS organization, b) take advantage of drastically improved price performance ratio of personal computers as compute engines, c) increase reliability and reduce maintenance and down time by replacing custom hardware-embedded board computers with PC-based workstations, and d) drastically improve the baseline capabilities of video distribution and collection through the installation of additional cameras, a larger video distribution system, and multiple digital video recording workstations.

Table 1 Summary of NADS Subsystem Specifications

Subsystem/module	**Specifications**
Visual Subsystem	
Update Rate	60 Hz
Refresh Rate	60 Hz
Polygons	21,000 at 60 Hz
Total Pixels	5 million
Transport Delay	≤ 50 ms
Contrast Ratio	25:1
Luminance	5 fL
Inset Resolution	1.1 Arc Min. per Optical line
Forward Area Resolution	3.5 Arc Min. per Optical line
Other Resolution	7.5 Arc Min. per Optical line
Motion Subsystem	
X-Y Platform	
Displacement	± 32.0 ft
Velocity	± 20.0 ft/s
Acceleration	± 20.0 ft/s^2
Motion Base	
Z (heave)	± 2.0 ft
Z (velocity)	± 5.0 ft/s
Z (acceleration)	± 32.0 ft/s^2
Pitch, roll	± 25 deg
Pitch, roll rates	± 45 deg/s
Yaw rates	± 60 deg/s
Pitch, roll, yaw acceleration	± 120 deg/s^2
Yaw (turntable)	± 330 deg
Vibration Actuator	
Vibration Displacement	± 0.2 in
Vibration frequency	20 Hz
Audio Subsystem	
Dynamic Range	100 dB above 20 dB noise floor reference
Bandwidth	15 Hz - 20 KHz
Signal/Noise Ratio	96 db
Distortion	≤ 1% excluding speakers
Dynamic Synchronization	≤ 28 ms measured from Host trigger to Audio amplifier output

