VEHICLE DYNAMICS VALIDATION FOR REAL-TIME SIMULATION

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ABSTRACT

Vehicle dynamics models are critical to driving simulation sensory cueing. If the model is not appropriate, or inaccurate in various ways, then the resultant sensory cues that are fed back to the driver will be inappropriate. These issues apply to both the low to moderate g (lateral acceleration) maneuvering regime, which is relatively linear, and the high g regime that can be quite nonlinear. This paper discusses the development and validation of a ground vehicle dynamics computer simulation that includes complete models for sprung and unsprung masses, tires, suspension, steering and brake systems, and power train including engine, transmission and differentials. The models have been developed over the last decade, and have been applied to single unit passenger cars, trucks and buses, and articulated tractor/trailer vehicles up to limit performance operating conditions. The tire and vehicle models use composite parameters that are relatively easy to measure. However, the measurements must cover the key operating regime where the simulation is expected to be applied. For example, limit performance maneuvering conditions require tire data over large slip conditions and high normal load (beyond the design load) to cover the full range of dynamic operating conditions. Spring and damper response should also take into account large deflections and high velocities, respectively, to cover relevant nonlinearities. This paper will discuss validation issues and procedures, and will present validation data obtained for a range of vehicles.

INTRODUCTION

In man-in-the-loop simulation the vehicle dynamics model (VDM) provides the connection between control inputs (i.e. steering, throttle, brake) and sensory output (i.e. visual, proprioceptive and auditory). The VDM generates the vehicle body axis motions and final state (perceptual) variables perceived by the driver. The VDM must be properly formulated and the parameter set must be appropriate for a given vehicle. Simulation can also add artifacts such as transport delays that can distort the stimulus-response behavior of the VDM as perceived by the driver. The simulation must be implemented and compensated to minimize these artifacts. VDM validation is important in order to ensure the basic stimulus response properties of the simulation, and to verify unique stability and control properties of specific vehicles.

Vehicle dynamics modeling has been used extensively over the years to develop and extend our understanding of ground vehicle handling and stability, and this modeling background is appropriate for human-in-the-loop simulation. One of the first comprehensive models was developed by Segel (1) at Calspan. Subsequent modeling was carried forward by Weir (2) and Ellis (3). A significant amount of analysis of early linear models was carried out in the frequency domain (i.e. Laplace and Fourier transforms), which is particularly insightful for understanding dynamic modes and stability properties, e.g. (4). The understanding of limit performance handling and stability in particular requires a nonlinear tire model that in general must be analyzed in the time domain. This analysis requires nonlinear computer simulation modeling, e.g. (5). More recently, computer simulation has been advanced significantly by the multibody modeling approach, e.g. (6, 7). Multibody modeling tends to require a significant number of parameters to define a vehicle, however, and solution procedures may require substantial computing resources and lengthy, iterative computation times. The iterative procedures can cause problems in real-time simulation when convergence problems are encountered that may result in increased transport delay and even pauses in the solution update.

This paper includes consideration of a vehicle dynamics model (VDM) that was designed for computer simulation analysis and also more recently, with the advent of ever faster PC's, to run in real time. The model, referred to as VDANL (Vehicle Dynamics Analysis, NonLinear), is based on a computer simulation developed for the National Highway Traffic Safety Administration (8) and extended to handle limit performance stability through rollover (9). The tire model covers the complete maneuvering range of loading, slip and camber (10). The complete VDANL model has been validated quite extensively (11, 13) up through 0.6 g maneuvering. A recent paper has extended the maneuvering range to the region of 0.85 g (14). Communications services have also been added to VDANL so that it can provide vehicle dynamic states for display image generators (IGs), feel and motion systems, sound cueing, and miscellaneous controls and displays, e.g. (14). Both the real time and computer analysis versions of VDANL run a DLL (Dynamic Link Library) under all Microsoft Windows operating systems.

VDANL is based on requirements established for vehicle dynamics models (e.g.,15, 17). For interactive simulator applications on fast PC's (i.e. Pentium) VDANL is capable of real-time execution at high update rates (200 Hz or

greater) that provide for numerical stability under extreme maneuvering and road surface input conditions and also provide sufficient bandwidth for realistic steering torque feel. In general, VDANL emphasizes providing realistic commands for interactive driving simulation sensory cueing including driving scene graphics, motion, steering feel and sound. The analysis version of VDANL contains a variety of analysis options that provide convenient procedures for the assessment of handling and stability and the prediction of vehicle motions and trajectories given control and roadway inputs.

BACKGROUND

A VDM basically provides the vehicle body axis response to control inputs. The body axis response includes vehicle translational velocities and angular rates. The body axis motions are in response to tire and aerodynamic forces. In human-in-the-loop simulation the tire lateral and longitudinal forces result from driver control inputs. Vertical tire forces derive from terrain profile and vehicle maneuvering. Given body axis motions, kinematic transformations and integrations then are used to compute the final vehicle state in terms of translation (position) and orientation. Vehicle dynamics have traditionally been subdivided into lateral/directional and longitudinal components. The lateral/directional dynamics account for the yawing, rolling and lateral translation, and longitudinal dynamics account for pitching and longitudinal and vertical translation. Lateral/directional dynamics account for handling due to steering while longitudinal dynamics account for vehicle ride and drivability.

