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# Requirements for Vehicle Dynamics Simulation Models

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Systems Technology, Inc.

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# Requirements for Vehicle Dynamics Simulation Models

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## ABSTRACT

Computer simulation and real-time, interactive approaches for analysis, interactive driving simulation, and hardware-in-the-loop testing are finding increasing application in the research and development of advanced automotive concepts, highway design, etc. Vehicle dynamics models serve a variety of purposes in simulation. A model must have sufficient complexity for a given application but should not be overly complicated. In interactive driving simulation, vehicle dynamics models must provide appropriate computation for sensory feedback such as visual, motion, auditory, and proprioceptive cuing. In stability and handling simulations, various modes must be properly represented, including lateral/directional and longitudinal degrees of freedom. Limit performance effects of tire saturation that lead to plow out, spin out, and skidding require adequate tire force response models. Additional steering and braking subsystem characterizations are necessary to represent important handling and stability requirements. Steering compliance and appropriate tire aligning torque effects provide a significant component of understeer. Front-to-rear brake proportioning plays a significant role in limit performance directional stability, including the effects of nonlinear brake pressure proportioning valves.

This paper summarizes vehicle dynamics model requirements for various classes of interactive and computer simulations. General formulations include sets of force and moment equations, with subsidiary equations for effects such as tire force response, antilock, traction control, four-wheel steering, and other advanced vehicle control systems (AVCS). Examples of simple and complex models will be given, including validation methods, for vehicle and driver models.


## INTRODUCTION

Vehicle dynamics models (VDMs) have been developed over the years for a variety of applications, including analysis, e.g. (1,2,3), driving simulation, e.g. (4,5), and hardware-in-the-loop simulation (6). A given application will define the necessary model complexity, numerical methods, and solution procedures. The requirements for a VDM depend on the specific application. Gross handling characteristics and vehicle stability can be managed with relatively simple models, but load transfer and tire force response are critical. Vehicle heave response to severe road profiles requires good deflection models for both suspension and tires. For interactive driving simulations, the VDM may be required to provide commands for visual, motion, auditory, and control feel cuing. For hardware-in-the-loop simulation, such as steering or braking systems, the VDM must provide system inputs and accept system outputs in real time in order to properly accommodate hardware operation.

The basis for VDM development are equations that describe the forces and moments acting on various vehicle components and the response of the vehicle inertial properties to these external forces. The development of the inertial dynamic equations can be handled through several formulations, e.g. (7,8), and multibody formalisms allow for a generalized approach to the inertial component of VDM derivation, e.g. (9,10). The external force-producing elements typically require more eclectic means for modeling effects, such as aerodynamic and tire forces, engine and brake torque, etc. Since vehicle handling is dictated to a large degree by tire force response characteristics, some balance must be maintained between the complexity of the inertial dynamics versus the external force producing elements of VDM formulations.

In this paper, we will first discuss the components of an overall VDM and point out the important interrelationships among the components. We will then review the various aspects of vehicle dynamics and summarize what their importance is to various VDM applications.

## BACKGROUND

A general and fairly comprehensive set of VDM elements and their interrelationships are illustrated in the Fig. 1 block diagram. These elements include:

- The basic inertial vehicle dynamics, including the interaction of sprung and unsprung masses and the wheel spin modes
- A comprehensive tire model that includes lateral and longitudinal force response to normal load, slip, and camber
- Power train, including engine torque production and transmission and drive train components for transmitting the torque to the drive wheels
- Steering system with power assist characteristics and compliance that produces understeer
- Braking system, including proportioning and antilock characteristics to minimize rear wheel lockup
- Vehicle/road kinematics that compute vehicle position and orientation relative to the roadway and terrain
- A driver or automatic controller for steering, throttle, and brake control
- External forces and commands that produce system responses through vehicle motions and driver or automatic system control.

Clearly, the complete Fig. 1 structure is not required for all applications, and the detail carried out for any one component will vary from application to application.

The basic inertial dynamics and kinematic computations may allow for a large number of degrees of freedom, depending on the number of masses accounted for and whether the motions are considered to be planar or spatial. Inertial dynamic computations allow forces to produce vehicle body-axis accelerations, while the kinematic computations convert body-axis computations into angular and translational velocities and positions.

Vehicle motions are produced primarily by tire forces that result from power train, braking, and steering system commands. The tire forces represent a significant proportion (probably a majority!) of vehicle dynamics behavior; therefore, a comprehensive tire model is of considerable importance to the overall VDM. As shown in Fig. 1, tire forces and aligning torque interact with the wheel spin mode and the steering system, as well as the inertial vehicle dynamics. This interaction applies to both the linear maneuvering range (i.e., accelerations less than roughly 0.4 g) and the limit performance regions of braking and steering maneuvers. The tire model should respond properly to the four key inputs of longitudinal and lateral slip, camber angle, and normal load and the interaction of these inputs as the tire operating conditions approach saturation.

As mentioned above, the complete Fig. 1 model is obviously not required for all applications; and, in fact, simple and even rudimentary models are acceptable for many applications. The real issue is in setting the requirements for a given application, then realizing these requirements in an appropriate VDM. Complexity is to be minimized wherever possible in order to minimize software coding, checkout, and validation efforts. Increased complexity can lead to modeling and coding errors and difficulties with numerical solutions and validation.

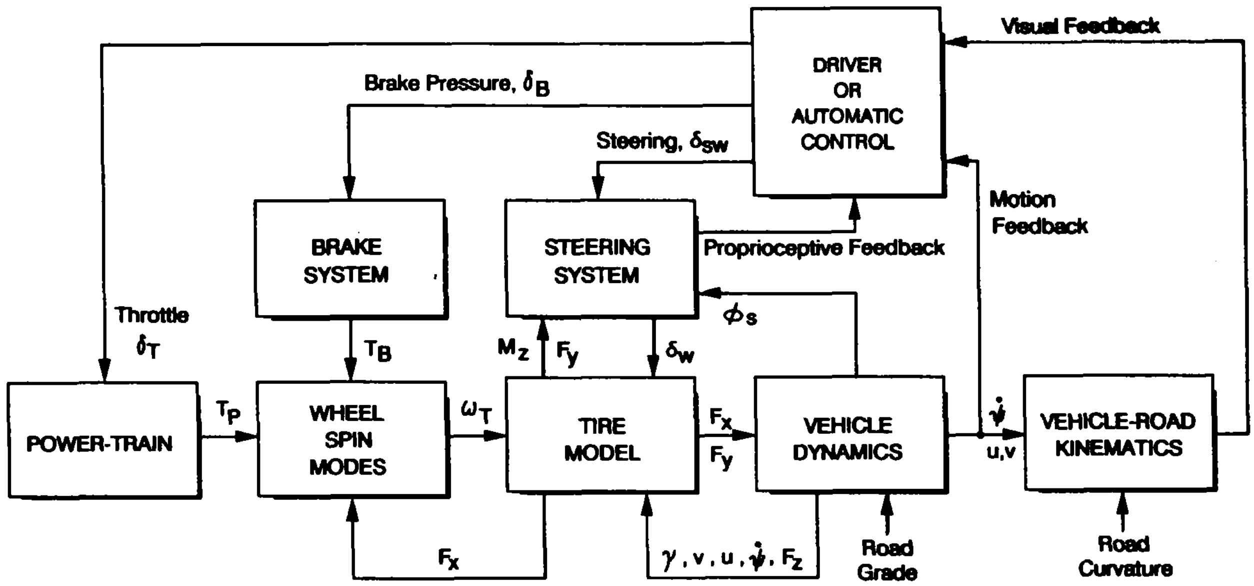
A range of multibody programs have been developed that simplify the model development process and specify the numerical solution procedures, e.g. (9,10). One multibody modeling program is even tailored to ground vehicle dynamics and generates optimized source code (11). The multibody programming approach is not necessarily a panacea, however, because users must still understand and specify the vehicle response effects they wish to model and work this into the multibody approach allowed by a given program. Furthermore, the multibody approach does not strictly cover force and torque generation by tires, engine, aerodynamics, driver or automatic control, etc., and these effects are typically provided by separate subroutines provided within the programming system or externally by the user. Moreover, the multibody approach does not absolve the user from validating the resulting VDM software to assure that the model specification has resulted in appropriate vehicle response to disturbance and command inputs.