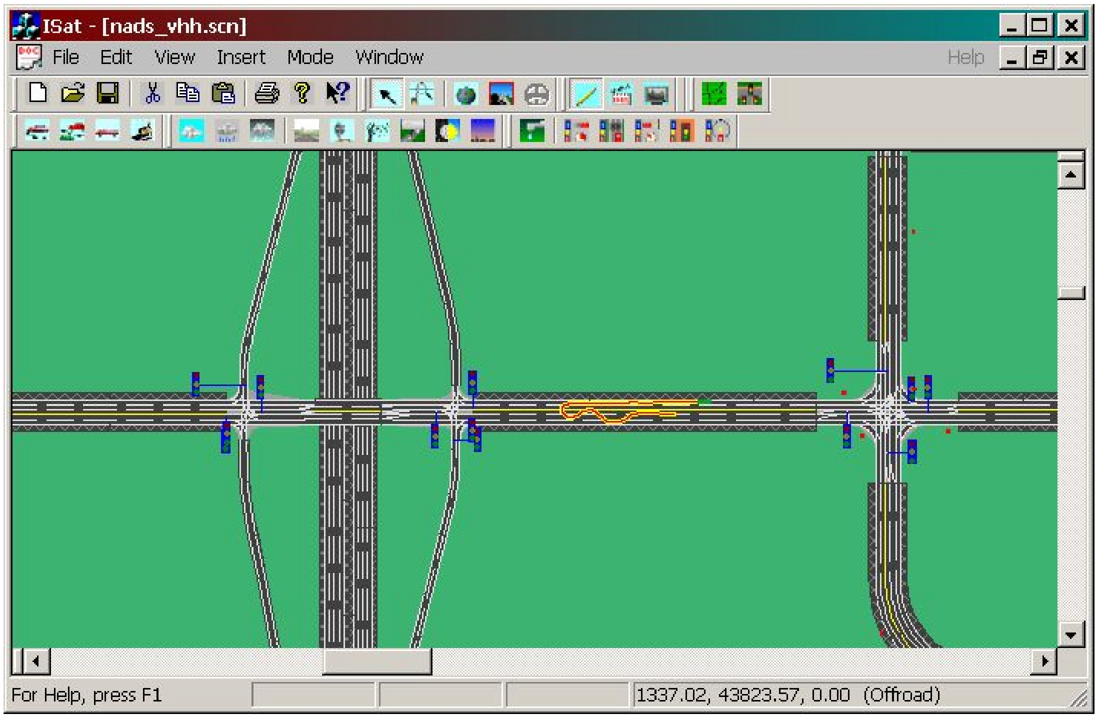
SCENARIO AUTHORING TOOLS AND SCENARIO CONTROL

Many factors contribute to the immersive experience of a simulator, but when the subject under study requires interaction with other vehicles, it is important that the virtual environment includes a microscopic traffic simulation model that generates traffic to populate the simulator's virtual environment. Collectively, the simulator modules responsible for these activities are referred to as scenario control. The NADS utilizes a sophisticated scenario definition and control (SDC) system that consists of a variety of software tools that can be used to author, rehearse, and test scenarios before executing on the simulator, along with a runtime engine that is responsible for executing scenarios in real time. Specifically, the NADS SDC system consists of a scene authoring component, a scenario authoring and rehearsal tool, and the runtime system. All three components are tightly integrated with other NADS components and post-processing tools.

The scene authoring component is responsible for producing the static elements of the virtual environment that include roads, intersections, buildings, static objects, and any other visible entities. The visual database produced by the scene authoring component is formatted according to the OpenFlight® standard and is ready for rendering by the NADS IG. Producing visual databases for the NADS is done using various methods. The most common and efficient method involves the use of the Tile Mosaic Tool (TMT), which allows a user to combine pre-built tiles into a larger environment. The NADS library currently contains approximately 70 tiles that include residential areas, rural areas, highways, industrial areas and mountainous roads. To minimize visual anomalies, the tool only allows side-by-side placement of tiles whose edges match. Typically, a database created by combining tiles requires some additional global tuning, but use of the TMT can rapidly produce databases that fit experimenter's needs. In addition to using the TMT to combine existing tiles, new tiles can be developed either for imaginary or geo-specific locations. An extensive library of features can be used to populate either type of new tiles, or new custom features can be built. To create geo-specific databases, a mobile sensor platform designed and integrated at NADS can be used to survey the actual roadways and produce OpenFlight databases capturing the road geometry within a 2-centimeter relative accuracy. The mobile sensor platform utilizes two differential L1/L2 GPS receivers mounted on a moving vehicle and samples position 10 times per second. Additional sensors are used to collect correction data. The collected data is combined with road feature libraries, road attribute information, and textures to produce the polygonal representation of the road network. Existing GIS data is then used to obtain terrain elevation for the surrounding region, and software developed at NADS can fuse all of this information into a ready-to-use database tile, including correlated information.

Along with the visual database, each tile contains a correlated version of the road network to be used by the scenario authoring tool and runtime system. The correlated database contains a very detailed description of the road network that includes topology, geometry, signage, road markings, and various static objects. A real-time Applications Programming Interface (API) allows programmatic access to the Correlated Virtual Environment Database (CVED) [8] that is used by the scenario authoring system and runtime engine. In addition, CVED is used for providing information about the terrain height and surface properties to other simulator subsystems such as the vehicle dynamics, the vibration system, and the audio subsystem. Specifically for the vehicle dynamics, a high-speed terrain interrogation function is available for profiling the terrain elevation and properties on or near roads.

The scenario authoring component allows a user to construct a scenario to be experienced by the simulator driver. Scenario authoring is facilitated through the Interactive Scenario Authoring Tool (ISAT). Figure 4 illustrates the main ISAT window. The ISAT supports authoring of all aspects of a NADS scenario. A scenario comprises various elements. It includes the simulator initial conditions (initial placement of the simulator driver, default environment conditions, baseline motion washout parameters, etc.), traffic light configurations and timing, and a specification of the traffic to be encountered by the driver. Traffic can either be specified explicitly, where each vehicle is placed at some initial position and let free to navigate around the database, or can be interactively managed by the traffic manager, a component that monitors a specified traffic density and selectively creates or deletes vehicles to maintain that density around the driver. Traffic can be placed either as autonomous objects, each of which utilizes a comprehensive driver model, or as deterministic route followers that are computationally cheap but exhibit no behavior other than following a geometric path and slowing down to avoid collisions. Both autonomous and trajectory follower traffic can be implemented using a variety of visual models (cars, trucks, vans, trains, bicycles, motorcycles, pedestrians etc.). In addition to the traffic, various rules can be defined though the use of triggers, sources, and other such coordinators that allow the orchestration of deterministic events despite the general randomness of the traffic. An environment model allows the arbitrary specification of varying weather, visibility and similar conditions, and fine grain control of time of day. Additional details on the scenario authoring capabilities of the NADS can be found in the paper by Papelis, Ahmad, and Schikore [2].