In a complete VDM there is some coupling between the lateral/directional and longitudinal dynamics, particularly due to load transfer and tire force interaction. However, for low to moderate maneuvering the lateral/directional and longitudinal dynamics are relatively uncoupled and this circumstance has traditionally been exploited for developing simplified VDMs and for checkout and validation of vehicle equations of motion. In fact, a great deal of insight can be gained by considering simplified vehicle response characteristics that suggest useful check case maneuvers. These maneuvers are convenient to conduct with instrumented test vehicles and can be easily applied to VDM simulations. These maneuvers and associated responses can be subdivided into: 1) steady state cases which are not influenced by transient response dynamics; 2) low g transient responses up to the region of 0.5 g (16 ft/sec^2) which are not influenced by vehicle nonlinearities; and 3) limit performance transient maneuvering which takes tire and suspension behavior to their limit performance.

Often times good linear VDMs can be used in real time simulation to capture the essence of vehicle response from the driver's point of view (e.g. Ref. 8). Simple nonlinearities can also be added to approximate the limitations imposed by the tires (e.g. Ref. 18). The significant VDM nonlinearties include tire saturation characteristics and suspension bumpstops and damper (shock absorber) force/velocity characteristics. Tire saturation becomes important beyond 0.5 g where the ratio of horizontal tire force to vertical load reaches a limit referred to as the peak coefficient of friction which varies as a function of vertical load (e.g. Refs. 10, 19). During limit performance maneuvering (steering and/or braking), tire saturation at the front and rear axles is important to properly represent directional stability (Ref. 14). For significant roll angles the suspension can contact bump stops where the stiffness is 3-4 times higher than the basic spring suspension gradient (e.g. Ref. 14).

Given a simulation VDM there are several approaches to validation (e.g. Refs. 15, 16). Verification of simulation code and checks of basic vehicle response characteristics (steady state and transient responses) should be done at a minimum. Instrumented vehicle response data for standardized maneuvers can also be employed, and this approach is particularly important for the simulation of specific vehicles with available VDM parameter sets. Instrumented vehicle data for standardized maneuvers can be used to compare with VDM responses under steady state and transient response conditions. Spectral analysis (FFT transfer functions) can also be used identify dynamic details (amplitude and phase lag response) that might indicate the nature of shortcomings in the VDM. A note of caution is indicated here as the VDM response depends on the parameter set which is typically determined through independent static test procedures (e.g. Ref. 9, appendix C). The VDM parameter set and simulation response should be checked for consistency with known vehicle characteristics as a cross check. Also, test procedures for characteristics such as roll damping due to suspension bushings, and high frequency lags due to steering system response are typically not measured. Finally, there is the possibility of instrumented vehicle sensor inaccuracies and scaling problems that could significantly influence the accuracy of field test data.

VALIDATION EXAMPLES

The simulation validation examples discussed below are all based on the VDANL VDM (Ref. 9, appendices A and B). Parameter sets for each vehicle were obtained using the procedures in Ref. 9, appendices B and C. Tire models for each vehicle are based on fitting the STIMOD tire model (Ref. 10) to tire machine data.

Tire Response

Tire behavior is probably the most complicated nonlinear effect in vehicle dynamics. Tire response has four independent input variables: 1) vertical load 2) lateral slip angle; 3) longitudinal slip ratio; and 4) camber angle. Speed can also be considered an input variable for the tire's relaxation length time delay in force development. Vertical load basically sets the value of several tire model parameters (e.g. Ref. 10). Figure 1 shows tire model fits to tire machine data carried out with Matlab[©] nonlinear regression routines. The tire model used for the representation is relatively complete and the close comparison over several normal loads illustrates the range of the model capability. A complete nonlinear tire model is complex enough and it is important to be able to verify response behavior for simulation VDMs over the full range of operating conditions.
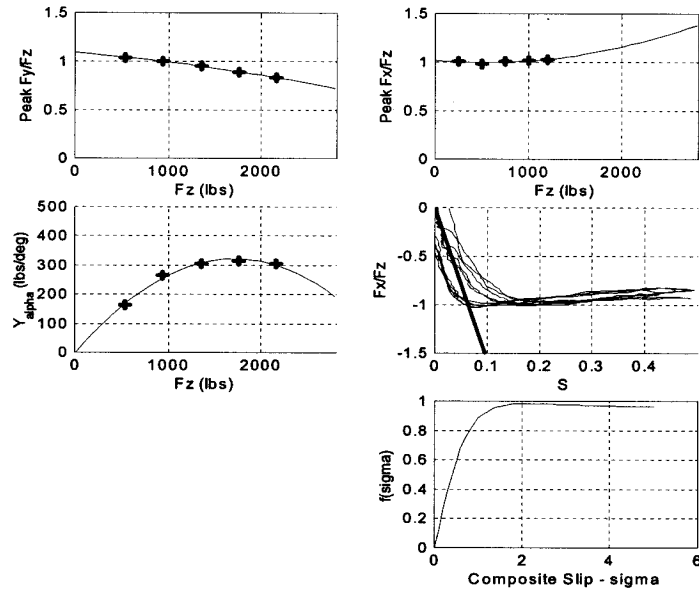
Steady State Response

The field test data for steady validation was obtained from a mid sized SUV (Ref. 20). The maneuver used for this test consists of an increasing ramp steer input applied slowly under a constant speed condition. The rate of speed increase is such as to minimize the influence of any transient dynamics effects. This maneuver takes the vehicle to increasingly higher lateral accelerations through tire saturation and plow out. Simulation model and instrumented vehicle responses are compared in Figure 2 for left and right steer inputs. Here we see that the vehicle reaches plowout (front axle tire saturation) with lateral acceleration reaching 0.75 g. Lateral acceleration and yaw rate matches are comparable between the model and experimental data, although the test data reaches saturation a little more abruptly than the VDANL simulation model. There is a clear disparity in roll angle between the test data and simulation response. There may be some problem with the roll angle instrumentation (acoustic ride height sensors) for the test data.

