Validation of Vehicle Stability and Control Simulations

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A methodology for validating computer simulations of physical systems is applied to vehicle stability and control simulations. Validation is defined, within some specified operating range of the system, as a simulation's predictability of system responses' being able to agree with actual measured system responses within some specified level of accuracy. The method uses repeated experimental runs at each test condition to generate sufficient data for statistical analyses. Acquisition and reduction of experimental data and the processing path for simulation data are described. Usefulness of time-domain validation for steady state and slowly varying transients is discussed. Importance of frequency domain validation for thoroughly validating a simulation is shown. Both qualitative and quantitative methods for comparison of simulation predictions with actual test measurements are developed. In order to illustrate the validation methodology, experimental testing of four different vehicles was performed. Comparisons between actual test measurements and simulation predictions are shown.

During the past 30 years, substantial effort has gone into development of numerous vehicle stability and control computer simulations. Unfortunately, much less effort has gone into answering the important question of the validity of these simulations. Because experimental testing of full-scale vehicles for validation procedures is quite expensive and time consuming, many vehicle dynamics simulations have had little or no validation work performed. Many modified and new simulations have been compared with predictions from existing simulations as the sole check of their validity. Others have been experimentally substantiated only for limited vehicle operating conditions and then assumed to be valid for all other operating conditions.

NHTSA desires a vehicle stability and control simulation that can simulate a wide range of light vehicles (passenger cars, pickup trucks, vans, and utility vehicles) in a broad range of cornering and braking maneuvers. NHTSA is studying existing simulations, selecting the most appropriate one for its purposes, and improving it to resolve problems identified during the selection process. Simulation validation methodology and procedure described were developed as part of this work.

For a particular application, the validation methodology described can distinguish the most appropriate simulation out of a group of simulations. In addition, it has proven itself to be useful for identifying measurement errors in simulation parameters. In the modification and improvement stages of simulation development, the procedure can be used to identify specific problem areas of a simulation model.

Validation methodology can be used to validate a variety of vehicle dynamics simulations besides the stability and control types discussed, which includes simulations dealing with vehicle rollover and ride quality. This methodology can also be extended and used for validating computer simulations of many other types of physical systems.

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BACKGROUND

Validation work using full-scale vehicle test results has been performed for several vehicle stability and control simulations developed during the past two decades.

One simulation for which substantial validation efforts were made is the Highway-Vehicle-Object Simulation Model (HVOSM) (*1*). This simulation was originally developed in the late 1960s and has matured through several versions to its present form. It includes general three-dimensional motions resulting from vehicle control inputs, traversals of terrain irregularities, and collisions with certain types of roadside obstacles.

HVOSM predictions were compared with experimental results for various handling and accident maneuvers. Although the validation work appears adequate for steady state conditions, little attention appears to have been paid to transient responses. Validation work in the frequency domain does not appear to have been performed. However, it does appear that some adjustment of vehicle parameters to better match simulation predictions to experimental vehicle responses did occur.

Two modified versions of the HVOSM simulation, the Hybrid Computer Vehicle Handling Program (HVHP) (*2*) and the Improved Hybrid Computer Vehicle Handling Program (IHVHP) (*3*) were implemented in the early 1970s at the Applied Physics Laboratory of the Johns Hopkins University. Principal modifications were addition of a steering system model and removal of obstacle impact dynamics. In 1979, a revised version of these simulations was implemented at the University of Michigan as the Improved Digital Simulation, Fully Comprehensive (IDSFC) (*4*). This simulation was used in the current research.

For validation purposes, predictions of the HVHP, IHVHP, and IDSFC simulations were compared with vehicle field test data for several handling maneuvers. Validation of these simulations, as with the previous versions of HVOSM, paid little attention to the transient response regime. Validation work in the frequency domain was not performed. As a result, the simulations' poor performance in predicting transient behavior was never identified. Finally, vehicle parameter measurement techniques that were available to the researchers were not accurate. As a result, adjustment of vehicle parameters to better match vehicle responses occurred, making the entire validation suspect.

In the mid-1980s, Systems Technology, Inc. (STI), developed the Vehicle Dynamics Analysis Nonlinear (VDANL) simulation for analyzing vehicle lateral and directional control and stability (*5*). This simulation differs from the preceding ones primarily by its suspension and tire models. It was validated by comparison with vehicle field test data for several handling maneuvers (*6*). The maneuver matrix used by STI was not extensive enough to provide simulation validation for the full range of vehicle operating conditions of interest to NHTSA. In addition to simulation validation in the time domain, STI performed validation in the frequency domain that involved comparison of experimentally measured yaw rate to handwheel steering angle frequency response functions (magnitude and phase angle) with simulation predictions. During validation of this simulation, some adjustment of vehicle parameters to better match vehicle responses occurred. The STI simulation was also used in the current research.

The preceding cases are typical of simulation validation work in the literature. In most cases, there was insufficient testing to cover all maneuver regimes of interest. In addition, little attention was paid to the transient maneuvers or the frequency domain. Because of parameter measurement problems, there was a strong tendency to adjust vehicle parameters to make simulation predictions match experimentally measured vehicle responses.

WHAT IS SIMULATION VALIDATION?

Mathematical models of physical systems, such as vehicle stability and control simulations, are valid when, within some specified operating range of a system, the simulation's predictions of system responses of interest to specified inputs agree with the system's actual physical responses to the same inputs within some specified level of accuracy. This definition contains several important points.

First, in general, simulation predictions will only be correct within some portion of the system's operating range. An example of this is that vehicle dynamics predictions may be correct for low lateral acceleration maneuvers, but become progressively worse as lateral acceleration increases and nonlinear effects become more important.