For Help, press F1

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Figure 4 Main ISAT window.

The runtime scenario system consists of the traffic simulation module combined with software that integrates it into the simulator. The NADS scenario control system utilizes a microscopic traffic simulation model. A microscopic simulation is one in which the individual behavior of each vehicle that comprises the traffic is modeled and simulated, as opposed to aggregate traffic simulation in which traffic is modeled as a number representing the density of traffic at different roads. The particular model used on the NADS [6], in addition to the typical lane tracking and following behaviors, incorporates various additional behaviors whose purpose is to produce realistic interaction with the simulator driver. These include a complex intersection navigation model that can deal with arbitrary intersection topologies, lane changes [7], and passing [5]. The traffic simulation system is built using the Hierarchical Concurrent State Machine (or HCSM) model [4], which allows easy addition of new behaviors. A key capability of the NADS traffic simulation module is the ability to satisfy the two contradicting requirements of randomness and control. Deterministic and repeatable interactions are necessary for experimental control. At the same time, variability of the traffic behaviors is also a necessary component for realism. The NADS scenario utilizes the concept of coordinators paired with a suggestive communication scheme that allows the superposition of controlled interactions on top of naturally randomized behaviors. Coordinators are autonomous agents responsible for sending messages to the various traffic elements. Coordinators can be programmed to act based on various predicates drawn from the virtual environment and include the actions of the driver. Messages sent to the autonomous driver models are smoothly incorporated into the behavior of the model, achieving the required result. For example, consider a scenario involving a vehicle running a red light while the driver is approaching an intersection. Successfully implementing this scenario requires several things to take place, some of which include the traffic light on the driver side being green when the driver approaches, the existence of a stopped vehicle on the intersection, and the lack of any vehicles immediately ahead of the driver to avoid the incursion from occurring with the vehicle ahead of the driver. Without coordinators, ensuring that all these constraints are met can be very challenging. When using the NADS SDC, a user can author a trigger coordinator that ensures the proper traffic light timing, then sends a signal to all vehicles ahead of the driver to increase their distance to the driver, and can select the object (actor) to implement the incursion, or even dynamically create a new vehicle if necessary.

DATA REDUCTION AND VERIFICATION

It is not atypical in the lifecycle of a driving simulation research study to spend half or more of the available time after data collection has been completed. The majority of this time is often spend in verifying, reducing, and analyzing the data collected during the simulator runs. In order to streamline this process, the NADS utilizes a set of in-house tools that support data reduction, verification, and visualization of simulator data. The goal of these tools is to allow easy specification of data reduction procedures, to make it simpler to identify technical blunders in the collection or interpretation of data, to reduce delays in delivering results, and to allow experimenters the ability to easily modify data reduction parameters and try what-if scenarios. A comprehensive description of the data reduction tools can be found in [3]. The NADS data reduction tools consist of three major components: the front-end tool, the execution engine, and the data reduction server.

The front-end graphical user interface (GUI) allows the user to create a data reduction specification using a visual dataflow language defined specifically for this purpose. A snapshot of the tool is shown in Figure 5.