Roll angle should be driven by lateral acceleration. The test data lateral acceleration follows a smoothly saturating function consistent with tire response characteristics, while the measured roll angle increases linearly with time then abruptly saturates. The lateral acceleration test data and simulation response are consistent in their smooth saturation, and the simulation roll angle response also is consistent with this behavior. The test roll angle seems to be the only variable at variance with this expected behavior. In the right turn test there is also significant noise (dropouts?) in the roll angle test data. The test vehicle appears to roll more than the simulation response, and there could be some issue with the simulation tire compliance and suspension modeling that does not give sufficient roll response. These results may be due to sensor calibration issues either with the test data or the parameter measurements related to the roll plane dynamics (spring stiffness, auxiliary roll stiffness, etc.) or actual vehicle effects that may not be properly modeled such as the compliance between the body and frame.

Given the data in Figure 2 other plotting formats can be employed to gain additional insight into the behavior of the VDM. Steering angle can be plotted as a function of lateral acceleration to reveal the understeer characteristic of the vehicle. Roll angle can also be plotted as a function of lateral acceleration to portray the VDM roll gradient.

Low g Transient Response

Field test data was obtained from the same mid sized SUV as for the steady state response above (Ref. 21). A pulse steer input was employed to stimulate the vehicle's lateral directional modes as illustrated in Figure 3 time responses. The lateral acceleration, roll angle and yaw rate responses are comparable in terms of the dominant mode, but the lateral acceleration test data also shows a higher frequency mode on the order of 10 Hz that is not represented in the simulation model output. This could be a structural mode that is not modeled in the VDANL computer simulation. The transfer functions between steering input and lateral acceleration, roll angle and yaw rate were also computed with FFT techniques applied to the pulse data above. The results are illustrated in the Figure 4 transfer functions. The phasing of the lateral acceleration transfer function looks quite good. The VDANL

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a) **Normal Load** Functions
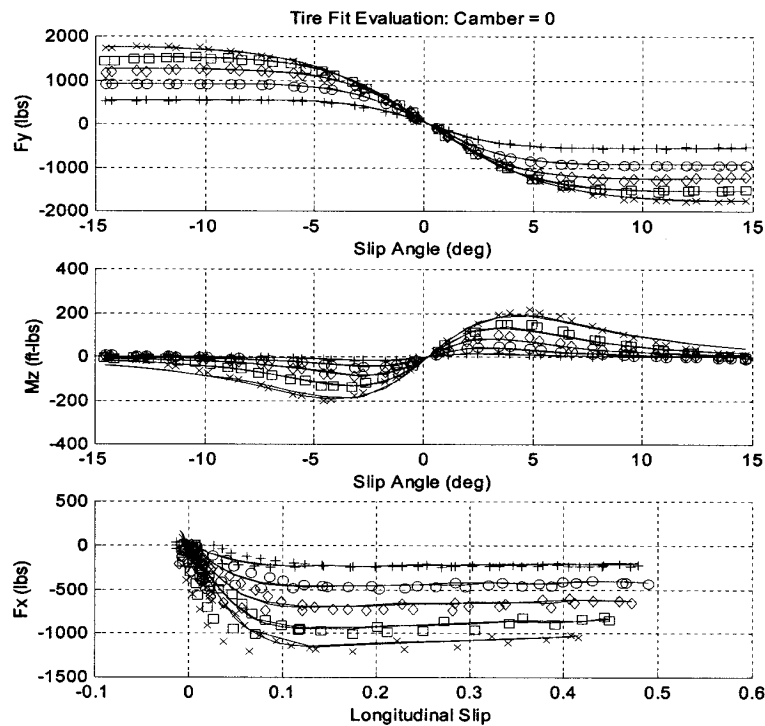
b) **Force and Moment Response**