Similarly, simulation predictions may only be correct for inputs that predominantly contain (following Fourier decomposition) frequencies within a specified range. Many vehicle dynamics simulations are valid for steady state and slowly varying input conditions but have problems with fast transients that contain high frequencies.

This last point illustrates why simulation validation needs to be performed in both time and frequency domains. Validation in the time domain demonstrates that the simulation can correctly predict steady-state conditions and that nonlinear effects are properly modeled. However, high-frequency transient phenomena are difficult to study in the time domain. The effects of increasing input frequency on the correctness of simulation predictions are best determined through frequency domain studies.

A second significant point in the definition of simulation validation is that simulations are valid only for specified groups of inputs and outputs. For example, in a vehicle stability and control simulation, because the simulation has been shown to be valid for braking and steering control inputs does not imply that response to a road disturbance will be correctly predicted.

The third significant point of whether a simulation can be considered valid depends on how much simulation predictions can acceptably vary from actual test results at a given operating point. The degree of accuracy required to classify a simulation as valid depends on intended uses of the simulation and the level of accuracy believed to be attainable. If only the trends of the response of a physical system are to be simulated, with little interest in predicting values, much less accuracy is required than when trying to predict exact values.

Determination of the amount of disagreement between a simulation's predictions and actual test measurements that is allowable while still having a valid simulation is difficult. One limit on attainable accuracy is that the accuracy of simulation predictions cannot be shown to be better than the repeatability of experimental measurements.

Every experimental measurement contains random error superimposed onto the signal. Random errors are defined as transducer measurement noise, unaccounted for variations disturbing the system's inputs, and random minor changes in the system. For vehicle testing of the type discussed, random error would include the effects of wind gusts, road roughness, tire nonuniformity, and brake changes from test to test. Other sources of experimental nonrepeatability include, for example, variability in control inputs.

Some disagreement between simulation predictions and experimental measurements will be caused by random error. Because the simulations studied here cannot predict random error, if simulation predictions agree with experimental measurements to within the experimental random error the simulation should be considered valid.

The easiest way to determine the experimental random error level present in data is to repeat all experimental runs multiple times. Given data from several tests, statistical procedures can be used to calculate random error levels.

Two important points about simulation validation not in the previous definition are

1. The parameters used to describe the physical system to a simulation must be measured independently—not from the experiments that obtain simulation validation data, and
2. While validating a simulation, parameters describing the system to a simulation must not be varied from their independently measured values to improve the accuracy of a simulation's predictions.

If either condition is not met, then a simulation is not actually being validated. Instead, the researcher is showing that by adjusting one or more parameters, curves can be generated to match experimental data. This process is not always unique because there may be several ways to change parameters to make simulation predictions match experimental measurements. This type of validation tells nothing about the ability

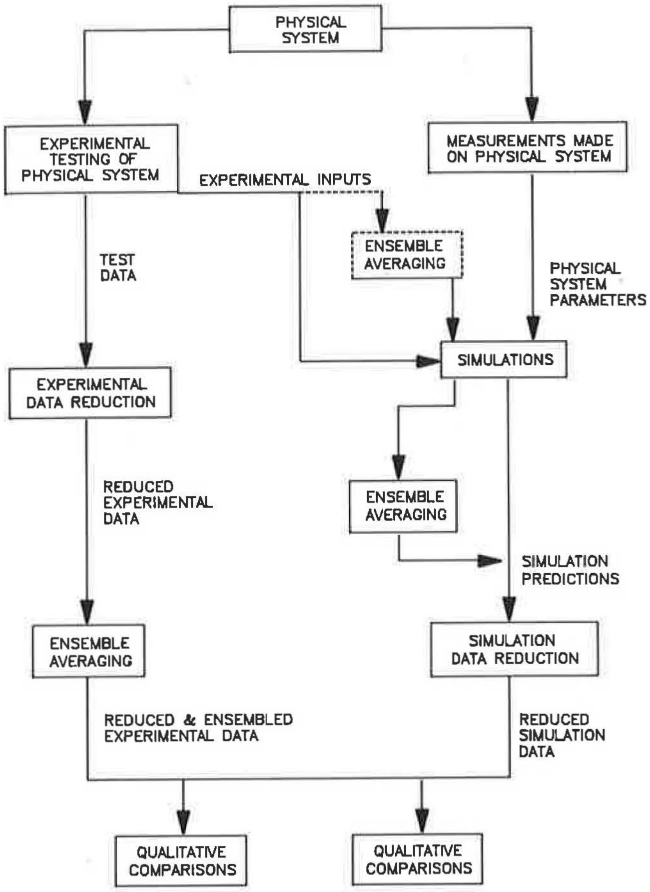

FIGURE 1 Simulation validation process data flow.

of a simulation to predict system performance when experimental data are not present.

SIMULATION VALIDATION METHODOLOGY—GENERAL CASE

The basic steps in the methodology are shown in Figure 1 as a block diagram. These steps indicate the general stages required to validate a computer simulation of a physical system. However, the steps shown are not entirely mandatory because specific details of data processing are unique to individual research programs.

Simulation validation involves the flow of information through two processes, the experimental and the simulation processes.

The experimental process begins by obtaining, via experimental testing, reliable measurements of behavior of the physical system. In order to obtain a measure of the random error present, and to improve reliability of experimental results, repeat runs of each test are made.