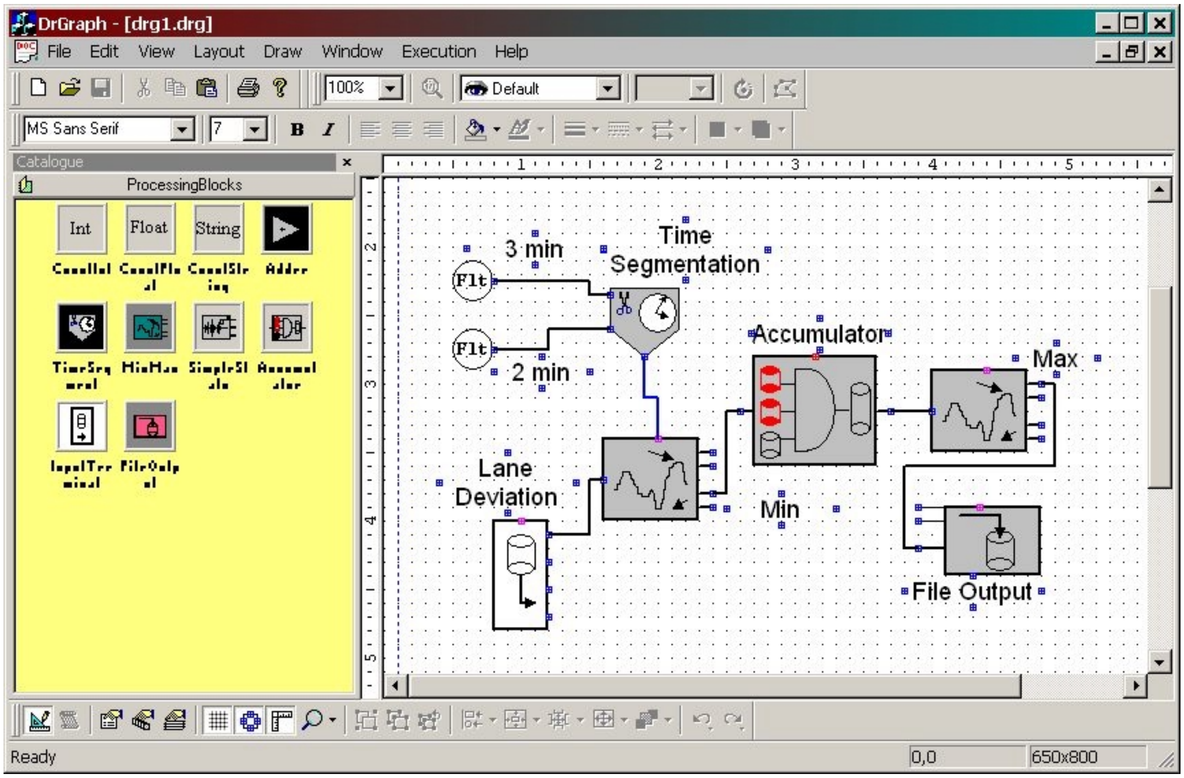


Figure 5 Data reduction specification tool.

The tool allows the user to create a dataflow graph whose execution performs transformations on the raw data collected at the simulator. The tool is fully integrated with other NADS tools and, in fact, uses a lot of the other tools such as the ISAT to provide user-friendly methods for displaying and manipulating data. For example, instead of displaying a textual description of the driver's path, the tool will use the ISAT and its top down mode to show the location of the driver within the context of the whole road network database. Through various nodes in the dataflow language, the user can manipulate images, videos, and sound clips obtained during data collection and, if necessary, produce new video clips, augment the collected data, override variables, and produce formatted text files that are ready to import to statistical or other analysis packages.

The execution engine is the component responsible for actually executing the data reduction graph and performing the necessary actions. In addition to the typical tasks involved in a dataflow execution engine, this software has some unique features that target application problems typical in driving simulation, one of which is the massive amount of non-changing data that has to be handled. The execution engine maintains a cache of intermediate result files produced by any node in the graph. Each intermediate result file has a unique tag, produced using strong hash functions typical of the ones used in cryptography, to identify all factors affecting the file. This includes items such as source data, graph layout, graph attributes, etc. The first time an execution for a particular graph takes place, the engine produces the results; however, in successive executions only intermediate files with changed dependencies are re-computed. This feature prevents a significant amount of re-computation, even when the user changes the execution graph, and allows the user to quickly obtain results after making small changes to the graph.

