SAE TECHNICAL PAPER SERIES

2000-01-0126

Vehicle Design Evaluation Using the Digital Proving Ground

Joseph H Canova
Engineering Dynamics Corporation

Reprinted From: Computer Applications for Crash, Optimization, and Simulation Research (SP–1496)

The Engineering Society For Advancing Mobility Land Sea Air and Space®
INTERNATIONAL

SAE 2000 World Congress
Detroit, Michigan
March 6-9, 2000

400 Commonwealth Drive, Warrendale, PA 15096-0001 U.S.A. Tel: (724) 776-4841 Fax: (724) 776-5760

The appearance of this ISSN code at the bottom of this page indicates SAE's consent that copies of the paper may be made for personal or internal use of specific clients. This consent is given on the condition, however, that the copier pay a $7.00 per article copy fee through the Copyright Clearance Center, Inc. Operations Center, 222 Rosewood Drive, Danvers, MA 01923 for copying beyond that permitted by Sections 107 or 108 of the U.S. Copyright Law. This consent does not extend to other kinds of copying such as copying for general distribution, for advertising or promotional purposes, for creating new collective works, or for resale.

SAE routinely stocks printed papers for a period of three years following date of publication. Direct your orders to SAE Customer Sales and Satisfaction Department.

Quantity reprint rates can be obtained from the Customer Sales and Satisfaction Department.

To request permission to reprint a technical paper or permission to use copyrighted SAE publications in other works, contact the SAE Publications Group.

GLOBAL MOBILITY DATABASE

All SAE papers, standards, and selected books are abstracted and indexed in the Global Mobility Database

No part of this publication may be reproduced in any form, in an electronic retrieval system or otherwise, without the prior written permission of the publisher.

ISSN 0148-7191
Copyright 2000 Society of Automotive Engineers, Inc.

Positions and opinions advanced in this paper are those of the author(s) and not necessarily those of SAE. The author is solely responsible for the content of the paper. A process is available by which discussions will be printed with the paper if it is published in SAE Transactions. For permission to publish this paper in full or in part, contact the SAE Publications Group.

Persons wishing to submit papers to be considered for presentation or publication through SAE should send the manuscript or a 300 word abstract of a proposed manuscript to: Secretary, Engineering Meetings Board, SAE.

Printed in USA

2000-01-0126

Vehicle Design Evaluation Using The Digital Proving Ground

Joseph H Canova
Engineering Dynamics Corporation

ABSTRACT

Recent advancements in three-dimensional digital terrain mapping and vehicle simulation technology present an opportunity to introduce “real-world feedback” early in the design process. Designers of suspension, braking, steering and safety systems can evaluate and optimize designs using computer simulation of a vehicle on the digital proving ground (DPG). A range of possible design behaviors can be identified and analyzed prior to expensive prototyping and testing. Even a series of specific test maneuvers may be evaluated prior to actual testing to ensure safety of the driver and prototype vehicle. As a result, the design process is more efficient and the use of the actual proving ground is more cost effective.

This paper presents an overview of the use of the digital proving ground for vehicle design evaluation. Several examples of digital proving ground tests will be discussed. Digital 3-D models of a test track facility may be available from the construction of the grounds, or they can be created with laser measurement techniques, such as LIDAR. Tire-terrain contact patch simulation techniques provide for the use of validated physics models to study 3-D vehicle behavior undergoing simulated tests for handling, ride, braking compliance or other maneuvers.

INTRODUCTION

A critical phase of the vehicle design process is physical testing of prototype designs at a proving ground. Vehicles may be subjected to tests involving various road and weather conditions, road grades, steering and braking maneuvers and even high speeds to study handling behavior, ride comfort, and compliance with FMVSS, SAE and European standards. Test results within design specifications are invaluable for proving the proper interaction of individually developed systems to provide for safe operation of a vehicle. Unsatisfactory test results require redesign and testing of system components until a suitable configuration provides the expected results. Both satisfactory and unsatisfactory results provide real-world feedback to engineers.

Ideally, a new vehicle design is subjected to a single round of proving ground tests, as the test results meet specifications every time. However, if a vehicle fails any portion of the tests, the process of repeated redesign and testing can dramatically affect the development schedule and budget. The average investment in a single prototype design and test vehicle is over $250,000. Greater confidence in the ability of a new vehicle design to efficiently pass proving ground tests is possible by simulating the performance and behavior of a vehicle prior to physical testing on a proving ground.

Computer models defining the dynamic behavior of prototype vehicle designs can be easily developed. Proving grounds can be surveyed to generate 3-dimensional terrain models. The combination of the vehicle and the terrain models within a simulation environment allows the scientific prediction of prototype vehicle behavior on the actual proving ground. This use of the DPG offers real-world feedback to engineers at any stage in the development process, rather than waiting until formal design reviews after physical testing is conducted.

INFLUENCE ON THE DESIGN PROCESS

The traditional design process begins with a preliminary concept or design modification request, then advances through several stages including design studies, computer-design, testing of individual systems, prototype vehicle development, and proving ground testing. Emphasis is continually placed on engineers to shorten the development time for new models, provide faster response to modifications for existing designs, plus produce better quality designs overall. One method to improve the efficiency of the design process is to focus on whole vehicle design, rather than compartmentalized design of individual systems, such as for suspension, steering, braking and safety systems. While the behavior and functionality of individual systems may be very well understood and easily modeled in computer studies, whole vehicle behavior analysis may be extremely complex. Often, the capabilities of a system operating effectively on one vehicle design can prove to be severely inadequate on another design. This inadequacy may not be discovered until proving ground tests. The DPG can be used to study the effects of changing single systems on identical vehicles, such as brake assembly designs. The DPG can also be used to develop specifications for individual systems by defining the dynamic performance characteristics of the whole vehicle, then identifying the parameters affecting each system. Sensitivity analyses can be performed to identify areas of significant importance that may require extensive design and analysis prior to prototype development. The DPG provides design performance feedback at any stage of development. Earlier efforts in applying limited computer modeling capabilities to vehicle design for crashworthiness have been discussed by Fischer and Haertle [1].