The remainder of this paper will be devoted to discussion of establishing VDM requirements in terms of effects desired by the user and resulting model components. Some discussion will also be devoted to the VDM validation problem.

## VEHICLE DYNAMICS COMPONENTS

Ground vehicle dynamics can be broken down conveniently into three components from a specification point of view:

- Lateral/directional components that deal with vehicle response to steering inputs and involve vehicle body-axis lateral acceleration and yawing and rolling velocity
- Longitudinal components involving vehicle longitudinal acceleration response to engine throttle and braking inputs
- Vertical or heave components involving vehicle pitching and normal acceleration response to roadway vertical profiles.

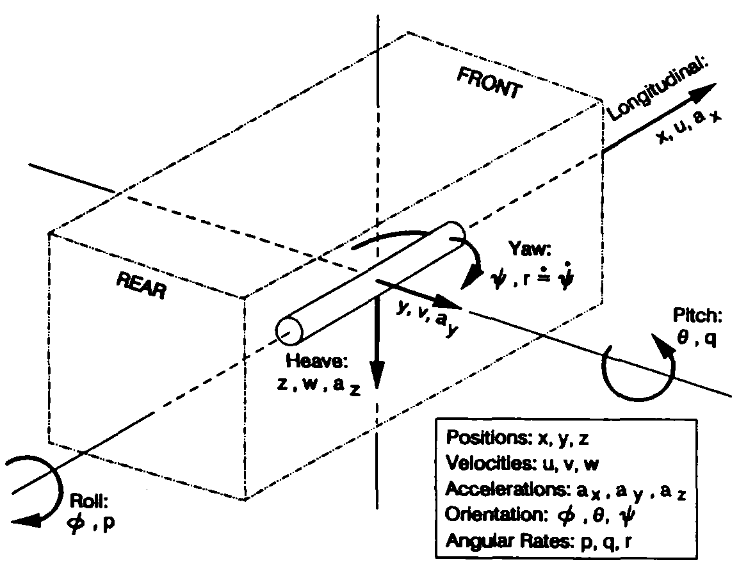



$F_x, F_y, F_z$ = x, y, z forces from or on tire
$M_z$ = Aligning moment from tire
$\omega_T$ = Wheel spin velocity
v, u = Vehicle side and forward velocities
$\delta_{SW}, \delta_W$ = Steering and road wheel angles

$\phi_S, \gamma$ = Body roll and wheel camber angles
$\dot{\psi}$ = Vehicle yaw rate

note that tire side slip = $\alpha = f(v, u, \dot{\psi}, \delta_{SW})$
tire longitudinal slip = $S = f(\omega_T, u)$

Figure 1. Overall Vehicle System Dynamics Model, Including Driver or Automatic Control




$\psi$, y, v, $a_y$, z are fixed to a sleeve over the longitudinal body axis, which allows $\psi$, y, v, $a_y$, to stay level with the road plane, (do not rotate with $\phi$), and z remain perpendicular to road plane.

| MASS | MOTION VARIABLES | D.O.F. |
|---|---|---|
| Sprung Mass ($m_s$) | $\theta_s$, $\phi_s$, $z_s$, $a_{y_s}$ | 4 |
| Total Mass (m) | $\psi$, u | 2 |
| Front Unsprung ($m_{UF}$) | $z_{UF}$, $\phi_{UF}$, $a_{yUF}$ | 3 |
| Rear Unsprung ($m_{UR}$) | $z_{UR}$, $\phi_{UR}$, $a_{yUR}$ | 3 |
| Wheel rotational inertial (4) ($I_W$) | $\omega_i$ (spin mode, 4 wheels) | 4 |
| Wheel inertia about steer axis ($I_{FW}$) | $\delta_{WF}$ | 1 |
| TOTAL DEGREES OF FREEDON | | 17 |

Figure 2. An Axis System and Degrees of Freedom for a Relatively Complex Vehicle Dynamics Model (12)

In actuality, there can be a significant amount of coupling among the above three VDM components. Longitudinal velocity (speed) is an important operating condition for lateral/directional dynamics as represented by understeer/oversteer effects. Longitudinal acceleration can also cause significant pitching motions in the vertical dynamics. Furthermore, under high "g" maneuvering conditions, the longitudinal and lateral tire force responses interact significantly, so that combined cornering and braking represent critical handling scenarios.

Figure 2 defines an axis system and necessary degrees of freedom to accommodate the Fig. 1 VDM model. Essential vehicle and tire force variables for handling a full range of maneuvering conditions from nominal performance to limit performance conditions are defined in Fig. 3. Limit performance conditions are important to simulate stability conditions that result in vehicle skidding, spin out, and roll over. An overall block diagram for vehicle dynamics components associated with handling and stability is given in Fig. 4, and the component module requirements are discussed below.

**Lateral/Directional Dynamics**

Lateral/directional dynamics involve yawing, rolling, and lateral acceleration motions; and stability concerns include spin out and roll over. These dynamics are dominated by tire force response, which depends on lateral slip angle, camber angle, and normal load. Vehicle limit maneuvering can lead to tire force responses that result in vehicle spin out or roll over, so that a comprehensive tire model is important to adequately model stability problems.

Lateral acceleration results primarily from lateral forces that are generated at the tires. The tire forces can then be used to compute the vehicle's lateral speed and position. The directional dynamics result from a vehicle's yaw moment response, which is also computed based on the forces acting at the tires. These values are then used to compute the lateral slip angle of each tire, which in turn determines the lateral forces developed by the tire. This process is critical, because it is the tire forces acting at each axle that determine whether a vehicle will spin out during extreme operating conditions, and a dynamics model should be able to account for directional stability.

Rolling motion should be incorporated into the model to account for the dynamics of vehicle lateral load transfer and roll over. When a vehicle corners, the sprung mass rolls in the opposite direction of cornering (corner to the right, vehicle rolls left), thus shifting some of its weight between one side and the other. This weight shift increases or decreases the amount of normal force that occurs at each tire and ultimately the amount of force the tire is capable of producing. Rolling motions can cause the vehicle to go unstable and eventually roll over. When incorporating roll motions into the model, large angle equations must be considered, if limit roll-over cases are important.

**Longitudinal Dynamics**

Longitudinal dynamics involve the speed, longitudinal acceleration, and pitching motions of the vehicle and are dominated by tire forces that depend on longitudinal slip and normal load. Longitudinal dynamics may be used to account for engine and braking accelerations and for wheel lock-up due to excessive braking that can lead to lateral/directional stability problems, e.g., spin out or plow out.

Forward speed is an important operating condition for lateral/directional maneuvering scenarios and, in many applications, may be held constant. Depending on a given application, a longitudinal model may include: aerodynamic drag created by the vehicle shape and speed, the rolling drag caused by the tire/roadway interaction and speed, the longitudinal road slope, and the longitudinal forces that are generated by the tires. The tire forces will ultimately determine the ability of the vehicle to accelerate and decelerate based on their force-producing capacity. This will determine if the tire is rolling or locked. The drag terms will determine the maximum speed the vehicle can obtain and will also be necessary for correctly modeling vehicle coast down. Finally, road slope must also be correctly accounted for in order to model gravity effects on vehicle motions.

Pitching motion must be incorporated into the model to account for the vehicle shifting weight from the front to the rear and vice versa (longitudinal load transfer). When a vehicle accelerates or decelerates, the sprung mass pitches backward or forward, thus shifting some of its weight between the front and rear axles. This weight shift will increase or decrease the amount of normal load that occurs at each tire and, ultimately, the amount of longitudinal force the tire is capable of producing.

**Vertical (Heave) Dynamics**

In general, ground vehicles do not display a great deal of vertical motion. There are vertical dynamics effects that play a major part in vehicle handling, however. Vertical dynamics involve tire normal loads, vertical terrain inputs, and heaving motion due to the suspension between the sprung and unsprung masses. The response to terrain and tire normal loading are key aspects of the vertical dynamics.