The data reduction server is a custom software package that is designed to work with the execution engine and the GUI tool. Its responsibility is storing everything associated with a simulator data collection and providing authorized access to it. The server is aware of the nature of the data, for example, it keeps associations of binary files with specific simulator subjects or runs. In addition to binary data, the server can store video or arbitrary documents, which can also be associated with a particular experiment, subject, or simulator run. Documents can be organized in arbitrary categories within a given experiment, and flexible data access rights can be associated with the server itself, data associated with an experiment, or data associated with a given category. For example, only authorized users can peruse the available experiments, and users can be given individual peruse, read, write, or administrative rights. The data reduction server simplifies logistics because it eliminates the need to maintain data on portable storage or on individual user's workstations. This approach also reduces security issues associated with numerous copies of data on CDs or other removable media. In addition, it eases configuration management and version control because of centralized storage. The server itself can be programmed to store experiment data in various back end servers for redundancy. For enhanced security, the server can be configured to use the Secure Sockets Layer (SSL) so all network transmissions are encrypted.

NADSDYNA VEHICLE DYNAMICS SOFTWARE

Modeling Approach and Formulations

The basic components of a vehicle and its environment are (1) major mechanical vehicle components such as chassis, suspension, and steering linkages, (2) vehicle subsystems such as vehicle steering, braking, engine, powertrain, tires and/or tracks, displays, and controls, and (3) environmental subsystems such as tire/track-soil interaction, aerodynamics, and other environmental effects.

Vehicle Main Mechanical Components

NADSdyna uses the multi-body approach for modeling the main vehicle moving mechanical parts. A general version of the multi-body modeling approach includes three key libraries. The first library consists of three types of bodies. These bodies are given by rigid bodies, flexible bodies with small deformation, and flexible bodies with large deformations. Only rigid bodies are supported within NADSdyna at this point. The second key library includes all kinematic constraints and their combinations to represent different single and composite-joint types. This library includes revolute, translational, cylindrical, spherical, universal, distance, revolute-spherical, revolute-translational, and spherical-translational joints. The third library contains vehicle force elements. This library includes general Translational-Spring-Damper-Actuator (TSDA), Revolute-Spring-Damper-Actuator (RSDA), leaf springs, stabilizing bars, and coulomb friction elements.

By using these three key libraries, a process that includes a model synthesis task, model resolution study, and model dynamic verification is followed to determine the number and types of bodies, joints, and force elements that are required. After the model is completed, the core dynamic simulation engine is used to generate the simulated vehicle response to be compared to either physical test data or to data generated using a high-fidelity non-real-time reference model provided by the customer.

Vehicle Subsystems

A library of vehicle subsystem models is currently available within the NADSdyna simulation environment corresponding to the standard NADS cabs. These models have been developed and validated by the Vehicle Research Test Center (VRTC) [9-13]. For new models, due to the varying nature of vehicle subsystems and depending on the nature of the simulator experiments to be conducted, parametric variations of the available models, or in some cases complete remodeling tasks, need to be conducted. The modeling approach used for the most basic vehicle subsystems is as follows. In modern vehicle designs, the prime mover for the vehicle is given by one or more diesel or gasoline internal combustion engines, gas turbines, batteries, ultra-capacitors, fuel cells, and electrical motors. The center's current prime mover capabilities consist of a steady-state power map of engine torque, as a function of engine speed and accelerator pedal input. This engine torque-generating model is linked to a second-order differential equation of the engine's rotating inertia, with accessory losses, to form the basic prime-mover model. This model is used in all validated NADS standard models. Dynamic engine models for both gasoline and diesel engines are also available in the library for more demanding applications. Figure 6 shows the interaction between the vehicle inputs, vehicle subsystems, and the vehicle Real Time Recursive Dynamics (RTRD) core.