Physical system responses of interest must be appropriately measured and recorded. Usually, the inputs or forcing functions used to excite the physical system must also be recorded. Inputs are then used to drive simulations during validation. In some cases, system inputs are predetermined and sufficiently well defined and need not be measured.

Typically, experimental test data require a data reduction stage. This stage usually includes transforming measured electrical signals into engineering units and digital filtering. Other data reduction operations that might be performed at this point include Fourier transformation of data into the frequency domain, computation of experimental quantities that cannot be measured directly, and subsampling of data to reduce the size of data files.

The next step in the flow of experimental data is ensemble averaging the repeated test runs. This step involves computing mean values as a function of the independent variable (time or frequency) for each response of interest. It also allows the use of statistical methods to compute a measure of experimental repeatability at 95 percent confidence intervals of the mean values. The result of this step is reduced and ensembled data (consisting of mean values and confidence limits) from the experimental testing of the physical system.

Next, the flow of information through the simulation process is considered. A simulation is an analytical model of a physical system that requires parameters to represent the physical system. These physical system parameters, such as mass or inertia, damping, compliance, geometry, etc., must be measured (or estimated when necessary) and supplied to the simulation model.

For a simulation to most accurately predict a specific physical behavior, it must be driven with the same inputs as the physical system. These driving inputs must be known (or measured) for each run to be simulated.

The validation methodology presented is based on analyses of data from repeated experimental runs. In general, a simulation should be driven by separate, measured, inputs from each run, followed by ensemble averaging of simulation predictions. This process corresponds to the case shown in the block diagram with solid lines.

However, from a practical point of view the procedure is time consuming and expensive. Although the correct procedure is to ensemble average following simulation, if individual inputs from repeated experimental runs are sufficiently alike and a simulation is not highly nonlinear, inputs may be ensemble averaged before they are fed into a simulation. The predictions obtained should closely approximate the means obtained by ensemble averaging the simulation predictions from separate runs. This process corresponds to the blocks with dotted lines shown in Figure 1.

Once the simulation predictions have been obtained, simulation data reduction may be necessary. This stage may include Fourier transforming the data to the frequency domain or subsampling data to reduce data file size. The result is reduced simulation data.

On completion of these steps, experimentally measured, reduced, and ensemble-averaged test data are compared both qualitatively and quantitatively to reduced simulation data. Qualitative and quantitative comparison schemes vary depending on the nature of the physical system and simulation. Some combination of both qualitative and quantitative comparison, as in this study, usually provides the most thorough validation.

The qualitative comparison scheme used in the current research consists of overlaying plots of experimental mean and simulated values versus an independent variable (time or frequency). The 95 percent confidence limits of the experimental mean are also plotted to indicate experimental variability. Researchers can then observe the agreement between simulation predictions and actual measured data.

Quantitative comparison schemes include the comparison of computed steady state gains, response times, peak response times, and percent overshoots from time domain data. Frequency response comparisons include peak frequencies, peak amplitude ratios, and bandwidths. Other methods involve the use of statistical methods for comparing simulation predictions with experimental mean values and confidence intervals.

VALIDATION OF VEHICLE STABILITY AND CONTROL SIMULATIONS

A goal of the current research was to develop a vehicle stability and control simulation that can simulate a wide range of vehicles and be valid for a broad range of crash avoidance maneuvers. The first step in the research was to study two existing vehicle stability and control simulations, namely the VDANL and IDSFC simulations. Simulation validation methodology presented was developed for use during this study to find areas of disparity between these simulations and field test results. Once problem areas have been identified, simulation model improvements can be implemented to reduce simulation disagreement. This work is expected to result in a more accurate (for the operating conditions and maneuvers of interest) vehicle stability and control simulation than any developed for NHTSA to date.

Four vehicles used in this research were significantly different in size, shape, and design function. They were a 1987 Ford E–150, standard-sized van, a 1987 Ford Thunderbird midsized passenger car, a 1987 Hyundai Excel small passenger car, and a 1988 Suzuki Samurai utility vehicle.

EXPERIMENTAL DATA COLLECTION AND PROCESSING

The experimental data collection and processing portion of Figure 1 that was actually performed for the four test vehicles is shown in Figure 2.

Each vehicle was tested using several types of maneuvers covering a broad range of crash avoidance situations. Five major types of vehicle maneuvers were studied: constant speed J-turns, braking in a turn, double lane changes, straight line braking, and sinusoidal sweep steering. This last maneuver was used to study the frequency domain response of each vehicle.

For each of these maneuver types, 2 to 18 specific test cases were run. Each case was run at a different severity level or speed. For example, for straight-line braking tests cases were run with nominal deceleration levels of 0.2, 0.4, and 0.6 *g*, and at the maximum deceleration achievable by the vehicle without wheel lockup. In addition, for maneuvers involving turns cases were run with both right turns (positive lateral acceleration) and left turns (negative lateral acceleration).