Figure 1. Tire Machine Data and Tire Model Fit

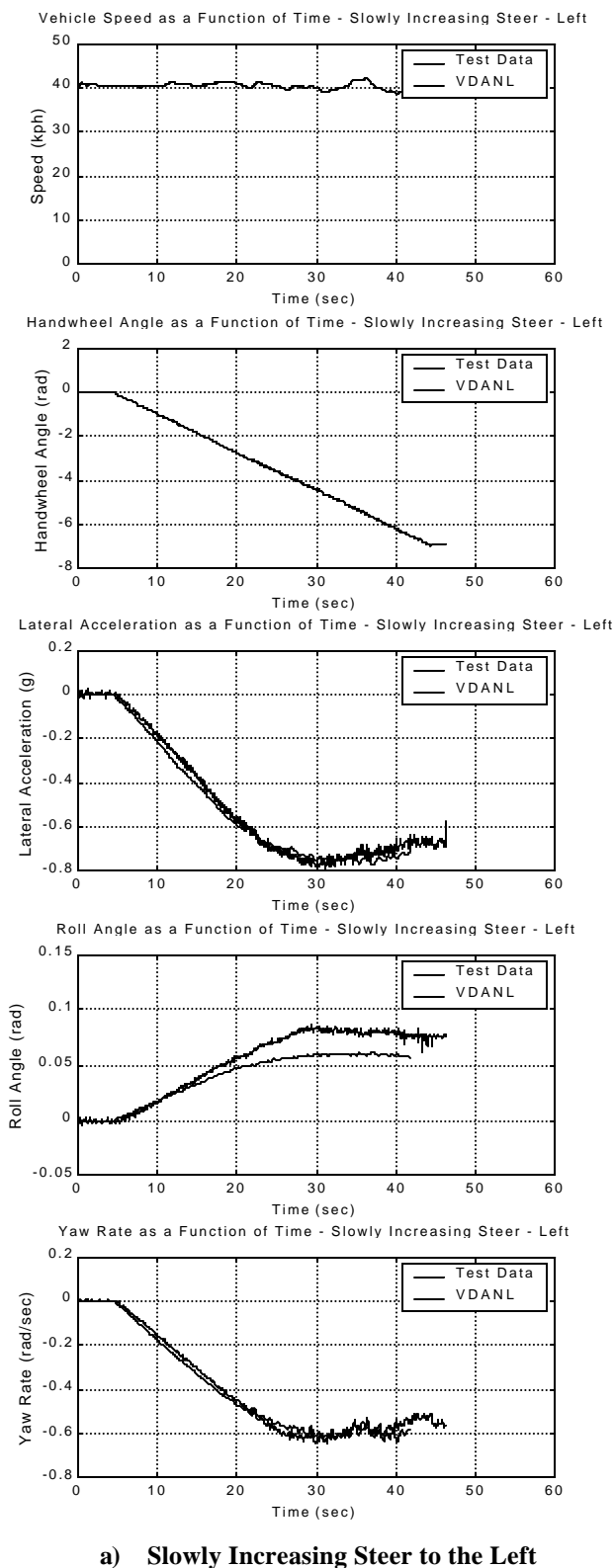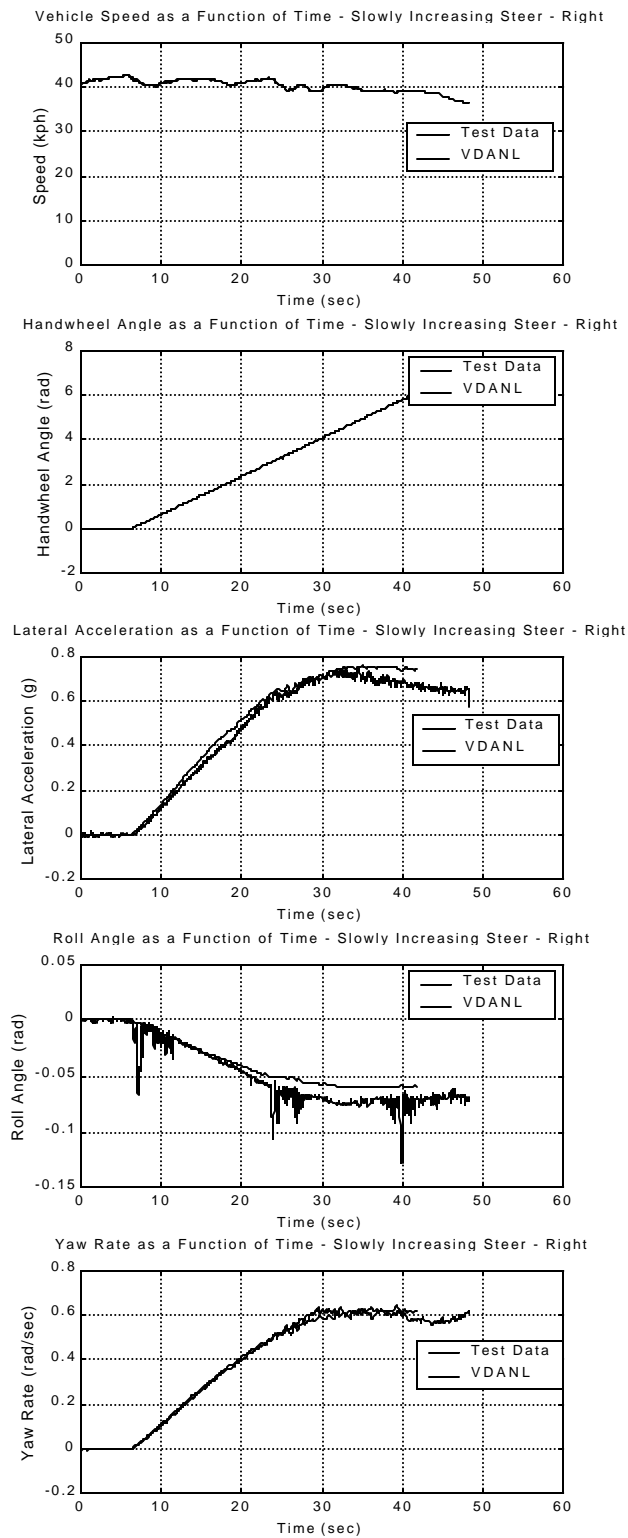a) **Slowly Increasing Steer to the Left**

Figure 2. Steady State VDM Responses Due to a Ramp Steer Input

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b) Slowly Increasing Steer to the Right