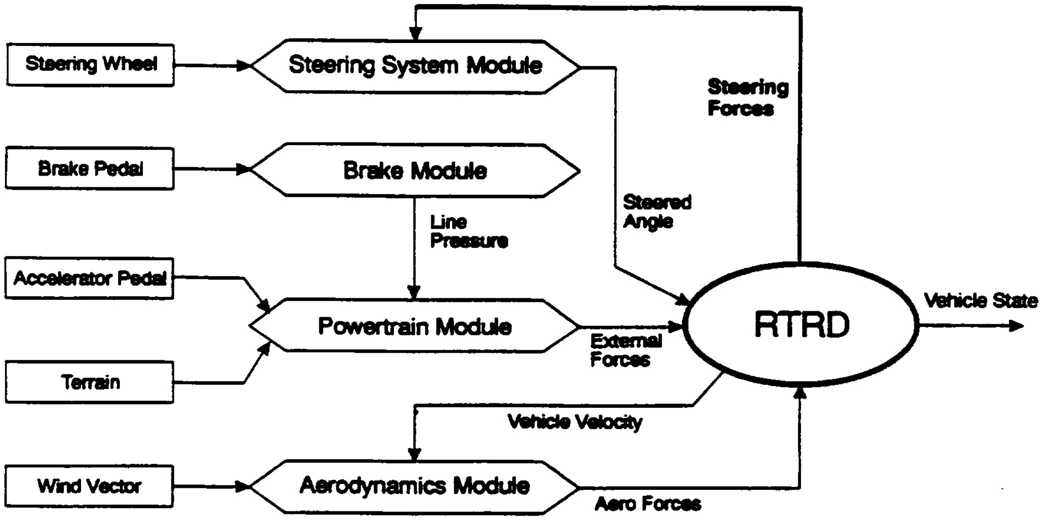


Figure 6 Vehicle subsystem modeling.

Hybrid-electric component models for batteries, electric motors, motor controllers, and generators have been formulated and demonstrated. These hybrid-electric vehicle (HEV) models are being updated and integrated to the latest version of the NADSdyna software for an upcoming Automotive Research Center (ARC) demonstration using the NADS. Models for other prime-mover types need to be developed as required by future experiments.

Vehicle powertrain topologies vary depending on the type of vehicle and its specific design. Typical configurations include different components such as: torque converters, transmissions, transfer cases, mechanical differentials, and final gears. Real-time models for all these elements are available in the NADSdyna environment. These models are available by default; however, more complex models can be developed and integrated as needed. This is commonly the case with dynamic transmission models, which are critical during shift quality assessment experiments.

Steering and braking subsystems are modeled using either hydraulic or pneumatic boosting capabilities. Although simple, the available models provide suitable representations for on-road vehicles. Test data to feed these models is essential to ensure a realistic feel during driving.

Current tire and track modeling capabilities include both basic and more complex modules, designed for both on-road and off-road applications. The tire model is divided into four components: (1) wheel rigid body, (2) tire flexible body, (3) contact element between the tire and the road, and (4) frictional force-generating component at the contact area. Depending on the application, the complexity of each of the model's components is determined. If small tires are involved, the tire inertial representation is lumped with that of the rigid wheel hub body and combined with tire contact and frictional force modules. This is the most common approach. For applications involving larger tire sizes, this is not a good approach and relative degrees of freedom between the wheel hub and the tire need to be included. In this case, higher-fidelity and parametric models that consists of a combined belt and tread body linked to the wheel body using a 3D-bushing force element is recommended for vehicle dynamic analysis. Compliance information to support this three-dimensional parametric tire model is obtained from experimental test results or from the virtual tire testing (VTT) process based on higher-fidelity Finite Element Analysis (FEA)-based models.

Aerodynamic and terrain/soil modules are considered under the environmental subsystem category. These two systems interact with the vehicle in completely different ways. The aerodynamic subsystem requires the vehicle external geometry for the calculation of basic aerodynamic coefficients. Since this geometric information is not usually required for dynamic analysis, a library of basic vehicle shapes and their aerodynamic coefficients has been provided with the goal of speeding up the modeling process. Wind tunnel test data for a particular target vehicle is also used, when available, to extract the model parameters for the real-time simulation. The current aerodynamic module is based on the SAE polynomial-based representation of force acting on the vehicle as a function of the wind vector magnitude and direction and vehicle geometrical description. Wind dynamic effects are represented by varying the direction and magnitude of the wind vector as a function of time. This effect is linked to the simulator scenario controller.