Ten repeat runs were made for each test case. Six of these runs were selected for further analysis. Runs were selected for analysis to minimize the range in test speeds at the start

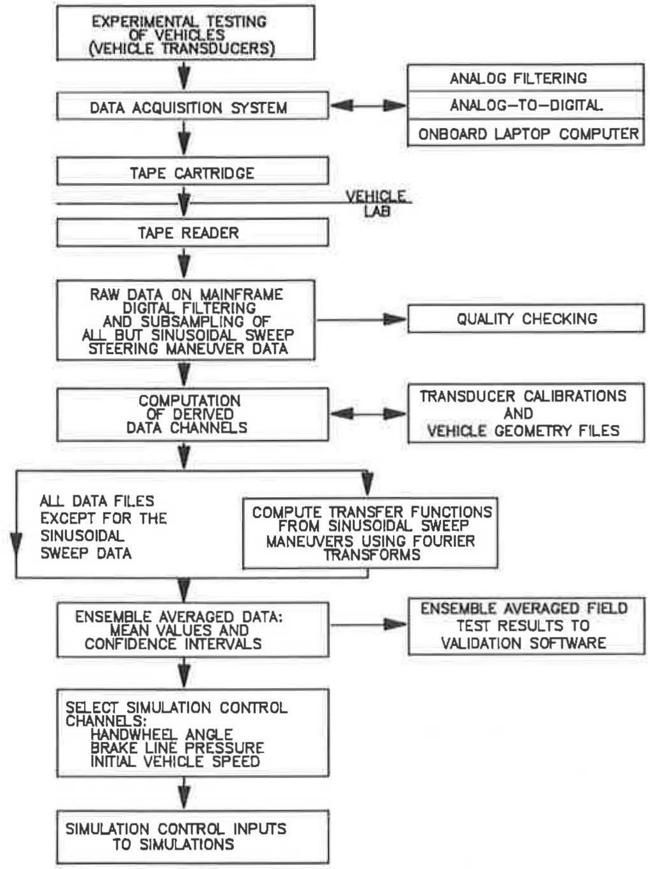

FIGURE 2 Experimental data flow.

of the runs. In most instances, all 10 test runs were performed at initial velocities within ±1 mph of the nominal test velocity. However, for some test cases several individual run initial velocities deviated too much from the nominal value; these runs were not included in any further analysis.

A total of approximately 40 cases with approximately 400 individual test runs were completed for each of the test vehicles.

Each test vehicle was instrumented to measure control inputs and vehicle outputs that were expected to provide useful comparisons with simulation predictions. This method resulted in the installation of 29 transducers per vehicle. Transducers used included linear and rotary potentiometers, tachometers, pressure gauges, angle and rate gyroscopes, accelerometers, and torque dynamometers. These devices were mounted to provide direct measurement of such quantities as vehicle sprung mass; lateral, longitudinal, and vertical accelerations; vehicle yaw rate; sprung-mass pitch and roll angles; vehicle speed; front and rear brake line pressures; handwheel steering angle and torque; suspension motions; roadwheel steering angles; and angular velocities.

Output signals from the in-vehicle transducers were amplified, filtered, digitized, and stored on tape by a Megadac 2210C digital data acquisition system. Data were transferred to a VAX computer in which all subsequent processing was done.

Next, the data were reduced by converting into engineering units, and quality checking was performed to look for transducer or data collection errors. Data were then digitally filtered to 3 Hz to reduce high-frequency noise and decimated to reduce the size of the data files. Data analyzed in the frequency domain, i.e., data from the sinusoidal sweep steering maneuver, were neither decimated nor filtered.

As shown in Figure 2, the next step in data reduction was the computation of data channels derived from the original data channels. Derived data channels are system responses of interest that cannot be measured directly by transducers mounted in the vehicle but must instead be computed from original, measured data channels. For example, experimental longitudinal wheel slips are not easy to measure directly. However, these wheel slips can be computed from wheel angular velocities and forward velocity of the vehicle.

Next, the vehicles' frequency response (transfer) functions were computed from sinusoidal sweep maneuvers. Sinusoidal sweep steering maneuvers were performed by sweeping the steering input in a smooth manner from the lowest to the highest frequency physically attainable by the driver while maintaining a generally straight vehicle path.

Along with frequency response functions, coherence functions (a function that indicates system noise and nonlinear system behavior) were also computed. For the frequency response functions found during the current research, the coherence functions are near unity (a value of unity indicates noise-free, linear, system behavior) except in frequency ranges in which the amplitude ratios exhibited very low magnitudes. In these ranges, poor coherence is expected because little system response is present so that even a small amount of random error dominates the measured signal. Although nonlinearities are accounted for in the simulation models, the high coherence values indicated that during the sinusoidal sweep steer maneuvers used to generate the frequency domain results the vehicles were being operated in a mostly linear manner.

The next stage in experimental data processing was ensemble averaging the reduced test data. For the purpose of simulation validation, the repeatability of experimental measurements must be known. This benchmark is achieved by making repeated experimental runs of each test case and using ensemble averaging and statistical methods to analyze data from repeated runs.

For test results being analyzed in the time domain, each data channel's mean values are computed for each increment of time.

Figure 3 shows typical measured lateral acceleration data and the mean value of the data and 95 percent confidence limits on the mean value. These data are from the six selected runs of a −0.2-*g* lateral acceleration, constant-speed, J-turn test case performed at a nominal speed of 25 mph. Figure 3 has magnified scales to make run-to-run variability easily visible. For each time increment, the distribution of the channel variables about some population mean value is assumed to be a normal or Gaussian distribution. Computing the mean from six repeated runs has a smoothing effect on the experimental data because random spikes caused by, e.g., electrical noise or road surface irregularities, become less pronounced after averaging.

At the completion of ensemble averaging, the experimental data have been processed to the point where the data can be used for simulation validation. Two ensemble-averaged channels, front brake line pressure and handwheel angle, along with average initial vehicle speed, are used as control inputs to the simulations.