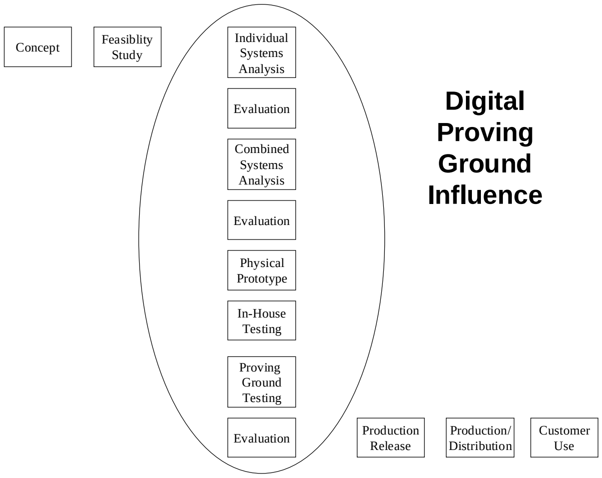


Figure 1. High-level concept diagram of the areas of influence of the DPG on the design process.

ADVANCEMENTS IN SIMULATION TECHNOLOGY

A variety of approaches to develop a greater understanding of dynamic vehicle behavior based on experimental testing are presently being explored. The development of stationary vehicle dynamics testing platforms and full-size simulators such as discussed by Langer [2] and others, are offering great potential to designers. However, easy access to these testing methods may not be readily available to all participants in the design process. Extensive physical testing and data analysis may be required to determine the appropriate inputs to excite the suspension as if it was traveling on a rough road. Expensive equipment may need be purchased or developed. An entire specialized department may be required to maintain the systems. The DPG concept however, is centered on providing greater access to real-world feedback to all phases of the design process. To accomplish this goal, the DPG must be available and easily used by all members of the design and testing processes.

With the continual advancements in computer technology for computational speed and graphics capabilities, the DPG provides a means to visualize voluminous amounts of numerical data from a simulation in an easily understood visual format. Additionally, the DPG employs an appropriate level of detail to provide accurate analysis of the systems involved in the study, without requiring extensive computing time. By providing vehicle dynamics simulation quickly and accurately, the DPG concept can be used as a pre-processor for FEA type studies required in many areas of the vehicle design. The DPG allows the systems engineer to study the effects of changing their system on the overall behavior of the vehicle design, without extensive investment in time and efforts for model development and analysis.

The DPG concept will be demonstrated and discussed using the HVE simulation environment as a DPG for vehicle testing. There are other available computer simulation environments which could be used as a DPG, however the goal of the paper is to clearly present concepts and the author is most familiar with using HVE. HVE is a simulation environment that engineers use to perform studies of complex real-world events involving human and vehicle dynamics. HVE uses sophisticated models for representing human, vehicle and terrain objects used in simulations. HVE also uses sophisticated calculation methods for model interactions, such as the calculation of forces at the tire/terrain contact patch as discussed by Day [3]. At every timestep of simulation, the contact patch between the tire and terrain is calculated to identify the forces acting upon the vehicle. In this manner, the vehicle model responds to the terrain features, as would the actual vehicle traveling on a real road surface, such as a proving ground.

Specialized simulation models for the dynamics of vehicles and humans may be used during proving ground test simulation studies. Human simulation models, passenger vehicle simulation models and commercial vehicle simulation models have been developed to model the proper physical/mathematical behavior for objects involved in a study. A passenger car design engineer may focus on the use of a validated passenger vehicle simulation model, such as EDVSM [4], while a commercial vehicle design engineer may focus on using a commercial vehicle model for heavy truck and articulated vehicle studies [5]. These simulation models have been validated against results from industry-recognized staged experiments and simulation models. HVE also has an open architecture allowing the design engineer to port their own highly-validated OEM simulation models to use in DPG studies.

Robust, detailed models of tire behavior, such as those discussed by Allen, et al [6] are extremely important for accurate modeling of real-world vehicle dynamics. Using these models in combination with the proper calculation method provides a reliable modeling approach for investigating real-world events. Additionally, the performance and influence of tires fitted to new production vehicles can be evaluated by using the appropriate data from manufacturer tests to build the tire for simulation study.

DEVELOPMENT OF HUMAN MODELS – Human modeling allows engineers to study restraint system effectiveness and other human-related safety issues normally identified by barrier crash tests. While this paper is focused more on vehicle dynamics than human dynamics, crash tests are often a factor in overall vehicle design.

Human models in HVE are physical/mathematical models based on GEBOD and are discussed in great detail by Day [7]. The model has 15 segments and 14 joints. The visual representation of the human model is shown in Figure 2. Human model parameters include inertial properties, contact ellipsoid properties and joint properties for each segment, plus injury tolerances. The collision pulse (acceleration vs. time history) calculated from a crash test simulation is transferred directly to the human simulation model providing biomechanical engineers with an efficient means to identify conditions for detailed occupant modeling.

Figure 2. Visual representation of the HVE human model.

DEVELOPMENT OF VEHICLE MODELS – The physical/mathematical model of the vehicle represents a superset of vehicle dynamics simulators, providing a high-fidelity model for use in dynamic simulations [8]. The 3-D vehicle geometry is used to visualize the vehicle model and to assign mechanical/structural properties to the vehicle exterior. The visual representation of the vehicle model is shown in Figure 3. The mesh of the vehicle model may be used in collision algorithms required in crash test or rollover simulations, such as the DyMESH method developed by York & Day [9].

The vehicle model contains extensive parameters defining the exterior geometry, sprung mass, unsprung masses, tires, brake system, steering system, safety systems and drivetrain. The sprung mass of the vehicle is defined by parameter groups including inertias, c.g. location, inter-vehicle connections, aerodynamic drag and body torsional stiffness. The unsprung masses of the vehicle are defined by parameter groups including physical location, brake assembly design, suspension and tires.

Proper tire modeling is extremely critical for accurate 3-D simulation. The calculation of the forces acting at the tire-terrain contact patch must be properly transmitted to the sprung mass of the vehicle through the tire and suspension models. The HVE tire model is defined by over a hundred physical properties, and load- and speed-dependent parameters. The data used in the model may be obtained from actual flatbed tire tests.