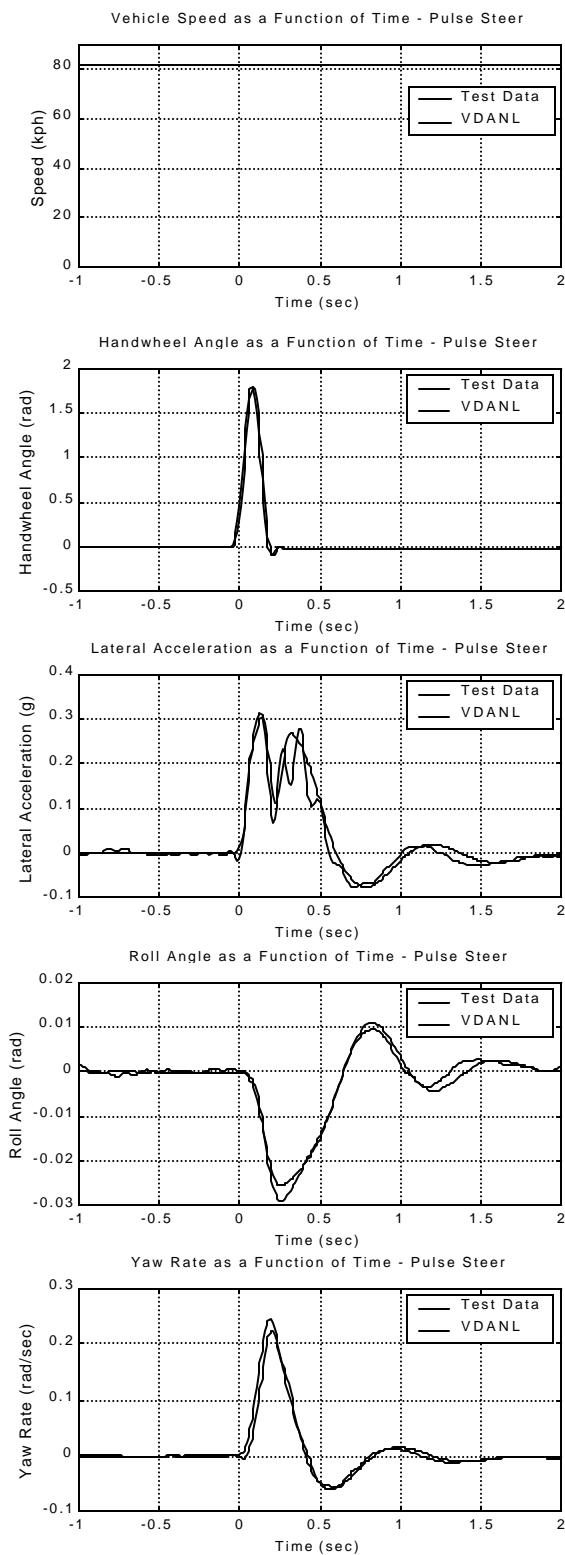Figure 2. Steady State VDM Responses Due to a Ramp Steer Input (Concluded)

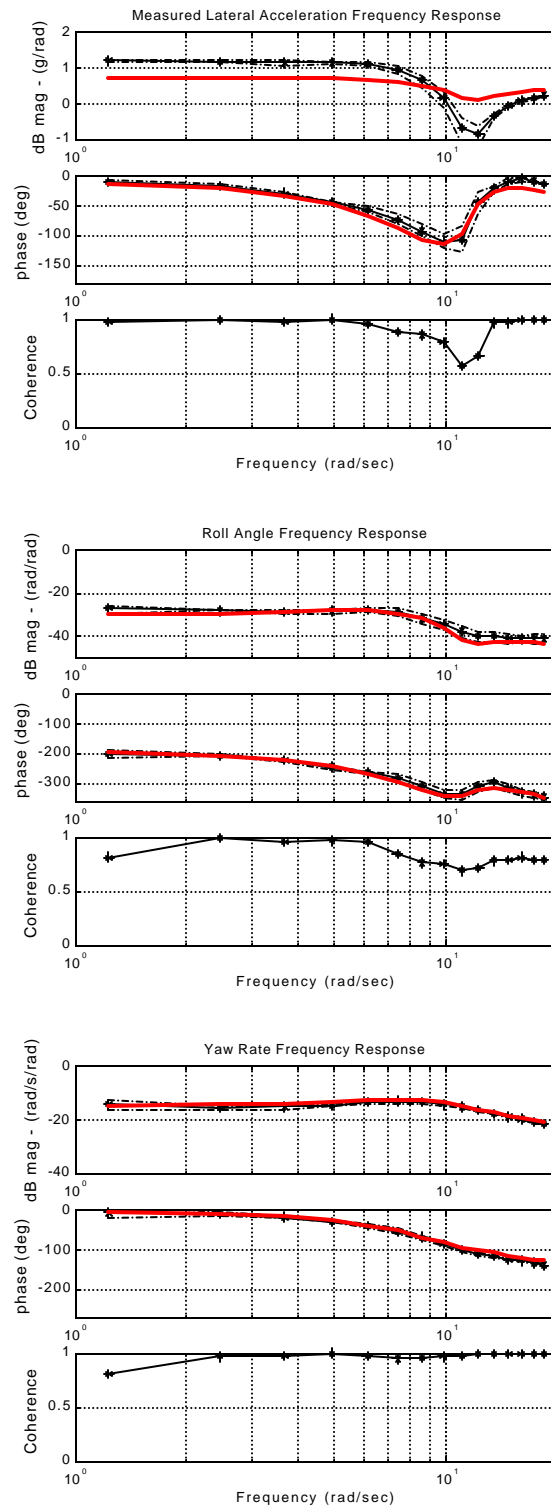Figure 3. Transient Response Due to a Low g Pulse Steer Input