The amount of normal load available at each tire is dependent on the stiffness of the tire and the amount the tire deflects when weight is applied to the tire. Since the tire normal force is a major contribution to the magnitudes of the longitudinal and lateral forces that the tire can produce, the calculation of the tire deflection is one of the more important aspects of the vertical dynamics. At a minimum, the normal-load computations should include

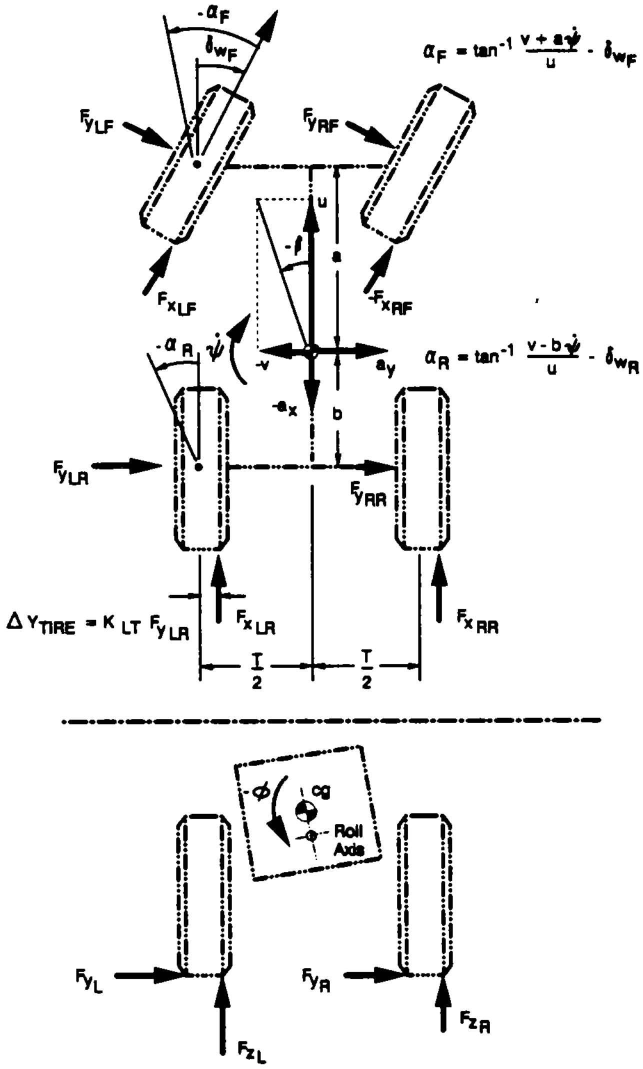



Figure 3. Vehicle and Tire Force Variables Necessary to Simulate Limit Performance Maneuvering

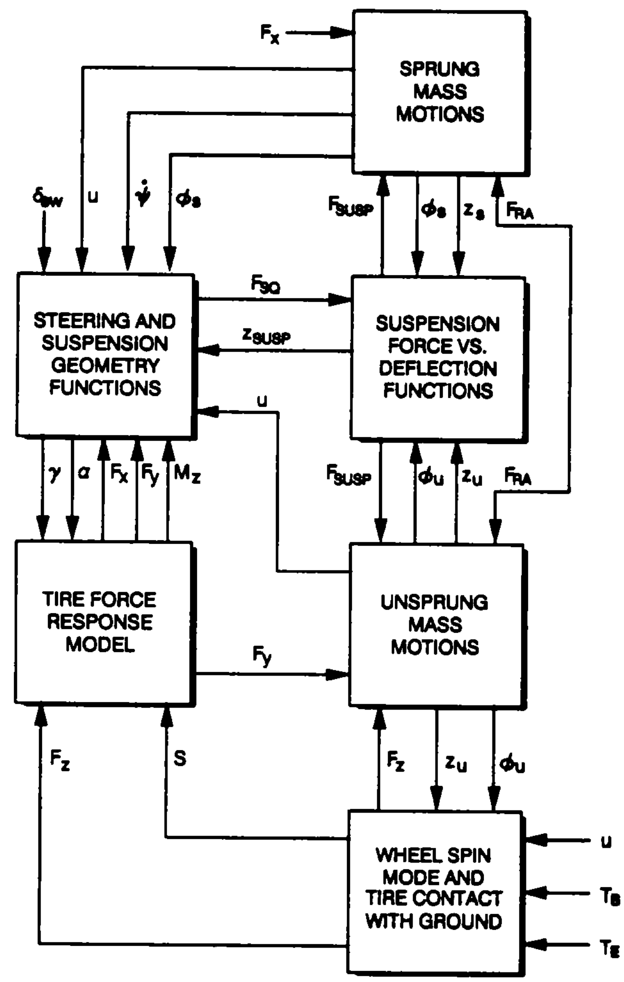



Figure 4. Vehicle Dynamics Components Necessary for Limit Performance Handling and Stability Analysis

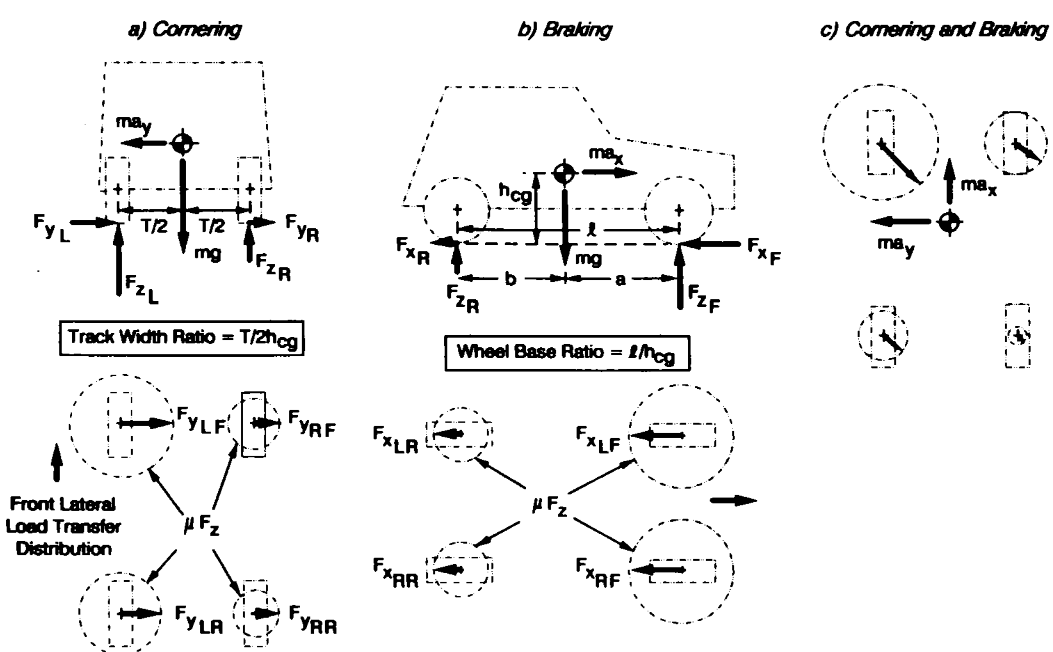



Figure 5. Maneuvering Effects on Tire Normal Loads

the pitch and roll of the vehicle, the positions from the sprung and unsprung masses, terrain undulations, and the tire spring rates.

Vertical terrain inputs affect the vehicle model both in terms of small undulations and general slope changes. The heave mode dynamics will affect the vertical positions of the sprung and unsprung masses and the tire defections. As the vehicle traverses the terrain, the sprung and unsprung masses will move relative to one another, causing the suspension to expand and compress and changing the suspension forces and damping. Therefore, heave dynamics modeling must incorporate suspension effects as discussed below.

### Suspension Dynamics

Suspension systems are used to isolate the vehicle's sprung mass from road irregularities to achieve acceptable ride quality and to control load transfer in order to maintain directional stability. The trick is to design the system so that the tires stay in contact with the roadway in such a way that the vehicle's motions in heave, pitch, and roll do not affect the directional control and stability of the vehicle.