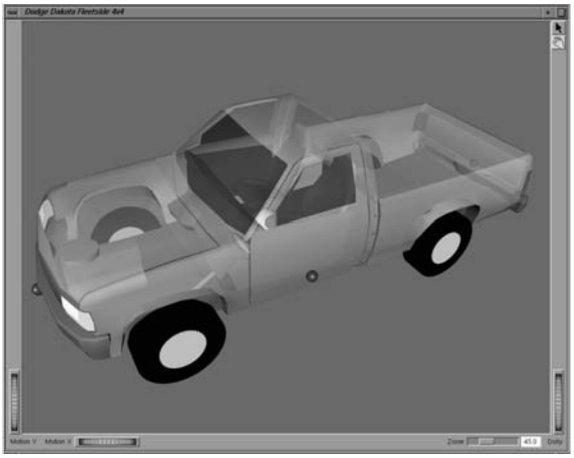
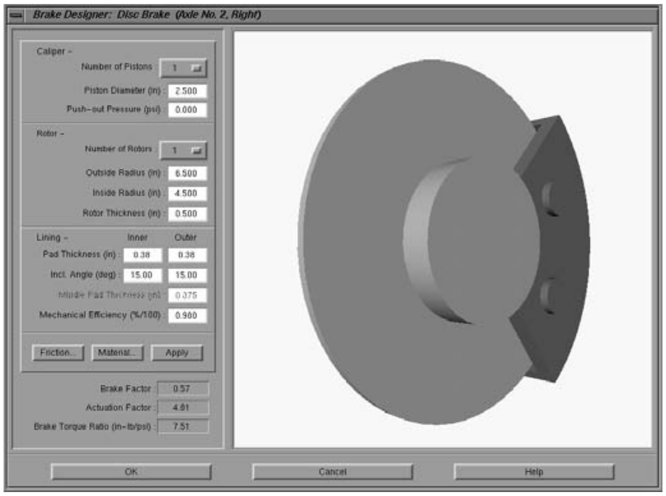


Figure 3. Visual representation of the HVE vehicle model.

INTEGRATED DESIGN CAPABILITIES – An example of a design capability integrated within the DPG is the HVE Brake Designer. The HVE Brake Designer provides an extensive definition of individual components comprising the brake assembly for each wheel of the vehicle. Physical and mechanical properties of the caliper, wheel cylinder, air chamber, rotor/drum and pad/shoe may be specified. Additionally, sliding speed and temperature dependent friction properties of the lining material may be defined.

Integrating a design capability within the DPG allows an engineer to design and analyze an assembly at the same time. The DPG is used to subject the design to a battery of tests, such as the performance of the brake design under in-use conditions of extensive braking on downhill grades. In this manner, the assembly design can be optimized to produce the desired behavior of the vehicle model under the tested conditions. The disc brake design dialog used to define the parameters of the disc brake assembly is shown in Figure 4.



Brake Designer: Disc Brake (Axle No. 2, Right)

Caliper –
Number of Pistons : 1
Piston Diameter (in) : 2.500
Push–out Pressure (psi) : 0.000

Rotor –
Number of Rotors : 1
Outside Radius (in) : 6.500
Inside Radius (in) : 4.500
Rotor Thickness (in) : 0.500

Lining –	Inner	Outer
Pad Thickness (in) :	0.38	0.38
Incl. Angle (deg) :	15.00	15.00

Middle Pad Thickness (in) : 0.375
Mechanical Efficiency (%/100) : 0.900

Brake Factor : 0.57
Actuation Factor : 4.61
Brake Torque Ratio (in–lb/psi) : 7.51

Figure 4. Disc-brake design dialog from HVE Brake Designer.

DEVELOPMENT OF TERRAIN MODELS – The value of the DPG rests in the ability to not only properly model vehicles, but also to model the terrain on which they drive. Testing areas within proving grounds may be used for off-road handling studies, durability testing and other evaluations. The proving ground may even build new test areas for manufacturers based upon their special requirements. The terrain model used in HVE is a mesh of polygons representing the actual proving ground terrain, with each polygon having a surface normal, elevation and surface friction attributes. Terrain models may contain any terrain feature required for studies using the DPG. Inputs to the vehicle model tires caused by a terrain feature are calculated, providing a means to apply a transient input to a vehicle system, such as suspension, without having to generate a complex equation to describe the input firsthand.

The resolution of the terrain model is dependent upon the portion of the proving ground being used for a test. If the test surface is a flat steering pad with a lengthwise gradient of 0°, then the surface may be represented by several large polygons. If the test surface is an off-road circuit containing wheel ruts, steep gradients and other irregular terrain features, the model may need to be constructed of tens of thousands of polygons. An example of a terrain model is shown in Figure 5.

The engineer can develop their own terrain features or may use other resources to build the proving ground terrain model. Standard objects may be used in simulations to provide a reference point for other vehicles subjected to similar studies. These objects may be contained in a library and include ramps, bumps, blocks and cobblestones. Various elements of the proving ground can be modeled in simple or complex detail.

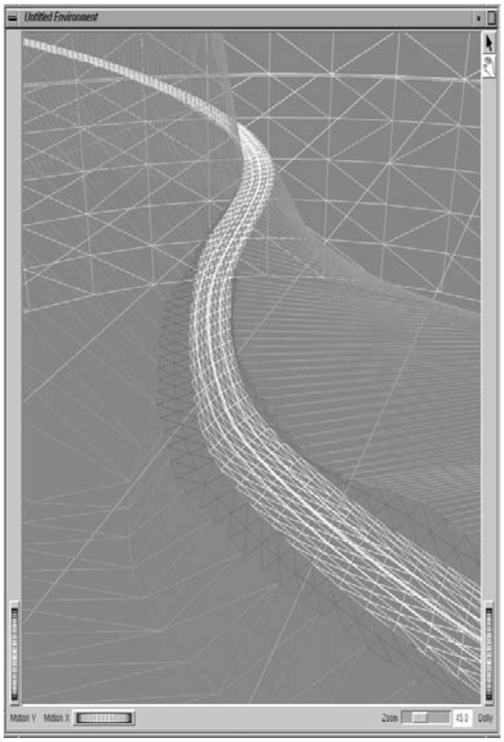


Figure 5. Wireframe of terrain model developed from total station survey data.