Simulation Approach

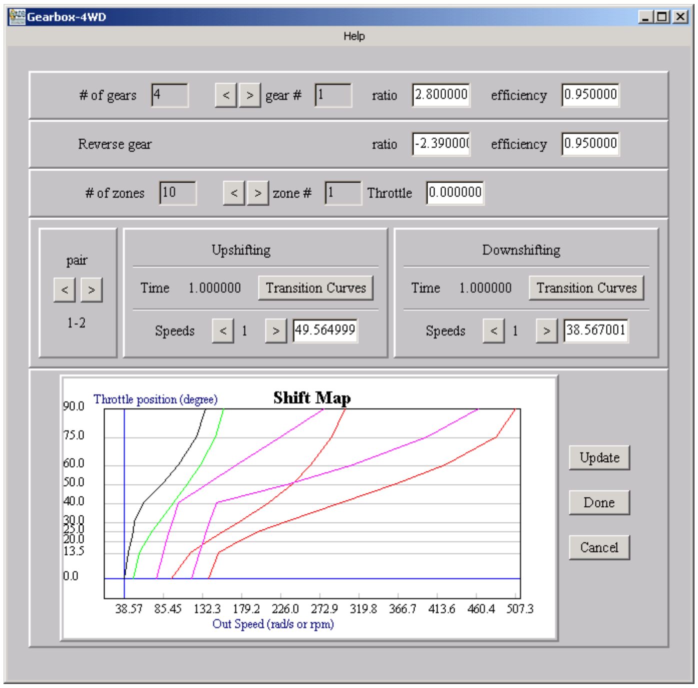
Multi-body Simulation Formulations

Based on a model realization that includes bodies, joints, and force elements, the vehicle system equations of motion (EOM) are generated using the Cartesian approach. This approach is simple and directly related to the way designs are represented within CAD systems. These equations of motion are given in terms of the inertia matrix, the vector of constraint equations, the Jacobian matrix of this vector with respect to generalized positions and velocities, and the generalized force vector. For vehicle simulation, special interfaces have been defined between the multi-body core and the vehicle subsystem models to allow for a proper representation of the physical system. This interface is based on the premise that each subsystem module generates forces and/or torques that are applied to one or more bodies in the multi-body core. This approach allows for an efficient and modular implementation.

At the core of NADSdyna, Differential Algebraic Equation (DAE) sets resulting from the constrained equations of motion are solved in real time using advanced computational techniques. Currently, the recursive dynamics formulation is used in combination with the Coordinate Partitioning method to reduce the set of DAE to a set of ODE that can be integrated using standard numerical integrators. Numerical integration is key in dynamic simulation because it dictates the amount of effort required per solution step, the stability and robustness of the simulation, and the attainable efficiency of the simulation using serial or parallel computing. Currently, explicit integration formulas of the Adams type are used within the NADSdyna simulation environment for real-time vehicle applications.

Vehicle Modeling Tools

This multi-body dynamics package was developed to provide an environment for flexible vehicle modeling and simulation. Basic components for vehicle subsystems are included, and a number of vehicle models have been validated using test data. The interface originally developed for this application was based on the X-windows system. This interface has not been updated since the original software was delivered to the government for the NADS subcontractors to integrate it with the rest of the NADS software system. However, as a part of the NADS software enhancement activities, new interfaces based on Java technology have been developed to allow for multi-platform execution. This new Java-based graphical user interface developed for the NADSdyna software is currently being integrated and tested. Figure 7 shows a sample window for the transmission model from the NADSdyna interface.



# of gears 4 gear # 1 ratio 2.800000 efficiency 0.950000

Reverse gear ratio -2.39000(efficiency 0.950000

# of zones 10 zone # 1 Throttle 0.000000

pair 1-2

Upshifting Time 1.000000 Speeds 1 49.564999

Downshifting Time 1.000000 Speeds 1 38.567001

Figure 7 Sample window for the transmission model from the NADSdyna interface.

POTENTIAL RESEARCH AREAS

Using NADS-based virtual environments, highway safety research and development specialists will be able to achieve fundamental objectives not possible before. NADS-based research will quantify the effects of human factors such as driver reaction to road conditions, fatigue, aging, drug and alcohol use, physical and mental impairments, and increased information flow on the driver's ability to control a vehicle and avoid crashes. Such tests will be carried out in crash-prone situations, which is not feasible on real roads or test tracks, in order to evaluate the impact of design alternatives on performance and crash avoidance response of vehicles in the hands of typical and impaired drivers. Safety and driver comfort devices, ergonomic factors, driver fatigue, and cumulative trauma due to vibration and stressful driving environments will also be considered.