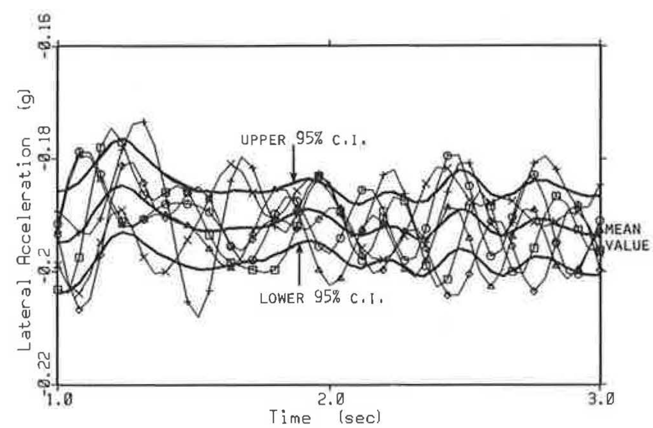

FIGURE 3 Steady state lateral accelerations from six repeat vehicle test runs and their mean value and 95 percent confidence intervals for the mean value.

SIMULATION DATA PROCESSING

The first stage in simulation data processing is vehicle parameter measurement. All vehicle simulations must be supplied with physical system parameters that describe the particular vehicle being simulated. These parameters vary from simulation to simulation, but typically include vehicle geometric and inertial properties; component inertial properties; suspension-kinematic, damping, and stiffness properties; tire force generation properties; and brake torque generation properties.

Adjusting of one or more parameters to improve simulation predictions is tempting in simulation validation. This type of parameter adjustment is ill-advised if the goal of validation is to determine the predictive capability of the simulation. Rather, the validation process should be used to identify possible errors in parameter measurement techniques.

Specialized test machines were used to measure, for each vehicle, the parameters required by the two simulations. NHTSA's inertia parameter measurement device (*7*) and small parts inertia rig were used to measure inertial properties of entire vehicles and of selected components, respectively. The suspension parameter measurement device (*8*) was used to measure suspension-kinematic, compliance, and Coulomb damping parameters. Data obtained from manufacturers was used to find shock absorber properties. Braking characteristics were measured using NHTSA's road transducer plate (*9*). Finally, tire parameters were measured by Calspan Corporation on its flat-belt tire tester (*10*).

Following completion of vehicle parameter measurement, the actual simulation runs were made. Inputs required by the simulations were vehicle parameters and control inputs from the experimental program.

Both simulations were run in open-loop control mode (no driver feedback) with control inputs being read from the ensemble-averaged mean-value channels. One exception was the sinusoidal sweep steering maneuvers. For this case, it was decided that mathematically generated control inputs would be fed into the simulation instead of using experimental time histories. Frequency response curves generated from mathematically generated inputs demonstrate no appreciable differences when compared with curves produced from experimental inputs, but result in a savings of time and ensure that sufficient input signal power is present throughout the input frequency range of interest.

Data reduction was mainly performed by modifications that were made to the actual simulation codes. These modifications involved computing vehicle accelerations that could be directly related to the accelerations measured by in-vehicle accelerometers.

For sinusoidal sweep steering maneuvers, one other data reduction operation was performed—computation of simulated frequency response functions from simulation output.

Because the simulations were driven by the mean ensemble-averaged control inputs, no further ensemble averaging was necessary. At this point, the simulation predictions were ready for comparison with the reduced and ensemble-averaged experimental data.

QUALITATIVE SIMULATION VALIDATION

The qualitative validation methods use graphs overlaying results from both simulations (VDANL and IDSFC) and experimental data to determine simulation validity. Graphs are prepared showing simulation predictions overlaid with the mean and 95 percent confidence level of the mean of the experimental data for each channel to be compared for both time and frequency domain data.

The first priority in validating a simulation is to check its ability to predict steady state gains and transient behavior during simple maneuvers. Only after this check has been satisfactorily completed should a simulation be checked against more complex maneuvers that are meant to duplicate real-world driving scenarios (lane change, braking during a turn, etc.). Both time and frequency domain data should be used to see the full range of vehicle responses.

Graphs of constant-speed J-turn maneuvers provide a good way to check steady state gains. Figure 4 shows the vehicle's yaw rate and sprung-mass roll angle. Comparison of simulation output with experimental data should be made after transient behavior has died out. The yaw rate graph indicates that both simulations do a good job of predicting steady state yaw rate gain for this maneuver at this severity level.

The graph of sprung-mass roll angle shows that the predictions of both simulations have considerable errors. Because the vehicle's roll moment is driven by lateral acceleration (at steady state, lateral acceleration is related to yaw rate), which has been predicted accurately, and because roll stiffness values for both simulations were computed from the same vehicle measurement data, the roll moment modeling of both simulations appeared to be in error.

When validating a simulation's ability to predict vehicle behavior, it is important to avoid chasing cross talk between vehicle responses. That is, the value of a particular response may be strongly influenced by values of other responses. For example, the force input for sprung-mass roll results from lateral acceleration. If the simulation is not doing a good job