Suspension dynamics are a complex part of the overall vehicle dynamics and are important, because they define how the sprung and unsprung masses react to one another as well as affecting tire dynamics and steering. Furthermore, the modeling of suspensions becomes even trickier because of the number of different suspension systems that are used. There are several suspension force mechanisms that may be included in any suspension model. They include: compliance, damping (shock absorbers), bump stops, auxiliary roll stiffness (anti roll bars), squat/lift effects (lateral and longitudinal force effects on suspension vertical deflection), roll steer, and tire camber angle. All of these mechanisms affect the vehicle's handling, especially during critical maneuvering.

The suspension model will determine the amount of pitching and rolling that the sprung mass generates relative to the unsprung mass. This will affect the load transfer to the tires, the forces the tires produce, and, ultimately, the stability of the vehicle. At limit conditions, this will also determine if the vehicle will roll over.

Additionally, the suspension model will affect the tire camber and steering. The tire camber angle generates additional side force and is directly related to the roll angle of the vehicle and the bounce of the tire due to the road and suspension. The vehicle's steering is affected because of the suspension linkages that are attached to the front wheels. As the suspension flexes, this may cause some additional steering angle to be produced by the wheels. These effects can influence vehicle understeer properties and, ultimately, lateral/directional handling and stability.

### Load Transfer

As referred to several times above, load transfer effects can be critical in modeling vehicle limit performance stability due to normal load effects on horizontal tire forces. As summarized in Fig. 5, maneuvering results in load transfer between the left and right sides and the front and rear of a vehicle. This load transfer is a reaction to the horizontal maneuvering accelerations. Load transfer affects vehicle directional stability because of the influence of normal load on tire-force response. Auxiliary roll stiffness is typically added at the front suspension in order to obtain desired understeer characteristics and to ensure that the front axle composite side force saturates before the rear axle in order to maintain limit performance directional stability (12).

It is possible to include load transfer as a quasi-steady state effect based on maneuvering acceleration (2). If the dynamic effects of maneuvering and vehicle response are important, then more complete models are required that include the dynamic effects of pitch and roll response, e.g., (12). Stability effects influenced by load transfer include directional and roll motions and rear axle lockup. When combined steering and braking maneuvers are considered, the full dynamics are almost certainly important to appropriate stability analysis.

## TIRE FORCES AND ROADWAY INTERACTION

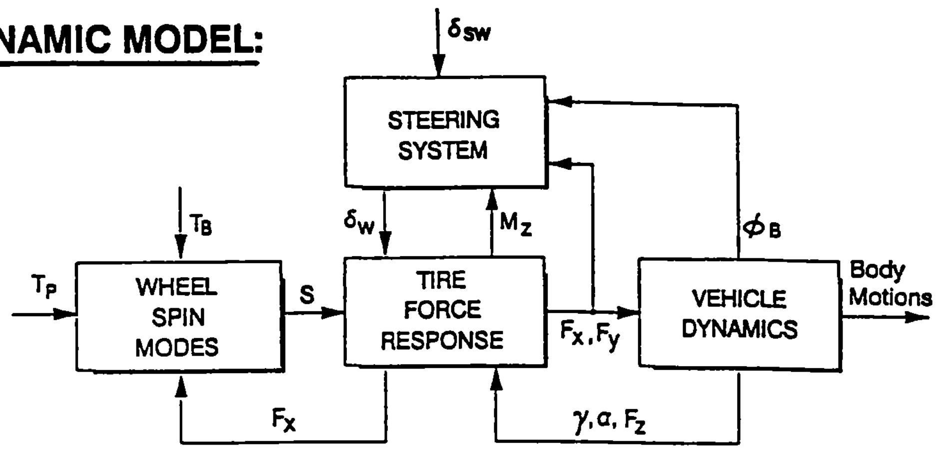
The objective of tire/roadway interaction is to provide a useful force-producing element for the simulation model. The most important part of any ground vehicle simulation dynamics are the forces that drive the vehicle. These forces are created at the tires. Forces due to lateral maneuvering and to longitudinal acceleration and braking are the predominant forces acting on a ground vehicle. In order to simulate the complete vehicle operational range, it is important to properly model maneuvering forces, including the interaction of longitudinal and lateral forces from small levels through saturation. Since the forces are generated at the tires, and are ultimately caused by the contact between the tire and the roadway, the interaction between the tire and the roadway surface must also be taken into account.

With this in mind, two different areas must be included for a complete model. They are: maneuvering force generation and the tire/roadway interaction.

### Maneuvering Force Generation

Tire forces interact intimately with vehicle dynamics as illustrated in Fig. 6. Side forces derive from lateral slip and camber angle and provide the main input to lateral/directional maneuvering. Longitudinal forces derive from longitudinal slip and interact with the tire/wheel spin mode. Longitudinal forces provide the main inputs for acceleration and braking and can lead to wheel spin and lockup under high-force development.