Several methods may be employed to develop terrain models. These include CAD models created by civil engineers to build the actual proving ground, airborne LIDAR (Light Detection and Ranging) measurements and Total Station surveys. LIDAR presents a cost-effective solution for developing a high-resolution model of a proving ground. This method uses transmitted laser light and measured reflection to develop a point cloud of data representing the terrain being measured. The LIDAR equipment may be mounted on a helicopter or airplane and flown over the proving ground during data collection. An example of a point cloud is shown in Figure 6. The point cloud is then defined into polygons creating a surface for vehicle models to drive on.

The resolution of the data contained within a LIDAR point cloud may be significantly greater than required for use in some DPG studies. Another method is to use a Total Station to survey the test area required for a study. Data points collected during the survey can be used to develop a terrain model identical to the test area. This type of survey allows the model builder to select the exact reference points they require to build a terrain model of sufficient detail for a DPG study.

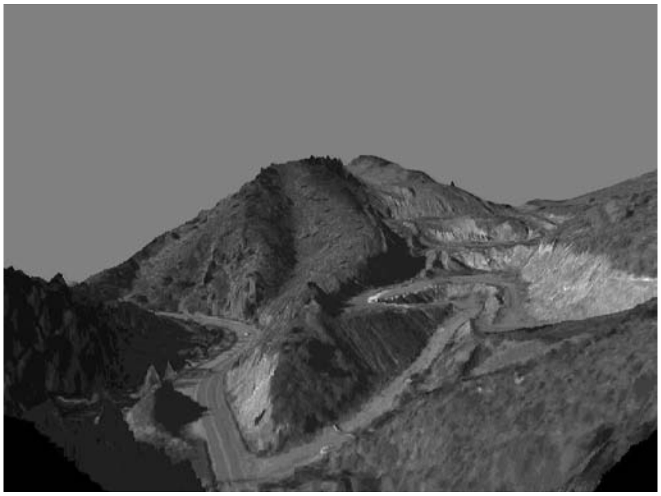


Figure 6. Point cloud model produced from LIDAR data collected by airborne survey.

APPLICATIONS OF THE DPG

Several examples demonstrating the use of the DPG for simulating proving ground tests will be discussed in the following section. The examples are meant to provide an overview of the capabilities of the DPG and not a comprehensive series of tests.

BRAKE SYSTEM COMPLIANCE – DPG studies may be used to predict compliance with government safety standards, such as the evaluation of the hydraulic brake system of a 1996 Ford Explorer conducted according to FMVSS No. 105. [10] Gunney and Bernard have previously discussed similar efforts for this type of simulation study. [11] The test procedures related to determination of the effectiveness of the hydraulic service brake under normal and emergency conditions can be set-up as separate simulation studies. The vehicle and terrain models used in the study can be built to represent the test vehicle and test ground used for the actual evaluation tests. The parameters defining the components of the foundation brakes on the vehicle model can be representative of the ideal conditions of the physical design, or they can be varied to study the effects of changing properties, such as lining friction and heat-transfer properties as may occur during actual physical testing. The simulation of the FMVSS No. 105 testing provides a means to study the issues related to brake temperatures, brake pedal pressure and target deceleration rates required by the dynamic braking tests outlined in the standard.

It should be noted that the DPG can only simulate the dynamic braking test portions of the standards. One of the reasons for the test standards is to subject the vehicle design to a rigorous in-use test scenario to determine if any of the components fail. The DPG can assist in prediction of compliance, but it can not identify if a component of the brake system may fail due to material imperfections or other flaw.

The vehicle model used in this example was built to represent a 1996 Ford Explorer. Several of the parameters used to exactly match the actual test vehicle are outlined in Table 1.

Table 1. Parameters used for test weights and disc brake assemblies of vehicle model.

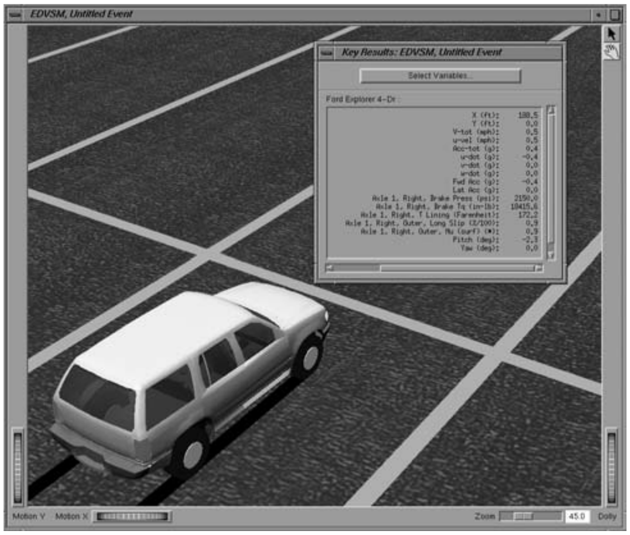
Vehicle Test Weight		
GVWR		4890 lbs
LLVW		4365 lbs
Disc Brake Assemblies		
	Front	*Rear*
Hydraulic Piston Dia.	1.81 in	1.89 in
Rotor Diameter	11.28 in	11.22 in
Rotor Thickness	1.023 in	0.472 in
Pad Width	1.719 in	1.199 in
Pad Length	5.354 in	4.914 in
Pad Thickness	0.390 in	0.374 in
Pad Code	EE	EE

The environment model used in this example was built to provide a road surface and atmospheric conditions to comply with the specifications in FMVSS No. 105. The terrain model is a flat roadway surface with 0% grade in all directions. The road surface has been assigned a peak friction coefficient (PCF) of 0.80 for all tests. The atmospheric parameters figuring in aerodynamic drag calculations were set to ideal conditions of 0.0 mph of wind and 70°F ambient temperature. The visual representation of the terrain model and the vehicle model are shown in Figure 7.