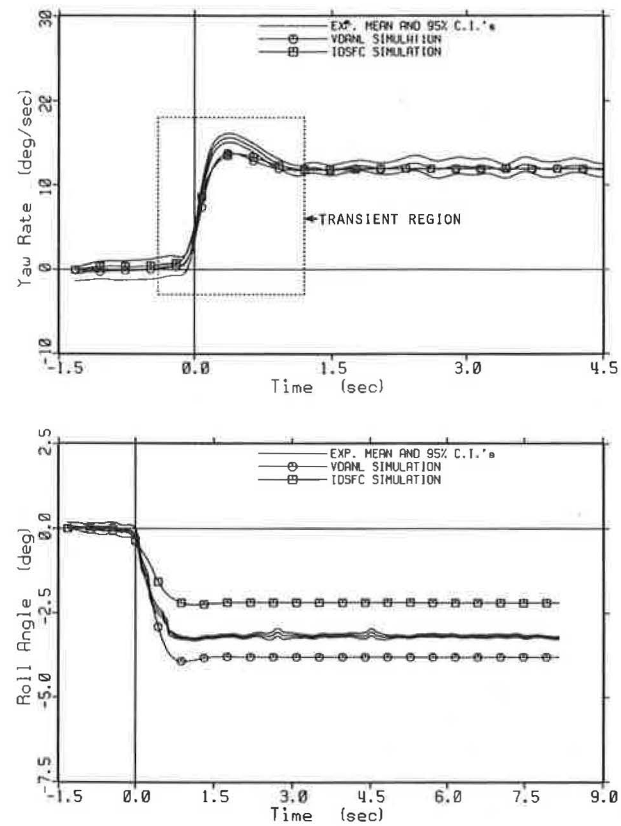

FIGURE 4 Yaw rate and sprung-mass roll angle for a 50-mph constant-speed J-turn (1987 Hyundai Excel).

with lateral acceleration in a particular frequency range, it will directly affect roll dynamics. Therefore, there is no point in looking at roll mode correlation until lateral acceleration problems are resolved.

This same approach of visually comparing time domain graphs can be carried out for longitudinal acceleration and other channels. Comparisons should be made over the entire operating range of interest because the simulation may show good agreement in the linear operating range (<0.3 g) but have problems for limit maneuvers. This condition would indicate more work is necessary in the modeling or parameter measurement of the tire and suspension nonlinearities.

Once steady state responses are being accurately predicted, predictions of transient responses can be checked. A good view of a simulation's ability to predict vehicle transient behavior is given by plotting frequency response curves. For this research, frequency response curves were generated from sinusoidal sweep steering maneuvers. Figure 5 shows yaw rate frequency response (magnitude and phase angle) to steering wheel angle inputs.

Figure 4 shows that both simulations do a good job of predicting yaw response for this vehicle for this J-turn maneuver. The simulations' steady state responses are excellent, whereas examination of the transient region reveals only slight discrepancies. The yaw rate frequency response curves (Figure 5) contain differences between predicted and measured yaw rate response. The frequency at which the peak magnitude in the frequency response occurs and the magnitude of this peak highlight discrepancies that were not as apparent when examining time domain responses. Both simulations

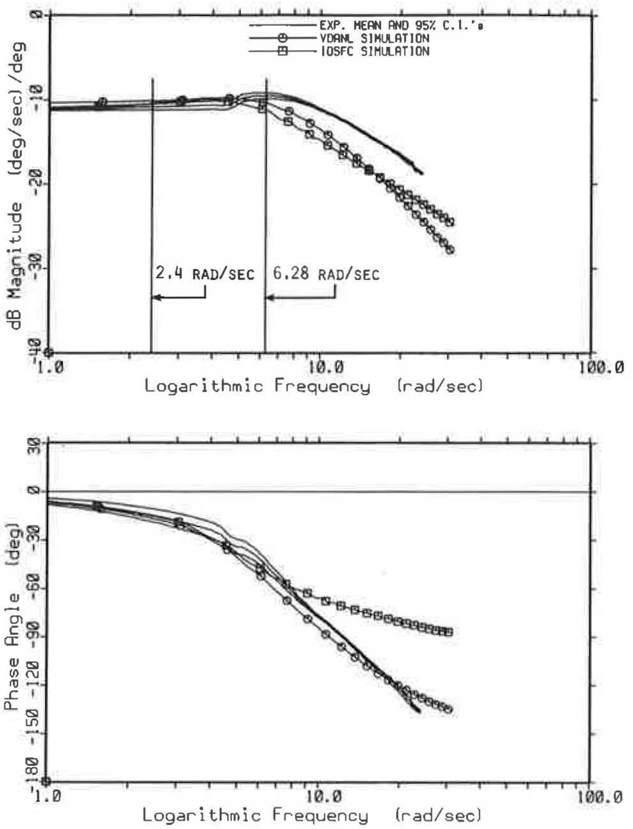

FIGURE 5 Yaw rate frequency response (magnitude and phase angle) from a 50-mph sinusoidal sweep steering maneuver (1987 Hyundai Excel).

predict low values for peak yaw rate frequency and both simulations exhibit more efficient yaw rate damping than is experimentally measured. Some of the other vehicles, especially the Suzuki Samurai (see Figure 6), show a large peak in yaw rate magnitude at the yaw rate peak frequency. If the magnitude and frequency of this peak are not predicted properly, then the transient response of the vehicle cannot be simulated accurately.

Too often, researchers have overlooked differences in the transient region of vehicle response by examining only time domain data. Errors in the transient region of time response results may be small for some maneuvers, but large for others, depending on the shape and speed of the steering (or other) input. This result is the reason why it is important to study several different types and severities of vehicle maneuvers and vehicles before claiming full-fledged simulation validity. This example indicates again the importance of generating frequency response curves, because they provide a great deal of information about system behavior.

Once steady state gain and frequency response predictions of the simulation have been validated, the simulation can be checked against maneuvers designed to simulate real-world driving conditions. The following discussion, which uses a lane change maneuver as an example, demonstrates the problems of trying to infer validity of a simulation at one operating condition from its performance at another.