Figure 4. Transfer Functions for a Low g Pulse Steer Input

amplitude is a little low by about 0.4 dB (about 10% low), and the amplitude zero at about 12-13 Hz is not as sharp as the experimental data (note, however, that the dB scale is quite expanded). The roll rate transfer functions look quite good, with the experimental data exhibiting some additional high frequency phase lag over the VDANL response. This is thought to be a matter of the steering system lag that was not measured. It appears that the VDANL steering model should be given slightly more lag. The roll angle transfer function also shows good match in amplitude and phase lag between the experimental data and VDANL response. Roll angle is essentially driven by lateral acceleration, so the matches in both variables are consistent.

High g Transient Response

Time response data for an SUV performing an obstacle avoidance maneuver (Ref. 21) are illustrated in Figure 5. This maneuver amounts to steering hard right to avoid the obstacle, then steering hard left to return back to the original lane of travel, then finally steer left to stabilize in the lane. The field test steering profiles were input to the computer simulation to produce the VDANL responses. The tire pressure had not been identified for this test, so simulation runs were performed at two tire vertical spring rates. The lateral acceleration, roll rate and yaw rate traces are quite comparable between the field test and simulation data. The lateral acceleration traces show similar saturation levels for both field test data and simulation responses. Note that an oscillatory mode of about 1.5 Hz for roll rate in the region of 6-8 seconds fits much better for the low tire pressure (i.e.. low vertical spring rate) condition. Note also that the computer simulation leads the field test data to a slight degree indicating slightly less response lag in the simulation data.

FFT transfer functions for roll rate response to steering input are shown in Figure 6. The amplitude and phase shift functions are quite consistent between the field test data and simulation response. Note that the simulation fit is improved in the region of 10 rad/sec (about 1.5 Hz) for the low tire pressure response. The transfer function peaks up in this region which is indicative of a resonant mode that is fit better with the low tire pressure VDM. The computer simulation generally shows less high frequency phase lag than the field test data, which is consistent with the slight leading shift in the Figure 5 time response data. The steering system gives phase lag at high frequencies, and the VDM response could probably be improved with additional steering lag. Independent steering system response tests are not typically performed aside from compliance, and FFT analysis of field test data is one way of identifying steering system response properties.

A second set of high g validation data is illustrated in Figure 7. This data was obtained from a NHTSA study to develop dynamic test procedures for identifying vehicles with high, on-road untripped rollover propensity (Ref. 22). The data represents the light, two door, four wheel drive SUV. To match the test data, the measured field test steering and braking profiles were put into the computer simulation. We also assumed a dropped throttle as indicated per the procedures discussed in Ref. 22. The speed profile is quite comparable between the field test data and VDM response. This requires that the engine drag, tire rolling resistance and cornering drag give appropriate deceleration during the maneuver. The major features of lateral acceleration, yaw rate and roll rate response, including peak values, are consistent between the field test data and VDM response. There is a high frequency mode in the field test data roll rate response (i.e. an 8-10 Hz oscillation occurring in the region of 4 seconds) not present in the VDM response. There is also a 2-3 Hz mode in the region of 5 to 8 seconds that is more damped and slightly faster frequency in the VDM. Inspection of the VDM tire normal loads (not available in the field test data) shows that the oscillations are associated with tires coming off the ground (Ref. 22 mentions observed tire lift). There could be some details associated with tire spring rate, damper characteristics and additional roll damping due to bushings that are influencing this behavior.

CONCLUDING REMARKS

Data from several instrumented field test studies have been shown to compare well with a VDM simulation with parameter sets determined using standard identification procedures. The comparisons are made for several test maneuvers that illustrate the steady state and transient dynamic behavior of the VDM. These procedures are relevant to the checkout of VDMs in real-time simulation in order to verify steady state and dynamic response properties under low g and high g maneuvering conditions. These validation procedures should be used to ensure that the VDM will provide the driver with a realistic stimulus/response experience, and that its high g stability properties are relevant. The detailed VDM response may not always match field test data obtained from