In the normal procedures for FMVSS No. 105, the test vehicle is subjected to several effectiveness braking tests intermixed with burnishing of the brakes, spike stops and tests of the parking brake system. This example will look at three different test scenarios.

SIMULATION # 1 – EFFECTIVENESS – This simulation is set-up by providing the vehicle model with an initial velocity of 5 mph greater than the desired velocity, setting the transmission in neutral without throttle and then allowing the vehicle model to decelerate until the desired test velocity is reached. This set-up allows the simulation model to reach steady conditions and avoid initial transient effects. When the vehicle decelerates to desired test velocity, the average brake pedal force from the actual FMVSS No. 105 test is applied to the braking system of the vehicle model. The deceleration rate and the distance to decelerate to a velocity of 0.5 mph are determined. These results are presented in Table 2 below. The value of 0.5 mph was used as the stopping point for the simulation rather than trying to implement procedures to perform calculations approaching 0.0 mph as discussed by Bernard and Clover [12].

As can be seen from the average test results presented, the DPG overpredicts the effectiveness of the braking system of the vehicle. This may be due to differences in actual test conditions not accounted for in the simulation study. A range of conditions of initial brake temperature and brake pedal force allowable by FMVSS No. 105 could also be performed to determine maximum deceleration rate without wheel lockup and also minimal brake pedal force to achieve target distance.



```
                                     X (ft):    180.5
                                     Y (ft):      0.0
                               V-tot (mph):      0.5
                               u-vel (mph):      0.5
                               Acc-tot (g):      0.4
                                 u-dot (g):     -0.4
                                 v-dot (g):      0.0
                                 w-dot (g):      0.0
                               Fwd Acc (g):     -0.4
                               Lat Acc (g):      0.0
        Axle 1, Right, Brake Press (psi):   2150.0
        Axle 1, Right, Brake Tq (in-lb):  18415.6
     Axle 1, Right, T Lining (Farenheit):    172.2
 Axle 1, Right, Outer, Long Slip (%/100):      0.9
     Axle 1, Right, Outer, Mu (surf) (*):      0.9
                               Pitch (deg):     -2.3
                                 Yaw (deg):      0.0
```

Figure 7. Visualization of the vehicle and terrain model used in the brake effectiveness simulation studies.

Table 2. Results of brake effectiveness testing in accordance with FMVSS No. 105.

Test	Speed	Average Stopping Distance	Avg Pedal Force	Avg Decel
Target	30 mph	58.0 ft	<150 lbs	21 fpsps
Actual	30 mph	56.8 ft	28.0 lbs	24 fpsps
DPG	30 mph	54.7 ft	28.0 lbs	21 fpsps
Target	60 mph	218.0 ft	<150 lbs	20 fpsps
Actual	60 mph	191.8 ft	64.6 lbs	23 fpsps
DPG	60 mph	184.5 ft	65.0 lbs	21 fpsps

SIMULATION # 2 – PARTIAL FAILURE – This simulation is set-up to study the ability of the vehicle to stop within a specified distance with either front or rear braking systems failed. The weight of the vehicle model is changed from the GVWR value used in the effectiveness simulations to the LLVW value. The same initial velocity and braking procedures used in the effectiveness simulations are repeated here. To simulate the failure of either the front braking system or the rear braking system, the calculated brake torque ratio for the failed assembly is set to zero. The results of the tests are shown in Table 3 and Table 4. The results indicate the DPG underpredicts the effective stopping distance of the vehicle under these conditions. This may be due to differences in wheel lock-up conditions during the actual tests or to effects of exact mode of failure simulation.

Table 3. Results of partial failure (rear brake system failed) brake effectiveness testing in accordance with FMVSS No. 105.

Test	Speed	Average Stopping Distance	Avg Pedal Force	Avg Decel
Target	60 mph	465.0 ft	<150 lbs	9 fpsps
Actual	60 mph	300.1 ft	44.4 lbs	15 fpsps
DPG	60 mph	343.6 ft	45.0 lbs	11 fpsps

Table 4. Results of partial failure (front brake system failed) brake effectiveness testing in accordance with FMVSS No. 105.

Test	Speed	Average Stopping Distance	Avg Pedal Force	Avg Decel
Target	60 mph	465.0 ft	<150 lbs	9 fpsps
Actual	60 mph	308.4 ft	124.0 lbs	10 fpsps
DPG	60 mph	426.3 ft	124.0 lbs	9 fpsps

Additional tests identified in FMVSS No. 105 for braking tests with failed power assist systems and failed anti-lock braking systems could have been performed by setting the parameters of the vehicle model to reflect the conditions to be studied. Measured data not contained in the report from the actual tests would be needed to provide an adequate comparison of simulation vs. actual results.

SIMULATION #3 - FITTED BRAKE ASSEMBLY COMPARISONS – DPG studies may be used to predict the behavior of a production vehicle model equipped with a new brake assembly design. The goal of fitting a new system to a vehicle may be to standardize components with other models in production or to improve the effectiveness of the current brake design.

In this example, the difference in braking distance between the 1996 Ford Explorer vehicle model used in the previous compliance simulation examples and the same vehicle fitted with disc brakes on the front axle and under-sized duo-servo drum brakes on the rear axle is studied. This simulation provides an example of how the DPG can be used to identify design specifications required for alternative brake assembly designs on the same vehicle. The results of the initial comparison of the two brake designs are shown in Table 5.

It should be noted that earlier model Ford Explorers did have front disc brakes and rear drum brakes and met the requirements of FMVSS No. 105. This example is provided to demonstrate the ability of simulating different brake assemblies fitted to the same vehicle. The design of the drum brake could be adjusted to determine the suitable design required to meet FMVSS standards, as is shown in the adjusted design results.

Table 5. Results of brake effectiveness simulation of vehicle with 4-wheel disc brakes and front disc/ rear drum brake assemblies.