Figure 7 shows vehicle yaw rate for a 50-mph lane change. Both simulations do a good job of predicting yaw rate for this maneuver. The predominant handwheel input frequency of this test is approximately 2.4 rad/sec (0.4 Hz). The ability to simulate vehicle response in this frequency range is influenced primarily by steady state predictions. Given the steady state predictions shown in Figure 4 and frequency response predictions at this frequency shown in Figure 5, it follows that simulation predictions for this lane change maneuver should be good. However, the lane change maneuver could have been designed differently and required a handwheel input frequency of 6.28 rad/sec (1 Hz), for example. Figure 5 clearly shows that the simulated response would not agree nearly as well as at the lower frequency. For a simulation to be valid for crash avoidance research, it must simulate with reasonable accuracy maneuvers likely to occur in crash avoidance situations. This validity test means a simulation should accurately predict vehicle frequency responses for any input drivers can generate.

QUANTITATIVE SIMULATION VALIDATION

In order to supplement the qualitative validation methods presented, quantitative validation methods provide significant insight into the vehicle modeling process. The method presented involved determining values, called "metrics," from simulation output and experimental data for direct comparison. Besides aiding the validation process, metrics also can be used to aid in quantifying vehicle performance by providing

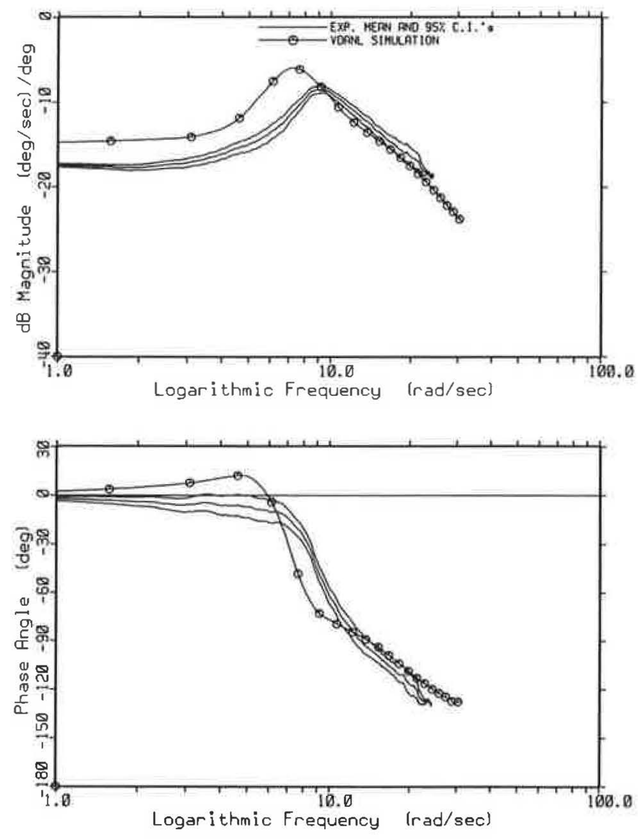

FIGURE 6 Yaw rate frequency response (magnitude and phase angle) from a 50-mph sinusoidal sweep steering maneuver (1988 Suzuki Samurai).

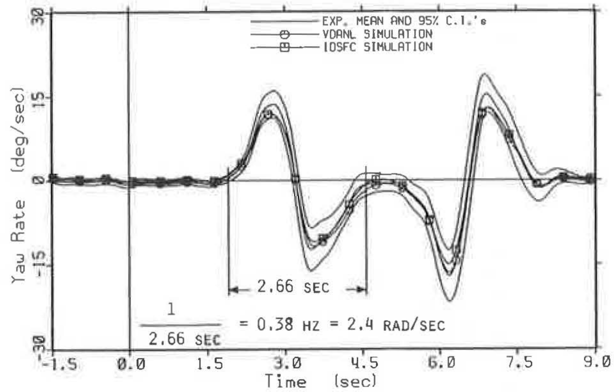

FIGURE 7 Yaw rate for a 50-mph right lane change maneuver (1987 Hyundai Excel).

direct measures of characteristic vehicle responses. Metrics are obtained both from time and from frequency domain data and are helpful, like the qualitative method, in locating and differentiating parameter and modeling problems.

The first set of metrics are derived from time domain data of pseudo-step steer, constant speed, and J-turn maneuvers. Steady state gain, response time, peak response time, and percent overshoot are standard time domain performance specifications. These specifications, as they relate to vehicle stability, have been presented and discussed previously by Nisonger and Fancher (*11*). Metrics can be computed for any of the experimental and simulated vehicle response channels with the selection depending on the intended application. In this program, lateral acceleration, yaw rate, and sprung-mass roll angle were the channels thought to be most important.

Table 1 presents yaw rate to handwheel angle steady state gains for all four vehicles while performing a constant-speed J-turn at a nominal lateral acceleration level of $+0.4\ g$. Mean values and corresponding 95 percent confidence intervals for the mean values are presented for experimentally measured gains, as are both VDANL and IDSFC simulation predicted gain values. Two different test speeds, at 25 and 50 mph, are presented.

Gains for the Ford Thunderbird are low for both simulations and at both speeds. Also, both simulations predict similar values, suggesting that a parameter common to both simulations is in error. In this case, the parameters defining steering system compliance are in error because they were measured without the power steering operating.

Measured yaw rate gains for the Suzuki Samurai show a trend opposite to the other three vehicles, i.e., the experimental yaw rate gain decreases with speed. As presented in Table 1, the VDANL simulated values do not reflect this trend. (The IDSFC simulation does not model vehicles, such as the Samurai, with solid front axles.) The reason for this discrepancy is that the Samurai has large steering system free play that the VDANL model does not model. When a steering system model including free play was added to the VDANL simulation, it resulted in correct predictions of this trend.