a) Normal Tire Pressure VDM

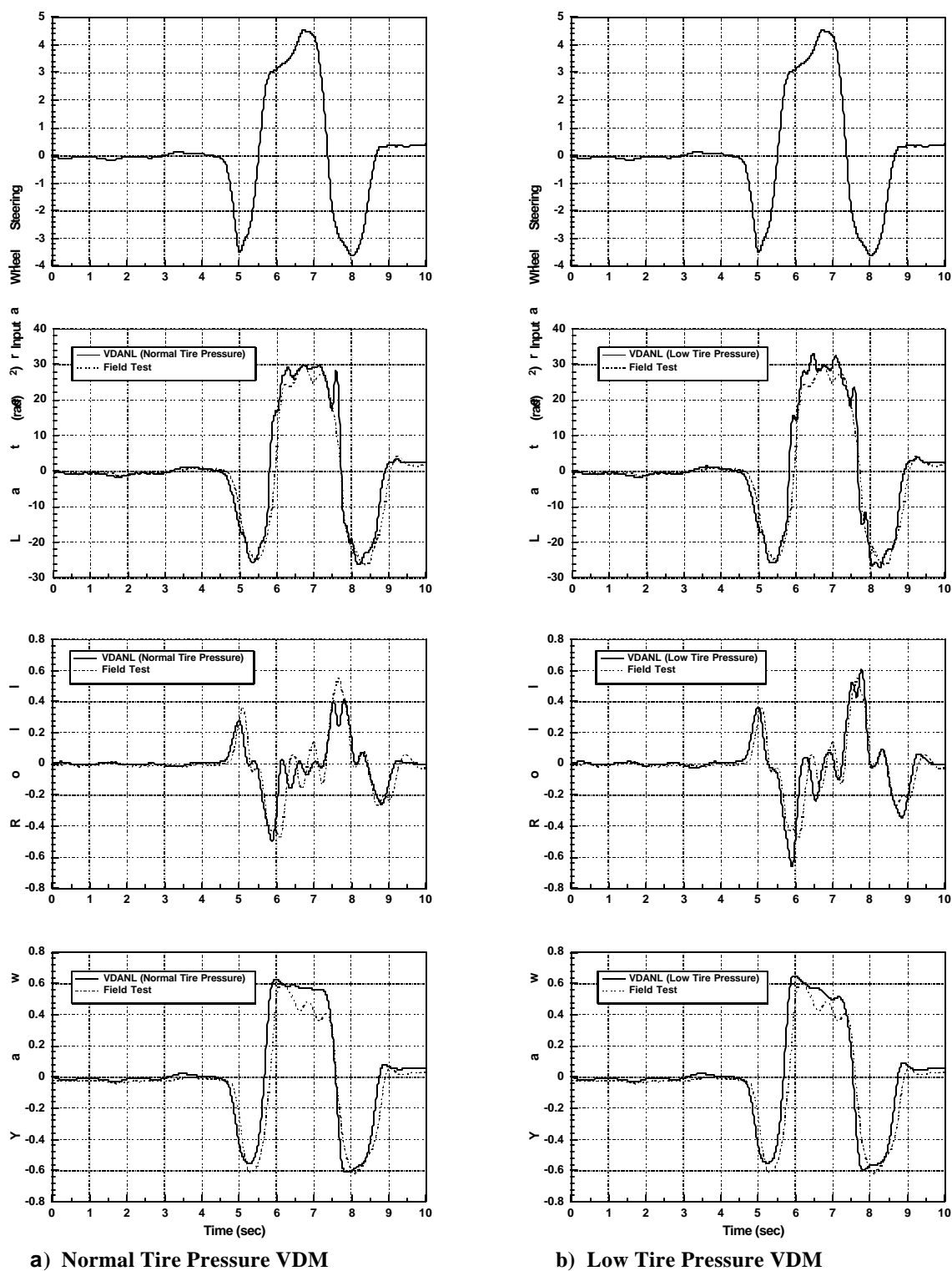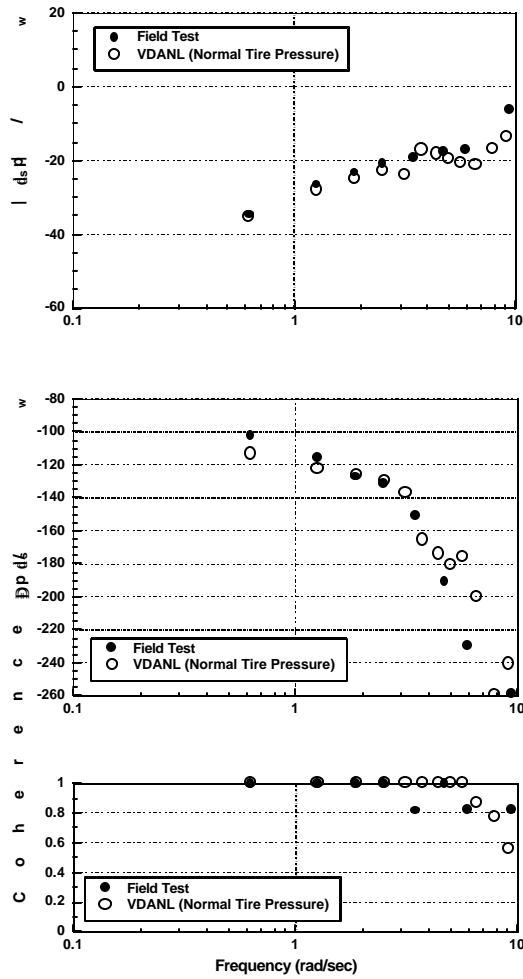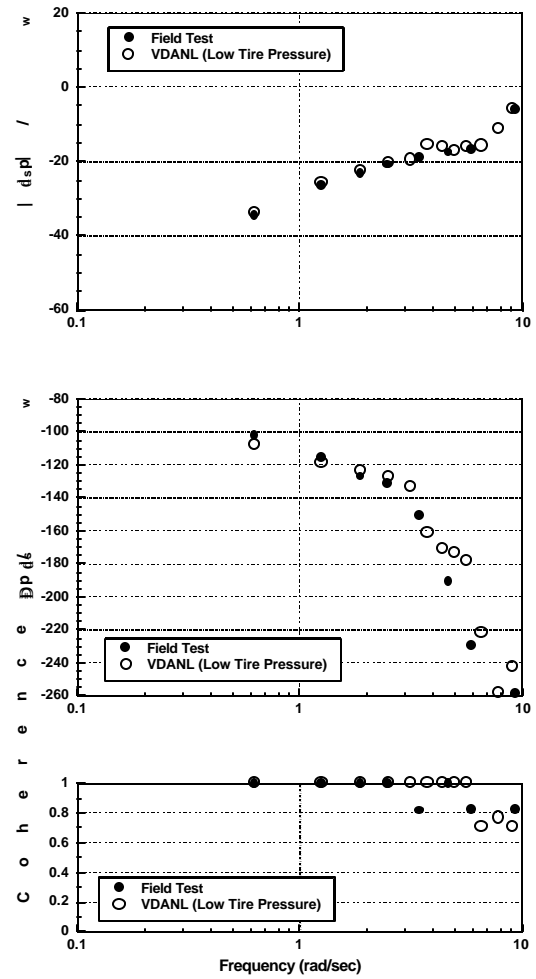**b) Low Tire Pressure VDM**