Test	Speed	Average Stopping Distance	Avg Pedal Force	Avg Decel
Target	30 mph	58.0 ft	<150 lbs	24 fpsps
DPG disc brakes	30 mph	54.7 ft	28.0 lbs	21 fpsps
DPG front disc rear drum brakes	30 mph	75.3 ft	28.0 lbs	18 fpsps
DPG front disc rear drum brakes (adjusted)	30 mph	56.2 ft	28.0 lbs	20 fpsps

Simulation of compliance testing of vehicle models equipped with different braking systems can be performed using terrain models containing high-friction, low-friction and split-friction surfaces to further study vehicle braking effectiveness under normal and emergency conditions. These terrain models may also be used for study of vehicle handling response to steering and braking at different speeds and loading conditions.

HANDLING – Desirable vehicle handling under both moderate and severe cornering and braking conditions is an important consideration of vehicle design. The DPG may be used to study single and double lane change maneuvers, J-turns, or other maneuvers involving simultaneous cornering and braking. The DPG also provides an efficient means to study these maneuvers on both a flat skid pad and inclined surface terrain models.

In this example, a 1994 Ford Taurus performing a sharp cornering maneuvering while braking is simulated. The vehicle was provided with an initial velocity of 90 m/s and allowed to reach steady conditions prior to steering and braking inputs. A steering input of -65° at the steering wheel and a brake pedal force of 65 N were applied simultaneously. The visualization from this simulation is shown in Figure 8. The simulation results for vehicle lateral and longitudinal acceleration, and pitch are presented in Figures 9 – 11. The results from the simulation are compared with experimental test results of a similar maneuver of a 1994 Ford Taurus as presented by Salaani, Heydinger and Guenther.[13]

The differences in the DPG simulation results and the experimental data are due to slight differences in the final simulated trajectory of the vehicle, possibly due to differences in parameters used for modeling the tires of the vehicle. The trends of the data however compare favorably between experiment and simulation.

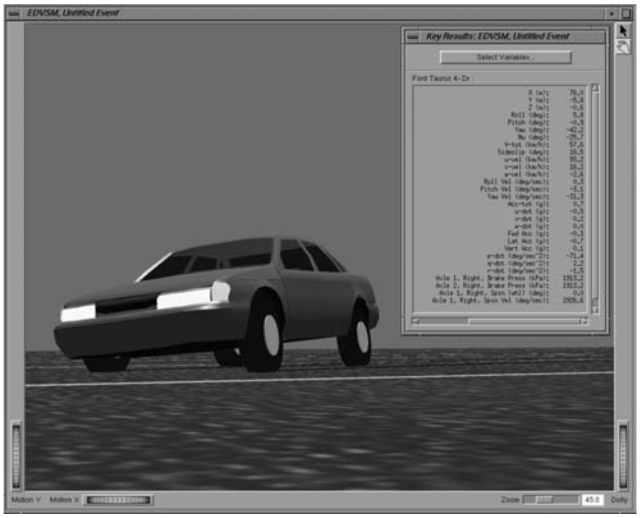


Figure 8. Visualization of the cornering and braking maneuver simulation.

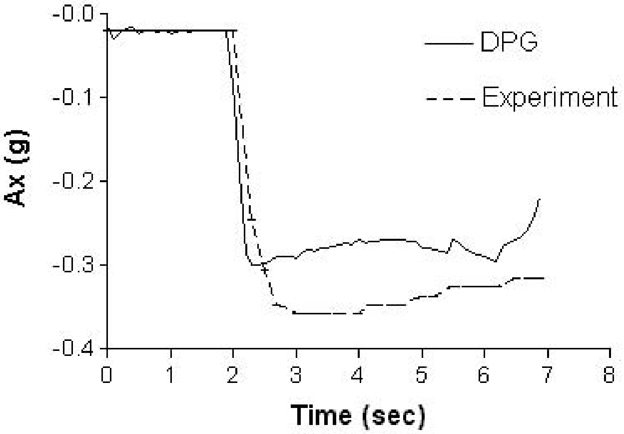


Figure 9. Forward acceleration results of steering and braking simulation example.

The DPG provides an easy means for further studies of vehicle handling under road conditions representative of wet or icy conditions. The terrain model may be modified to provide split-friction surfaces on the inside and outside lane of travel or intermittent patches of road conditions. A terrain model with an initial acceleration lane and a 500-foot radius curve could be created with a completely flat 0° gradient across the entire surface. The visual representation of such a terrain model that could be used for the simulation study is shown in Figure 12. Simulations could be run at the same speeds as the above conditions, but with a split-mu surface defined by the center of the lane of travel of the vehicle. Additionally, the vehicle may be studied over a range of speeds and accelerations, be fitted with different tires or varied suspension parameters. Additionally, the terrain model may have different friction properties defined in areas to account for different weather or terrain conditions.

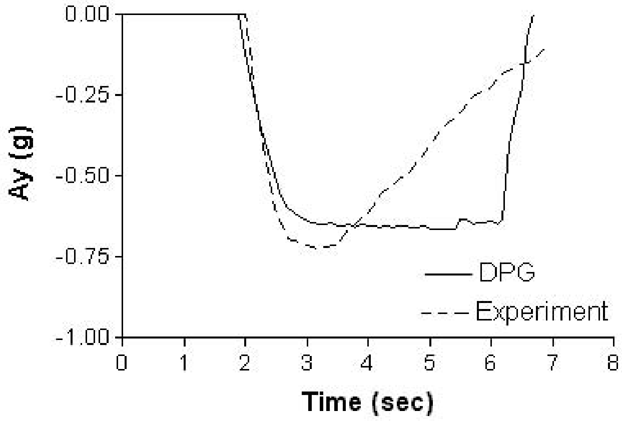


Figure 10. Lateral acceleration results of steering and braking simulation example.