**DYNAMIC MODEL:**




**TIRE CHARACTERISTICS:**

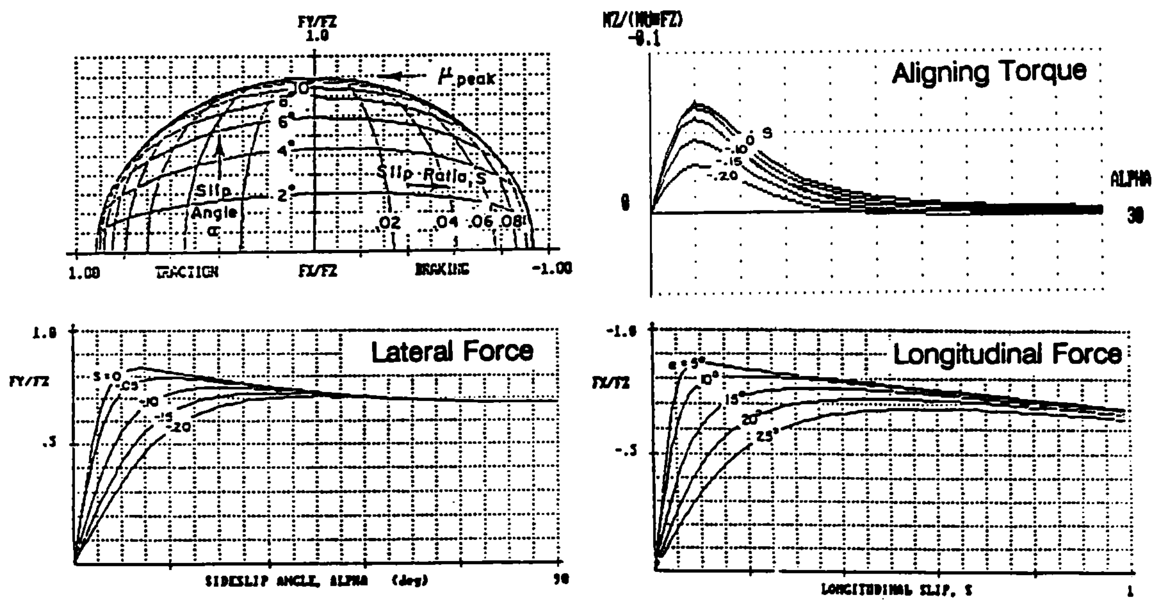



Figure 6. The Interaction of Tire Maneuvering Forces and Vehicle Dynamics

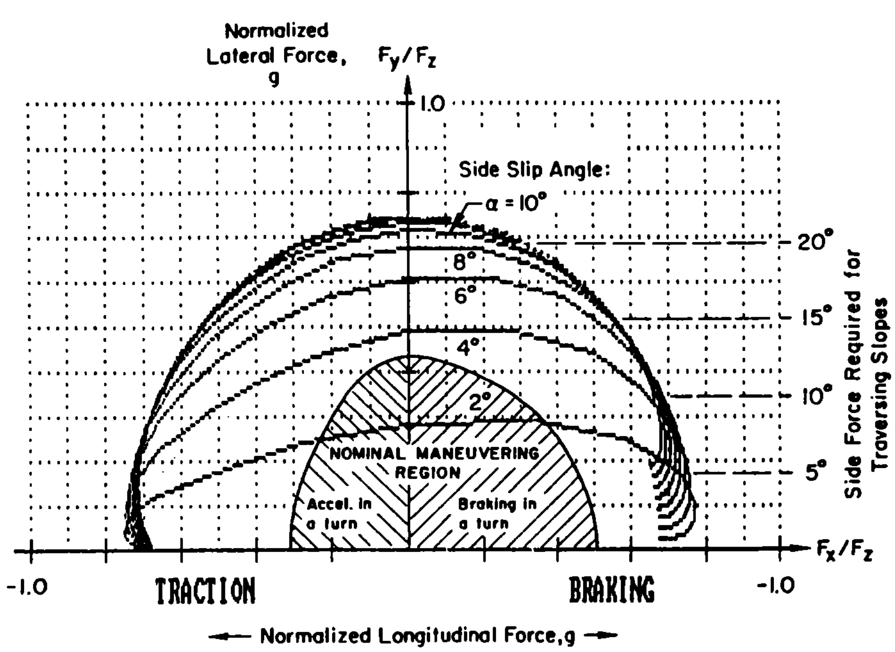



Figure 7. Maneuvering Effects on Tire Force Operating Conditions

Tire force can be modeled as simply as a linear coefficient in linear lateral/directional and longitudinal dynamics, e.g., (1,2). If aggressive maneuvering is at issue, however, and combined steering and braking characteristics are of concern, then the nonlinear saturation characteristics of tire-force production and the interaction between lateral and longitudinal forces become important, as suggested in Fig. 7. Here, the total composite tire force is limited by a friction ellipse, and the lateral and longitudinal forces interact significantly as the maneuvering approaches the saturation (high g) region.

In general, tire forces and moments are related to the magnitude of the tire's normal load, lateral and longitudinal slips, camber angle, and the surface coefficient of friction (13). The normal load will be determined by the weight of the vehicle and the amount of load transfer that occurs during maneuvering. In general, the larger the normal load, the more force producing capability the tire has. Therefore, in a complete model, it is very important that the vehicle dynamics model compute a realistic value for the normal load at each individual tire, as discussed above.

When the tires must be dealt with individually in a complete model, the inputs to the tires must also be computed for each individual tire. The longitudinal slip ratio and the tire sideslip angle are then used with each tire's normal load, coefficient of friction, and camber angle to compute the forces and moments. The basic interaction of the lateral and longitudinal forces can be modeled as a composite slip force expression, which can be modeled as a composite slip function operated upon by a saturation function (13). Composite slip refers to the vector combination of the longitudinal slip ratio and tire side slip angles into a single parameter that defines the current operating point of the tire. The composite slip parameter is then used in the composite force function to determine the combined forces that the tire produces, as indicated in Figs. 6 and 7.

A complete tire-force model should also account for the delay in force production that can result in a significant amount of delay in vehicle directional response (2). There is actually a dynamic delay involved in the tire's side force generation process. Basically, the tire must roll through some distance in order for the tire patch to fully develop a commanded input side slip. This tire force delay can amount to an appreciable portion of the vehicle lateral/directional maneuvering delay and thus may be an important effect for certain modeling efforts.

### Tire/Roadway Interaction

The tire/road coefficient of friction is a factor in determining tire maneuvering forces and can vary as a function of road surface, moisture, and cold-weather conditions resulting in snow and ice. There are two main friction coefficient properties that can be included in a complete model in order to correctly compute the tire forces. First, there is a peak friction coefficient that is a function of the tire's normal load that defines the maximum force output capacity of a tire. Typically, the maximum coefficient decreases with increasing normal load; and, since normal load changes with vehicle maneuvering, this effect should be included in models involving significant maneuvering. Second, the friction coefficient will decay at higher slip velocities to a slide value. This means that, as the vehicle approaches its performance limits, the friction coefficient will be reduced. This reduces the force-producing capabilities of the tires and contributes to wheel lockup and vehicle directional instability (2).

When a tire leaves the roadway and enters a non-paved roadside, some additional effects must be considered. On hard pavement, the only interaction is between the tire contact patch and the roadway surface; but, when a tire enters soft soil, there is a different interaction between the tire and soil shear properties (14). In this case, the tire actually digs into the soil, causing additional rolling drag, soil compression as a function of distance into the tire patch, and a change in coefficient of friction.

Tire interaction with the roadway vertical profile may also be important for certain classes of problems. Tires have an enveloping characteristic when encountering abrupt terrain undulations (e.g., curbs, potholes) that result in vertical and longitudinal force changes due to tire deflection, as illustrated in Fig. 8. This effect can be modeled with equivalent radial springs or by integrating pressure distribution over the terrain undulation.

## SUBSYSTEMS

In addition to the vehicle sprung and unsprung mass inertial dynamics and tire and aerodynamic force production, other vehicle subsystems have a significant effect on vehicle handling and stability and may be required in more complete models.

### Power and Drive Train

A fairly complete power and drive train is illustrated in Fig. 9. This model includes the engine, which produces torque as a function of throttle input and engine speed; a torque converter and transmission, which modify torque transmission; and the differentials and wheel spin modes. Models of this complexity are important to studying vehicle traction characteristics and traction control systems, two-wheel versus four-wheel drive, and the influence of drive-wheel traction on steering control.

### Steering

A reasonably complete steering system model is illustrated in Fig. 10. The steering system, including power boost, can have significant delay between steering-wheel deflection and front-wheel deflection. This delay is a function of the dynamics of the boost system and the basic mechanical response of the overall steering system. Steering compliance is also an important factor