The driver will be immersed in a virtual environment that simulates the driver's vehicle and its interaction with the highway and other elements of the environment, at a level of fidelity comparable to that of the actual vehicle-driver-highway environment. With this fundamentally new capability, researchers will carry out controlled experiments with a broad cross-section of drivers, vehicles, and highway situations to:

1. achieve a level of repeatability required for fundamental understanding of cause and effect of driver-vehicle-highway interaction, during both routine and critical crash avoidance maneuvers;
2. control variables characterizing vehicle performance, highway conditions, and behavior of other drivers far better than is possible on a real highway or on test tracks;
3. carry out experiments with advanced vehicle and highway system designs to determine limits of driver performance that would be life-threatening, hence impossible, on a real highway or test track;
4. determine optimal strategies for crash avoidance, yielding fundamental new scientific and engineering knowledge and information into means for reducing the trauma and enormous cost of crashes that occur each year on US highways;
5. design safe and high-quality vehicles and highway systems, including automated highway systems of the future.

NADS can also be used by highway safety researchers to develop methods for assessing fitness to drive for special populations, including older drivers, drivers under the influence of alcohol and prescription or non-prescription drugs, drivers with psychiatric disorders, and drivers with medical or physical disabilities that affect cognitive processes. Assessment techniques used to date have largely involved laboratory tests that are believed to be related to driving behavior, or lower fidelity simulations. Validation of the research, including that which uses the NADS, is needed to determine if the results can be generalized to real-world driving.

The study of special populations, in comparison to the general driving population, will identify response measures that discriminate between fit and unfit drivers. The research will identify cut-off points on response measures, beyond which a driver could be considered no longer fit to drive. Performance measures identified through this research are required to discriminate between poor, average, and superior subjects. These response measures can then be used to assess the abilities of drivers and the effects of various vehicle and roadway design features on the driving performance of different segments of the population. Specific developments anticipated in this area include the following [14]:

1. Design of Driver Performance Metrics - Appropriate measures of driver performance are necessary to allow researchers to scale the responses of test subjects. Discriminant functions that determine what is acceptable and unacceptable driving behavior and response measure performance will be determined. Driver response measures that will be recorded and evaluated include maximum tracking deviations, distances maintained between hazard threats, minimum and maximum speed, average course travel times, potential accident involvement, performance on secondary and concurrent distraction tasks, detection of intruding vehicles, obstacle avoidance, and reaction times to timed incidents. A statistical analysis of within subject and between subject variation, as well as differences between demographic groups, will be performed. Scenario and real-life accident experience will be compared for the test subjects. Many driver-sufficiency rating schemes will be compared, to determine reliability in measuring adequacy of driver performance and fitness to drive.

2. Evaluation of Driver Training Simulators - The application of vehicle simulators to training commercial drivers is a critical area of study that addresses safety problems that are of national concern. Applications will be focused on driver screening, development of improved training regimens, and exposure to high-risk hazard-avoidance situations. There is considerable debate over the benefits of training on low-end simulators because failure to adequately represent appropriate visual and motion cues can result in negative training and reinforce inappropriate reactions by the driver. The development of adequate representations of vehicle response and graphics systems will be performed with the NADS using real drivers and exposing them to different levels fidelity of vehicle dynamics, image quality, and audio cues. The results will be of immediate use to both simulator developers and training programmers.

3. Environmental Effects on Driver Performance - Environmental effects can temporarily affect the function of the vehicle, as in the case of wind gusts, passed vehicle interference, and induced air vortices and turbulence. These discrete events will be presented in simulation scenarios to determine the variety of driver responses and the resulting incident outcomes. Climatic conditions that modify the frictional characteristics of the roadway through accumulated ice or water and temporary vision loss from smoke, fog, industrial smog, and low light conditions will be created within the same set of experiments. The use of warning devices in the vehicle, traffic control devices on the roadway, and external driver information procedures will be evaluated and recommendations will be made regarding their implementation.

We also anticipate that NADS will be used by designers of highway and vehicle automation devices and techniques, as well as safety specialists concerned with the ability of a broad cross section of drivers to function effectively with new information and control devices. A high-fidelity driving simulator such as the NADS can provide safe and affordable experimental environments to make assessments of revolutionary concepts of transportation means, of which the infrastructure does not yet exist.

We firmly believe that human-centered simulation like that offered by the NADS will broaden the R&D capabilities to meet the current and future challenges of the transportation sector.

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