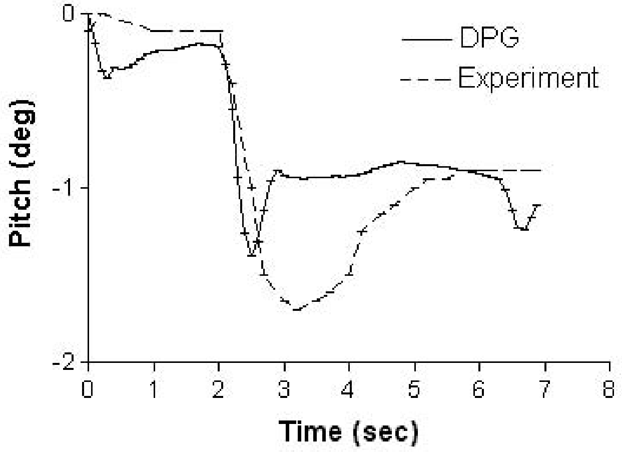


Figure 11. Forward acceleration results of steering and braking simulation example.

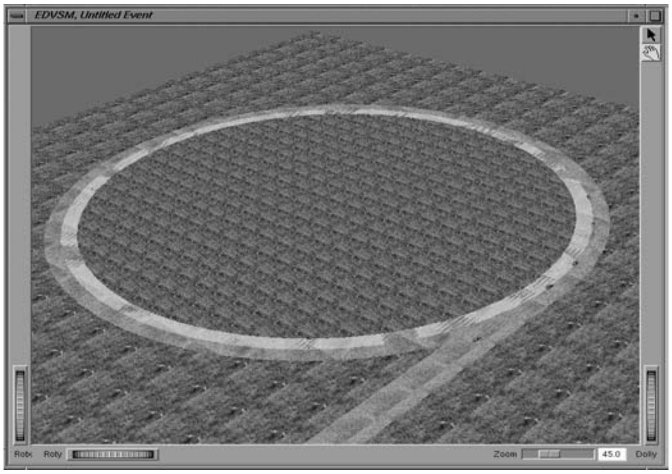


Figure 12. Terrain model of 500-ft radius curve test track with split-friction surface properties.

RIDE ANALYSIS – During the development of a new vehicle design, a prototype may be subjected to several rough road tests to study component durability, ride unpleasantness or discomfort due to suspension vibration characteristics and interior sound levels. The DPG can assist the engineer by providing a method of analyzing the ride response of a vehicle prior to physical testing.

Objectives for ride, roadholding and handling, together with practical requirements, such as physical constraints, influence the type of suspension and components fitted to a particular vehicle. The data obtained from the DPG simulation study of a vehicle traversing a rough road can be used to help develop an optimal suspension design to minimize the acceleration response of the sprung mass of the vehicle and also the change in static wheel load between tire and road. This optimal design provides for passenger comfort while still providing full braking and cornering performance on rough roads and irregular terrain.

For this example, a terrain model of a short section of rough road consisting of randomly placed pavers has been built. A traditional test track surface may be constructed of cobblestones, Belgian blocks or other irregular terrain features designed to generate a desired input acceleration frequency to the vehicle. On the terrain model used in this study, the pavers could easily be adjusted into any random or set pattern depending upon the desired conditions, whereas a proving ground may only have a few set rough road patterns available for testing purposes.

The simulation model used for the vehicle dynamics calculations in this example employs a fully 3-dimensional, 15-degree-of-freedom vehicle model. This allows for accurate simulation of ride as it provides greater than ten-degrees of freedom representative of the sprung and unsprung mass elements of a vehicle model with independent and solid-axle suspension types. [14]

The inputs of the roadway are transmitted to the sprung mass of the vehicle through a suspension modeled by parameters defining the relationship of suspension travel, stiffness of springs, damping of shocks and the load supported by the unsprung mass. The model does not compensate for elastomeric compliance of any connections between suspension components, so it is expected that a ride analysis would tend to overpredict the response of the sprung mass to road inputs.

The square pavers of the terrain model shown in Figure 13, have dimensions of 1.5 feet x 1.5 feet and are positioned to provide a profile height of 1.5 inches. The vertical acceleration, roll and pitch of the sprung mass are calculated as the vehicle travels over the irregular terrain. The results of these tests are shown in Figure 14 and Figure 15.

Study of the changes resulting from tire selection or suspension parameter variations can be performed by editing the vehicle model and repeating the simulation. These tests would normally require extensive time and equipment if performed at the proving ground, but can be performed quickly using the DPG.

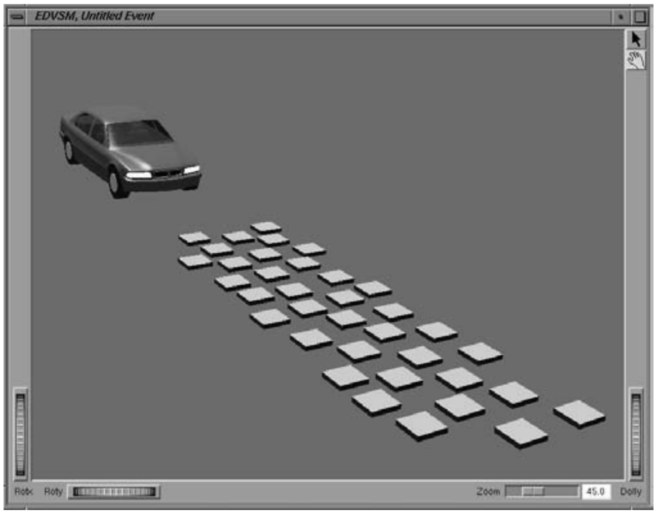


Figure 13. Visualization of the rough road (paver block) simulation example.

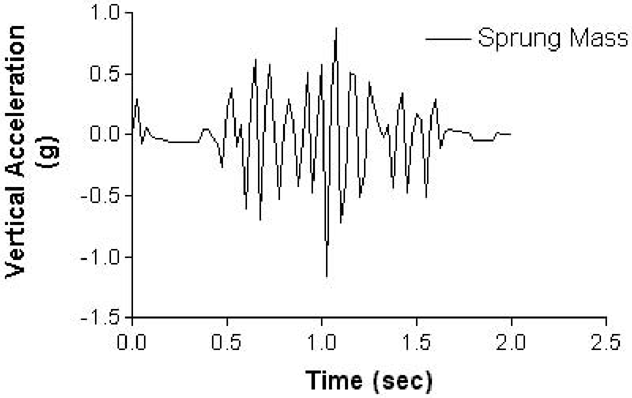


Figure 14. Vertical acceleration of the sprung mass of the vehicle for paver block simulation.