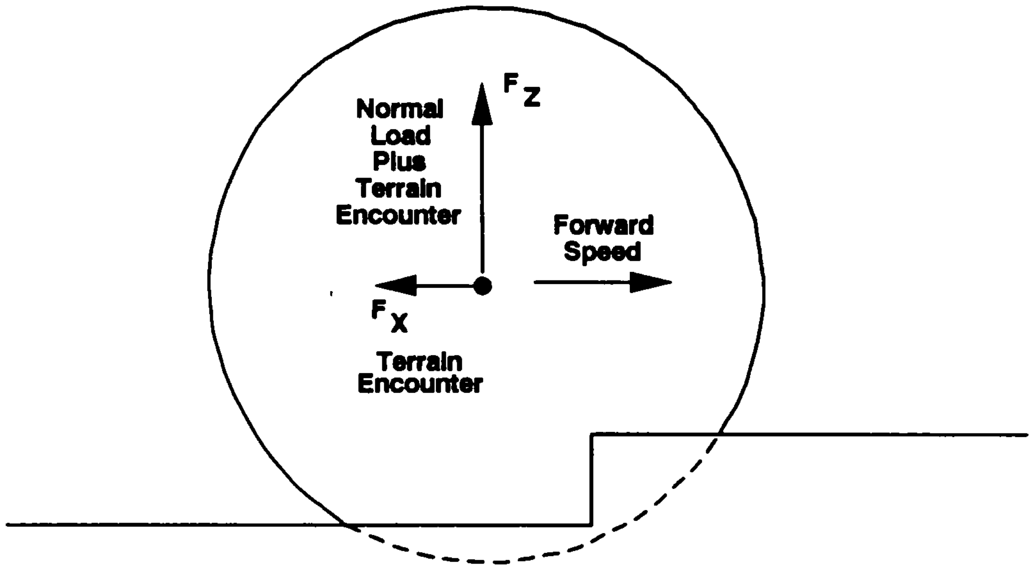



Figure 8. Tire Loads Due to Normal Load Plus Terrain Deflection

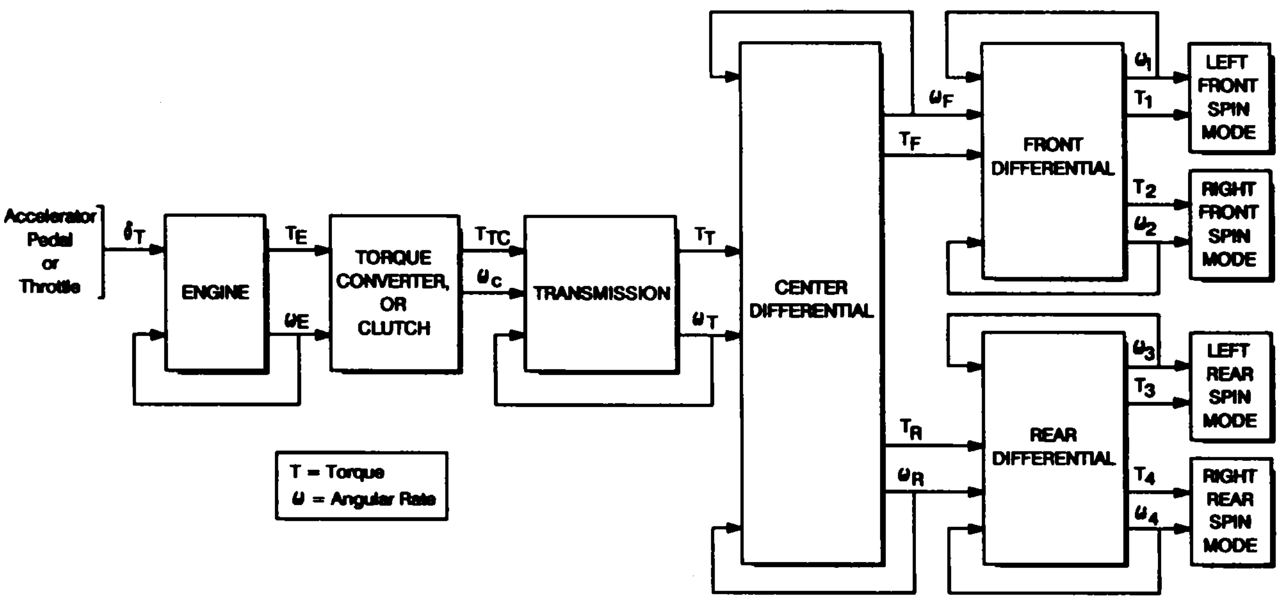



Figure 9. Power/Drive Train Components

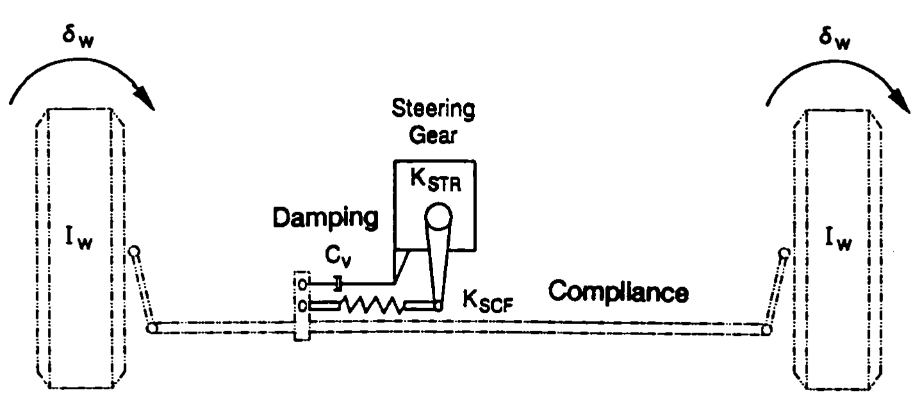



Figure 10. Steering System Mechanical Model

in vehicle understeer. The tire aligning moment (Fig. 6) acts on the steering compliance to straighten the wheels in a turn. The steady-state result of this effect is understeer that is proportional to steering compliance. Dynamically, steering compliance and the resulting understeer influence vehicle directional damping. At higher speeds with significant understeer, the vehicle steering response can be quite oscillatory.

### Brakes

A braking system model is illustrated in Fig. 11. The brake system can provide for power boost and pressure distribution to the front and rear axles. It is now common to have nonlinear proportioning valves that reduce pressure to the rear axle under hard braking conditions in order to minimize the chance of rear-axle lockup, which can precipitate vehicle spin out. Antilock systems further minimize the chance for wheel lockup by limiting brake pressure when wheel longitudinal slip exceeds a set value. The modeling of braking system characteristics is obviously important for the analysis of braking system characteristics, and it is also required when studying the influence of braking on hard steering maneuvers.

### Driver and Automatic Control

Driver and/or automatic control models are intended to exert steering, throttle, and brake commands based on feedback of vehicle motions, kinematic relationships in the visual field, and other system commands, such as obstacle avoidance. Driver and automatic control algorithms have been formulated for path control based on a "look ahead" error (2,15). Driver models for obstacle avoidance have also been developed and validated (16). Vehicle control models could be useful for evaluating vehicle crash avoidance potential and for developing Automated Highway Systems.

## MODEL INPUTS

Deriving the equations that will constitute the vehicle model is partially based on the type of inputs that will drive the model. The basic inertial equations will be the same no matter what inputs are used, but some additional dynamics will be required for certain inputs (steering, throttle, closed loop driver control, etc.). These inputs include: open-loop control of steering, throttle, braking, terrain, hazards, and driver inputs, such as path following, obstacle avoidance, curvature, and lane changes.

For many analyses, it may be desirable to provide open-loop control inputs to a model to evaluate basic vehicle response. These inputs may be designed to approximate driver steering and/or braking profiles that result in limit performance maneuvering conditions (12). Aerodynamic inputs can also be designed to approximate wind gusts, passing vehicles, etc. (21).

It may also be desirable to handle closed-loop inputs, such as path following (curvature and lane change) and obstacle avoidance. This approach requires driver or automatic control of the vehicle dynamics. The driver model includes various feedbacks to the driver. Using these feedbacks, the driver enters a steering wheel angle that will allow the vehicle to follow the desired path. By including a driver model, the response of the vehicle may be closer to that of a real vehicle.

Terrain model inputs may also be used in order to induce a vehicle model to traverse a roadway design and/or encounter vertical profiles. The inputs could include terrain profiles generated with CAD/CAM design programs. Because CAD/CAM surfaces are modeled with flat polygons, some smoothing of the terrain input is required to make it correspond to typical road-surface conditions as discussed below.

## SIMULATION SCENARIOS

Without a doubt, the most difficult aspect of vehicle dynamic modeling is (1) designing the model in such a way that it will be valid over a wide range of operating conditions and scenarios and (2) providing appropriate inputs for given scenarios. The operating conditions will be limited by the physics of the vehicle; and, if the mathematical equations are comprehensive enough, it should respond over the entire range of possible vehicle motion. This means that, on flat surfaces with no external influences, the model will react just like the real vehicle over the entire range of vehicle motion.

On the other hand, the scenarios are not quite that straight forward. There are an infinite number of driving scenarios that can be created. They can range from simple lane change maneuvers to complex roadway slopes with hazards on an icy road. Trying to develop a model that can handle every possible roadway and maneuvering scenario is one of the more difficult aspects of vehicle dynamic simulation. Therefore, care must be used when designing the abilities of the model to handle various scenarios.

Simple scenarios have been discussed previously in the section on model inputs. These scenarios deal with simply putting inputs into the vehicle and letting the vehicle respond. These are simple, because they deal with steering, throttle, and braking only and do not take into account any external influences. These scenarios will be much more complex by adding external influences, such as roadway hazards, roadway geometric design, and changing surface properties.