Time domain metrics, response time (T_r), and peak response time (T_p) are speed-of-response criteria that provide an indication of vehicle stability and, hence, controllability. Increased response time (sluggish vehicle response) as maneuver severity increases indicates decreased vehicle stability that may indicate a vehicle will be difficult to control in a high-severity, accident avoidance maneuver (*11*).

Response time and peak response time are defined relative to a reference time, the time at which the input reaches 50

TABLE 1 YAW RATE TO HANDWHEEL ANGLE STEADY STATE GAINS FOR NOMINAL +0.4-*g* LATERAL-ACCELERATION CONSTANT-SPEED J-TURN MANEUVERS [(deg/sec)/deg]

Vehicle	Experimental Mean and C.I.	IDSFC Simulation	VDANL Simulation
25 MPH			
1987 Hyundai Excel	0.219 ± 0.002	0.209	0.211
1987 Ford Thunderbird	0.203 ± 0.004	0.155	0.162
1987 Ford E-150 Van	0.125 ± 0.002	0.121	0.111
1988 Suzuki Samurai	0.162 ± 0.002	**	0.167
50 MPH			
1987 Hyundai Excel	0.302 ± 0.004	0.289	0.285
1987 Ford Thunderbird	0.224 ± 0.011	0.162	0.156
1987 Ford E-150 Van	0.156 ± 0.004	0.164	0.132
1988 Suzuki Samurai	0.140 ± 0.003	**	0.167

** The IDSFC simulation does not model vehicles with solid front axles.

percent of the steady state level. This time is used because the input is not a pure step or ramp and therefore does not have an easily measured starting or ending time. Response time is the time from the reference time to the time when the vehicle output reaches 90 percent of steady state value. Peak response time, which is only defined for responses that exhibit overshoot, is defined as the time from the reference time to the time when vehicle output reaches the maximum value of its first peak.

Percent overshoot (O_p) is a relative stability criterion. Because road vehicles behave as high-order systems, standard analysis techniques on the basis of second-order system behavior cannot be used to compute standard second-order system response parameters such as damping ratio for the total vehicle system. However, percent overshoot can be used instead of damping ratio to provide a metric related to vehicle damping and thus stability.

A second group of metrics can be derived from frequency domain data. Important frequency domain metrics are peak frequency, peak amplitude ratio, and bandwidth. These metrics are computed for yaw rate, lateral acceleration, and roll angle frequency response data. Again, as with time domain metrics, a road vehicle is a high-order system and the metrics computed are not standard second-order system parameters but are merely a means to quantify vehicle response and to provide a method to directly compare simulation predictions with experimental data.

The frequency domain metric, such as peak amplitude ratio, gives a measure of effective damping, with a higher value indicating a less damped response. For yaw rate frequency response data, if a vehicle has a high peak amplitude ratio it may become difficult to control if excited near its peak frequency. This situation, which could arise in a rapid lane change maneuver and lead to loss of control, emphasizes the importance of having good simulation predictions in the transient region. If simulation predictions for peak frequency or peak amplitude ratio are off, predictions for maneuvers, which excite frequencies near the peak frequency, will be wrong and may lead researchers to incorrect conclusions.

The final frequency domain metric, bandwidth, is defined as the frequency at which the magnitude drops 3 dB below its steady state magnitude. Bandwidth metric is a system speed-of-response measure; a wider bandwidth indicates that vehicle response characteristics will be maintained up to a higher input frequency.

CONCLUSION

A methodology for evaluating vehicle dynamics simulations by comparing simulation predictions with experimental data was presented. A general definition of simulation validation was given followed by a presentation of the steps involved in processing experimental and simulation data. Use was made both of qualitative and of quantitative comparison methods.

A methodology for simulation validation using repeated experimental runs was presented. Ensemble averaging was used for computing mean values and confidence limits on the mean values for experimental data both in time and in frequency domains. This statistical procedure had a smoothing effect on data by reducing random error in the measured signal. Ensemble averaging also safeguards against isolated measurement errors associated with data collection problems, transducer malfunction, etc. Errors of this type can go undetected if just a single experimental run is made. The validation methodology also indicated the importance of using several different vehicles as well as an assortment of maneuver types and severities.

The benefits of analyzing experimental and simulated vehicle behavior in the frequency domain were demonstrated by examples. Frequency domain results provide a great deal of information, some of which may not be revealed through time domain analyses. Transient response characteristics were examined using comparisons in both time and frequency domains.

Simulation predictions were qualitatively compared with experimental results in both time and frequency domains by plotting predictions, experimental mean values, and experimental confidence intervals on the same graphs. In addition to qualitative comparisons, quantitative comparison metrics such as steady state gain, response time, percent overshoot, peak frequency, and peak amplitude ratio were suggested.

Several possibilities resulted from this simulation validation process. A simulation may be deemed valid for predicting the particular physical system behavior that it was designed to model. The validation process may be used to select the best simulation, from a group of more than one, for a specific research project. If the simulation validation process is used to check validity of a fairly complicated simulation, most likely certain aspects of the simulation will result in good predictions whereas other aspects will not yield accurate predictions. In these cases, the simulation validation methodology presented provides a valuable tool for modifying and enhancing a simulation. Areas of simulation disagreement with experimental results can be recognized. Also, possible vehicle parameter errors and experimental data offset or calibration errors may become apparent during the validation process.

ACKNOWLEDGMENT

This research was sponsored and partially performed by NHTSA, U.S. Department of Transportation.

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Publication of this paper sponsored by Committee on Simulation and Measurements of Vehicle and Operator Performance.