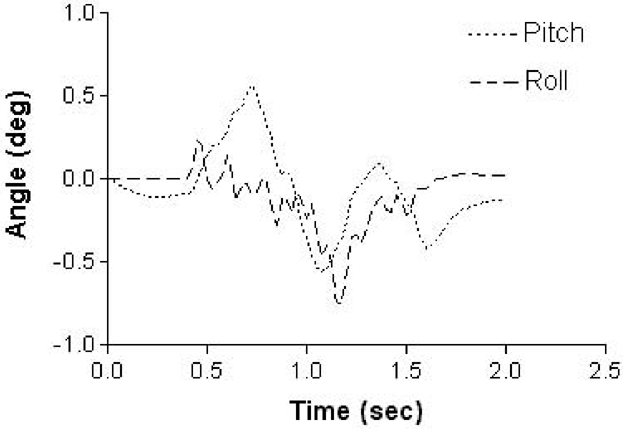


Figure 15. Roll and pitch of the sprung mass of the vehicle for paver block simulation.

Additional studies of different rough road conditions for the optimum vehicle model may be conducted by using different terrain models. Rather than an irregular terrain feature of pavers, alternate ramps and dips may be used to study the behavior with full travel of the suspension. The shape of the ramps and dips are arbitrarily defined by the user allowing any shape to be used, such as sloped surfaces with sharp drop-off or smooth, curved surfaces.

PRODUCTION MODEL EVALUATIONS – Passenger vehicle manufacturers typically produce large volumes of a specific model with limited customer options for tires, wheels, engine and transmission configurations. For instance, the Ford Focus sold in the United Kingdom is available in 25 different configurations. Extensive DPG testing of the available configurations can be completed prior to production to ensure compliance with standards, thereby optimizing test and certification expenses. Additionally, if a warranty issue related to vehicle dynamics arises with the vehicle, the DPG can be used to assist in identifying and developing a solution to correct the problem. The DPG provides a means to establish a simulation history of the vehicle model prior to production. An engineer can recall the simulation runs conducted during the design phase and then study the effects of the corresponding design modifications or driving under different conditions. The availability of the same DPG studies to several engineering disciplines within the same organization enhances the communication between the design and product analysis groups.

Commercial vehicle manufacturers often assemble vehicles according to exact customer specifications. While a general understanding of the overall vehicle dynamic behavior based on a limited number of combinations of options may be understood, the behavior of a specific combination of options subjected to actual customer use conditions and duty cycles may not be easily extrapolated. The DPG can be used to study the behavior of customer-selected combinations of options under real-world conditions in the same way the basic vehicle model had been analyzed with the DPG during development. If the additional DPG studies identify areas of potential in-use problems for the customer specified configuration, then further design and testing evaluations specific to resolving the problems can be performed.

CONCLUSIONS

The DPG offers analysis capabilities to several phases of the vehicle development cycle, including design and product analysis of real-world situations. Increased communication between design and analysis efforts by using the DPG for both purposes can assist with design optimization and reduce time and costs. Additionally, the DPG can provide benefits in the following ways:

1. The DPG provides a means to predict compliance or desired vehicle handling of a complete vehicle design prior to the actual physical testing of the prototype.
2. The DPG can be used to determine if an individual system component, such as a foundation brake, provides the desired functionality when fitted to a vehicle and subjected to a range of in-use conditions.

3. Vehicle dynamics engineers can use the DPG to study how design modifications and component changes affect the overall dynamic behavior of the vehicle.
4. A greater understanding of the performance of the production vehicle when under the control of the final owner may be obtained by simulating a wide range of potential real-world scenarios.
5. Delays in the development process caused by redesign and testing can be reduced and potentially avoided completely.
6. With the ability to model any road or terrain in the world, the DPG provides an easy means to integrate real-world analysis into the design and testing process, previously prohibited by distance, accessibility, cost, or other restrictions.

ACKNOWLEDGMENTS

The author would like to acknowledge EagleScan for providing the LIDAR image used in this paper.

REFERENCES

1. Fischer, R., Haertle, J., “Computer Modeling in New Vehicle Design”, SAE Paper No. 840863
2. Langer, W. "Validation of Flat Surface Roadway Technology", SAE Paper No. 950310
3. Day, T.D., “A Computer Graphics Interface Specification for Studying Humans, Vehicles and Their Environment,” SAE Paper No. 930903
4. Day, T.D.,”Validation of the EDVSM 3-Dimensional Vehicle Simulator,” SAE Paper No. 970958
5. Day, T.D., “Differences Between EDVDS and Phase 4,” SAE Paper No. 1999-01-0103
6. Allen, R.W. et al, "Tire Modeling Requirements for Vehicle Dynamics Simulation", SAE Paper No. 950312
7. Day, T.D., “An Overview of the HVE Human Model,” SAE Paper No.950659
8. Day, T.D., “An Overview of the HVE Vehicle Model,” SAE Paper No. 950308
9. York, A.R., Day, T.D., “The DyMesh Method for Three-Dimensional Multi-Vehicle Collision Simulation,” SAE Paper 1999-01-0104
10. Gurney, J.W., Bernard, J.E., “The Utilization of a Computer Simulation as an Aid to Predict Compliance with MVSS 121,” SAE Paper 740137
11. Bernard, J., Clover, C., "Tire Modeling for Low-Speed and High-Speed Calculations", SAE Paper No. 950311
12. Salaani, Heydinger, Guenther, “Validation Results from Using NADSdyna Vehicle Dynamics Simulation”, SAE Paper No. 970565
13. Chondros, T.G., et al, “Vehicle Dynamics Simulation and Suspension System Design”, SAE Paper No. 970105
14. Final Report - 1996 Ford Explorer, Ford Motor Company, "Safety Compliance Testing for FMVSS No. 105 Hydraulic Brake Systems", NHTSA No. CT0201, July 1, 1996

CONTACT

The author may be contacted by email at: canova@edccorp.com.