A critical implementation issue is the interfacing of a vehicle model with roadway design models. Several points must be considered in order for the interface to go smoothly. First, the roadway coordinates must be in a form that allows the vehicle model to determine the altitudes at each wheel, no matter where the wheels appear on the roadway. This is generally done by computing triangular or rectangular plates that represent

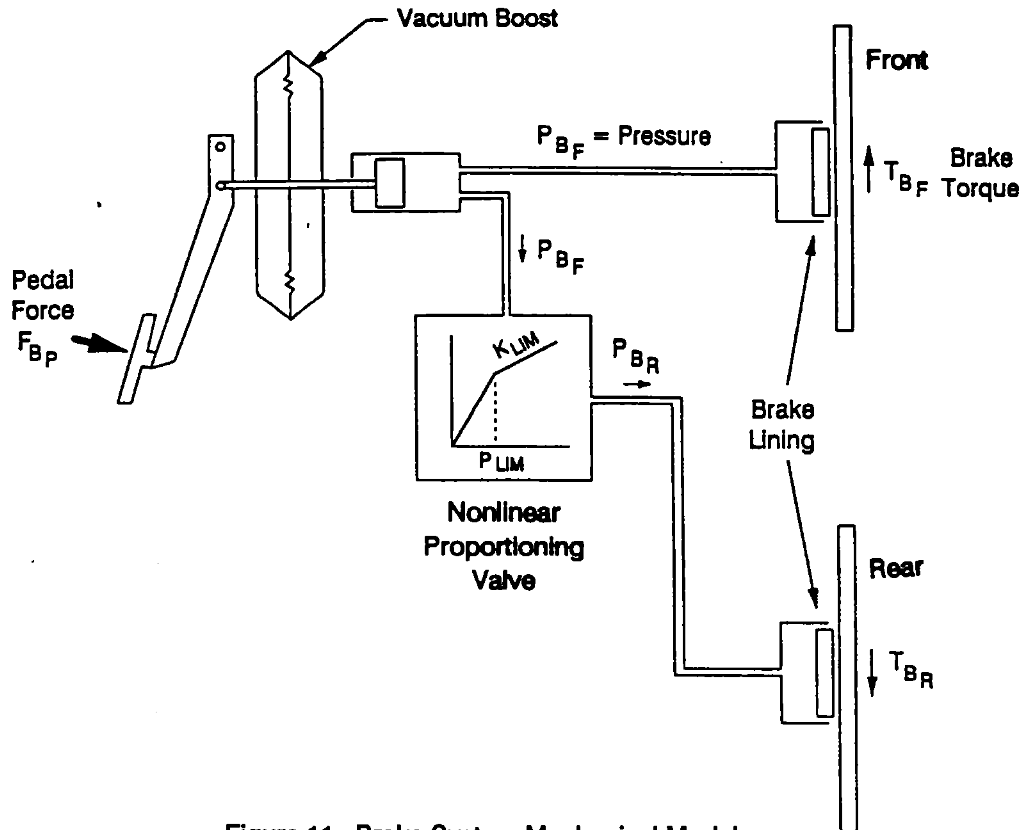



Figure 11. Brake System Mechanical Model

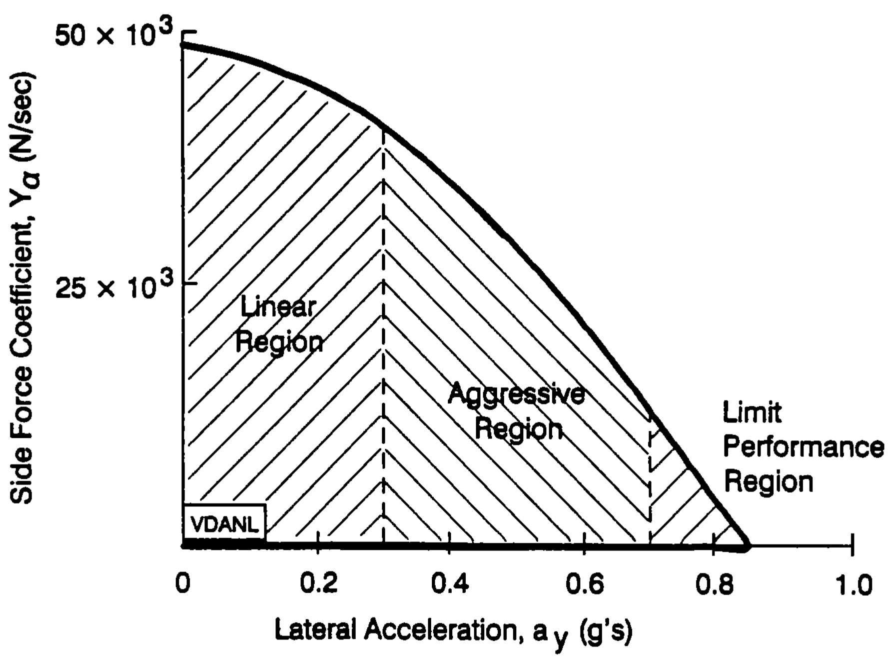



Figure 12. Composite Axle Side Force Coefficient as a Function of Maneuvering Acceleration

the roadway and then storing these coordinates. Second, since the vehicle model uses tire deflections to compute the tire normal loads and since CAD/CAM models typically represent terrain as a series of flat polygons, the vehicle model must use smoothing routines so that the transition from one plate to another is smooth, thus avoiding unrealistic stimulation of the vehicle suspension.

For roadway design applications, the road's surface properties must also be defined. These surface properties include the tire/roadway nominal friction coefficients, rolling drag coefficients, tire soil interaction coefficients, and delineated pathways that the driver should follow. It is conceivable that, as the vehicle follows a path, it could encounter a number of different road properties, such as wet areas, snow, and ice. There are also roadway hazards that should be considered, such as curbs, bumps, and holes that cannot be modeled adequately with roadway geometry. These considerations should be handled by some type of generic hazard scenario control module that can be used to specify desired simulation scenarios.

## VEHICLE CONFIGURATION AND MODEL PARAMETERS

An important aspect of vehicle dynamics modeling is the type of vehicle to be modeled. In the case of ground vehicles traveling over roadways, there is a wide range of vehicles that meet this criteria; thus, a flexible model must be able to account for most, if not all, classes and configurations of vehicles. These include the entire range of sedans (subcompacts to luxury models), light trucks (both two- and four-wheel drive), utility vehicles (full sized and compact, two- and four-wheel drive), and vans. These vehicles come in a variety of shapes and sizes, and the parameters that describe each vehicle will vary considerably. The most common vehicle is the passenger car.

The additional complexity of articulated vehicles may also be desirable. An example would be passenger vehicles towing trailers. Vehicle articulation adds additional dynamic modes and the jackknife instability condition. Articulated trucks add additional issues, because they have a higher center of gravity, are less directionally responsive, and have a tendency to roll over during cornering and other maneuvers. A vehicle dynamics model should be capable of modeling articulated trucks with multiple trailers in order to completely address highway safety issue. In general, the configuration of heavy trucks make them the worst-case scenario for severe maneuvering conditions.

One of the most critical issues for vehicle modeling is the model parameters describing the vehicle characteristics. Models should be flexible enough to accommodate different vehicles through simple parameter changes. The parameter sets should be as small as possible, however, and should be easily attainable. If parameters are difficult to obtain, or include parameters that cannot be measured, then it will be difficult to test all of the vehicles that may be of interest in future studies. A modest, identifiable parameter set should be the objective of all vehicle dynamics modeling efforts.

## APPLICATIONS AND VALIDATION

### Linear versus Nonlinear Modeling

Linear analysis models are of interest because of their simplicity relative to nonlinear models and because of the availability of formalized analysis procedures, such as transform and state-space methods, e.g., (18). A lateral/directional linear analysis model, including side slip and yaw and roll degrees of freedom, has been compared with the response of a full nonlinear model (2). In the linear model, tire side force response was modeled with a side force coefficient that can be adjusted to approximate maneuvering acceleration, as indicated in Fig. 12. As illustrated in Fig. 13, the transient responses of the two models match almost perfectly under low-g maneuvering; and even under high-g conditions when the tire side-force coefficient is set according to the maneuver (Fig. 12), the transient responses are still remarkably similar. This example would indicate that linear models can provide useful results over a wide range of conditions if applied appropriately.

### Simple Versus Complex Nonlinear Models

A rather complete nonlinear model with a relatively complex component suspension system has been developed for the study of vehicle dynamic stability and roll over (12). This complex model has been compared with a computationally simpler model developed for real-time applications that includes simple vertical wheel deflection to accommodate roll and pitch modes and load transfer in lieu of a complete suspension. Both VDMs used the same tire model (13). Transient responses resulting from a limit performance steering input are compared in Fig. 14. Here, we see that the yaw rate and the lateral acceleration response of the two models are quite similar. This would suggest that simplified models can be used for emergency and limit performance maneuvering situations. However, a comprehensive tire model would still seem to be important.