Figure 5. High g Transient Response Due to an Obstacle Avoidance Steering Input

a) Normal Tire Pressure VDM   b) Low Tire Pressure VDM

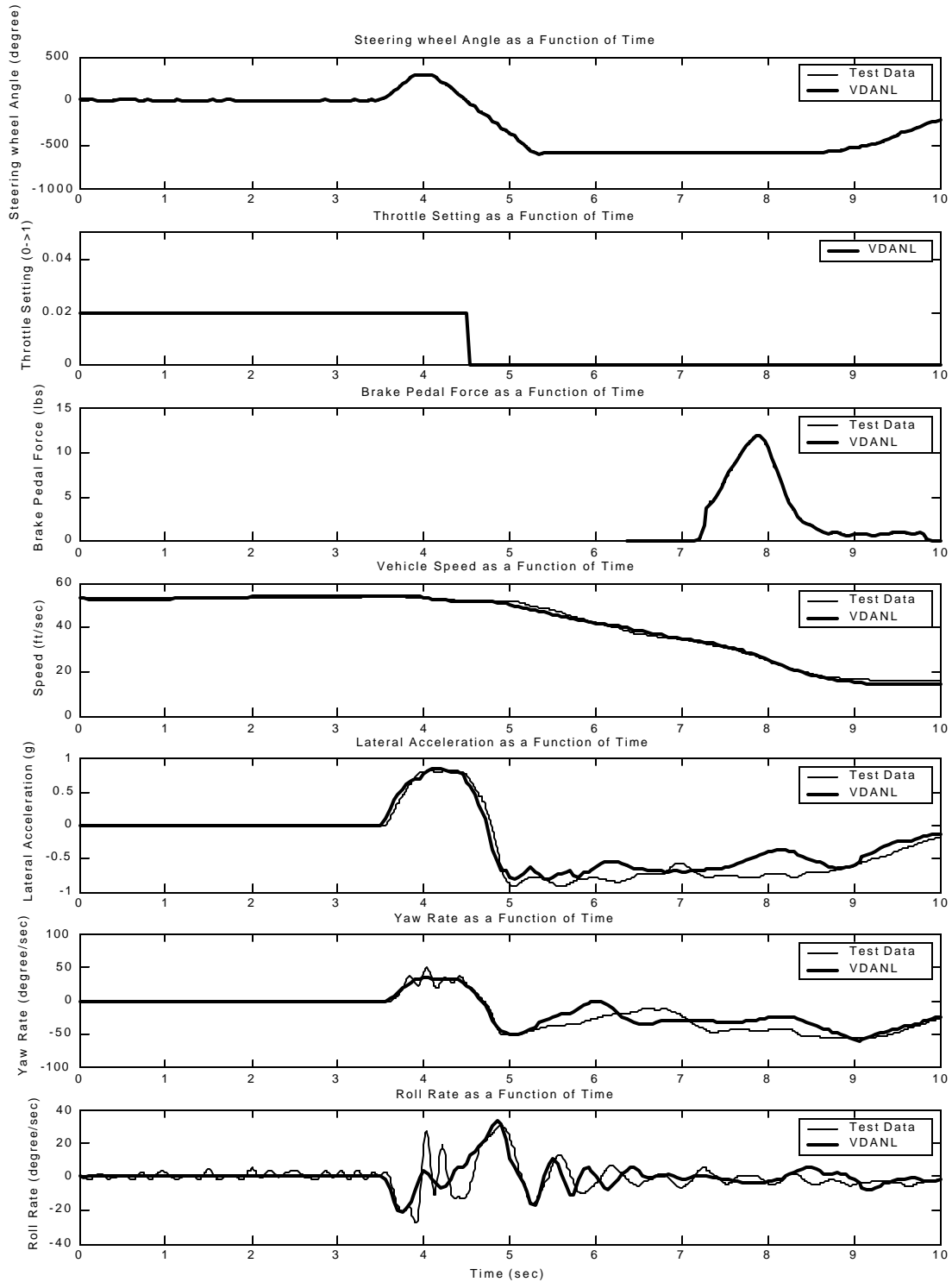Figure 6. High g Transfer Functions for an Obstacle Avoidance Steering Input

Figure 7. High g Transient Response Due to an Automated Fishhook Steering Response

instrumented vehicles. This could be due to several reasons: 1) the VDM does not represent all of the dynamic modes in the real vehicle; 2) the parameter set for the VDM is not appropriate (e.g. some parameters difficult to measure and are estimated); 3) the test vehicle data has some artifacts due to sensor characteristics and scaling problems. All of these possibilities should be kept in mind when validating VDMs against real world data.

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