### Articulated Vehicle

The complex nonlinear model discussed above (12) was expanded to include a trailer. The trailer model included the same degrees of freedom as the tow vehicle with the constraint that the trailer tongue was pinned to a hitch at the rear of the tow vehicle about which it could yaw and roll. The dynamics of trailer towing have been well developed (19), and the trailer towing model was validated against this past analysis. Figure 15 shows tow vehicle and trailer transient responses as a function of speed and hitch load. The trailer swing mode damping decreases with hitch load and increasing speed as expected (19). These relationships are illustrated in

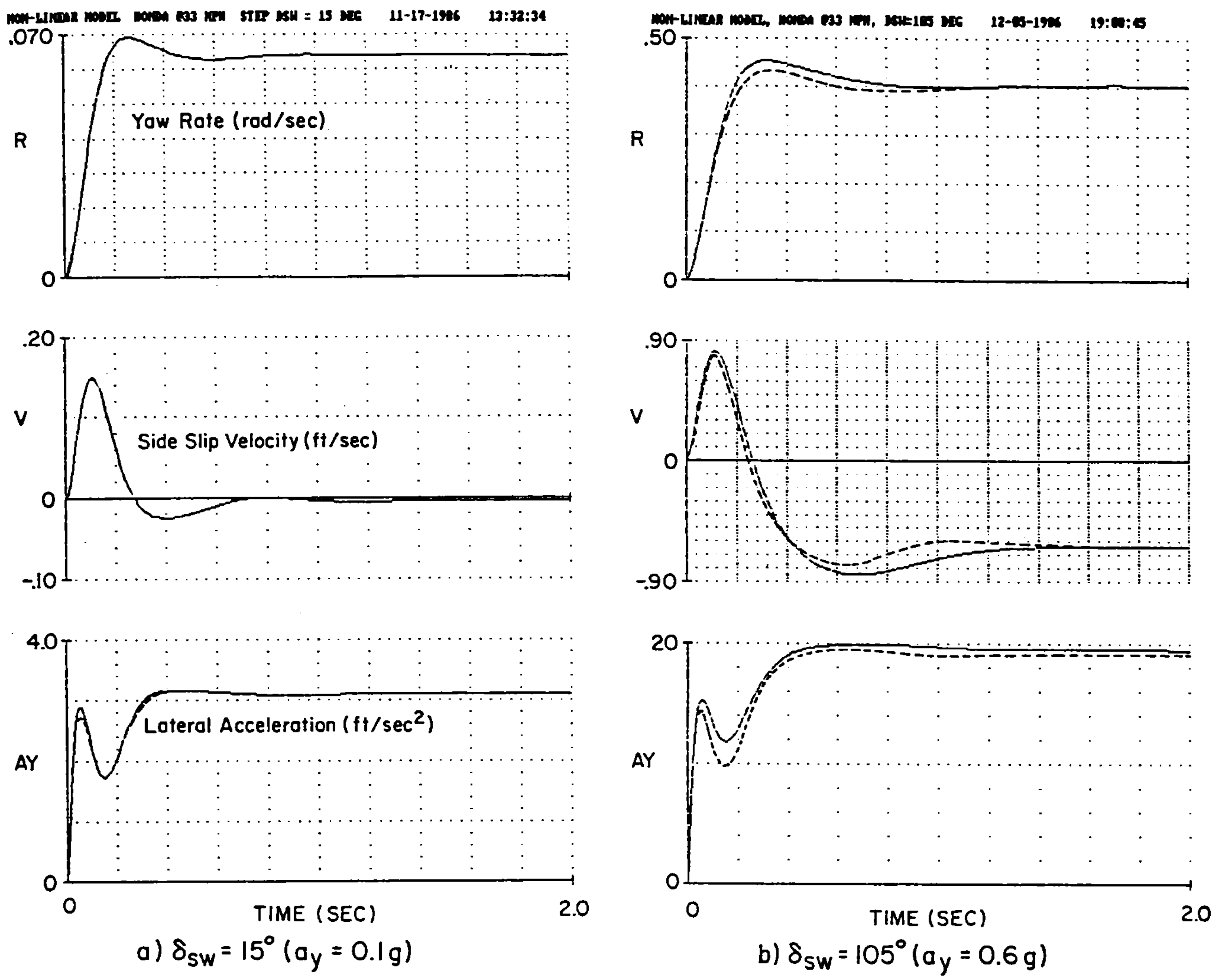



Figure 13. Transient Response Comparison Between Linear and Nonlinear Models

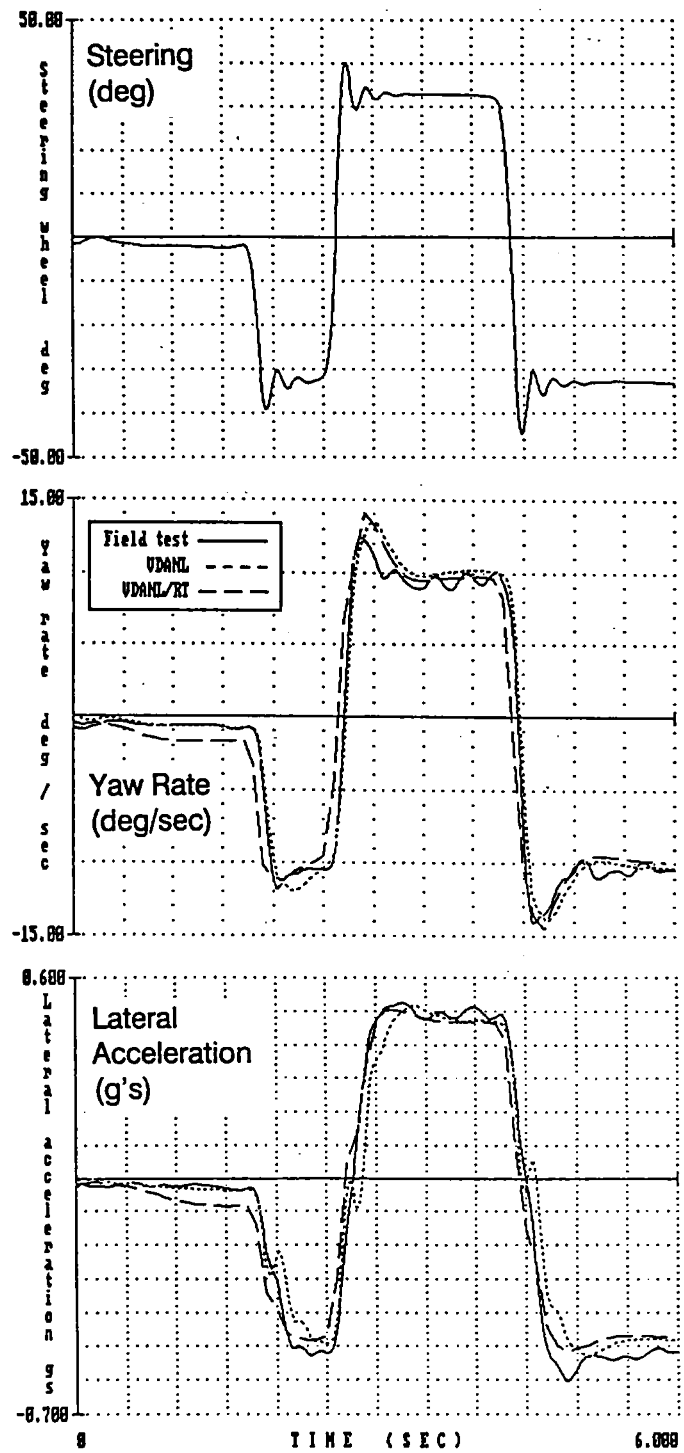



Figure 14. Transient Response Comparison of Field Test Data Against Simple (VDANL/RT) and Complex (VDANL) Nonlinear Models, Both Using the Same Tire Model

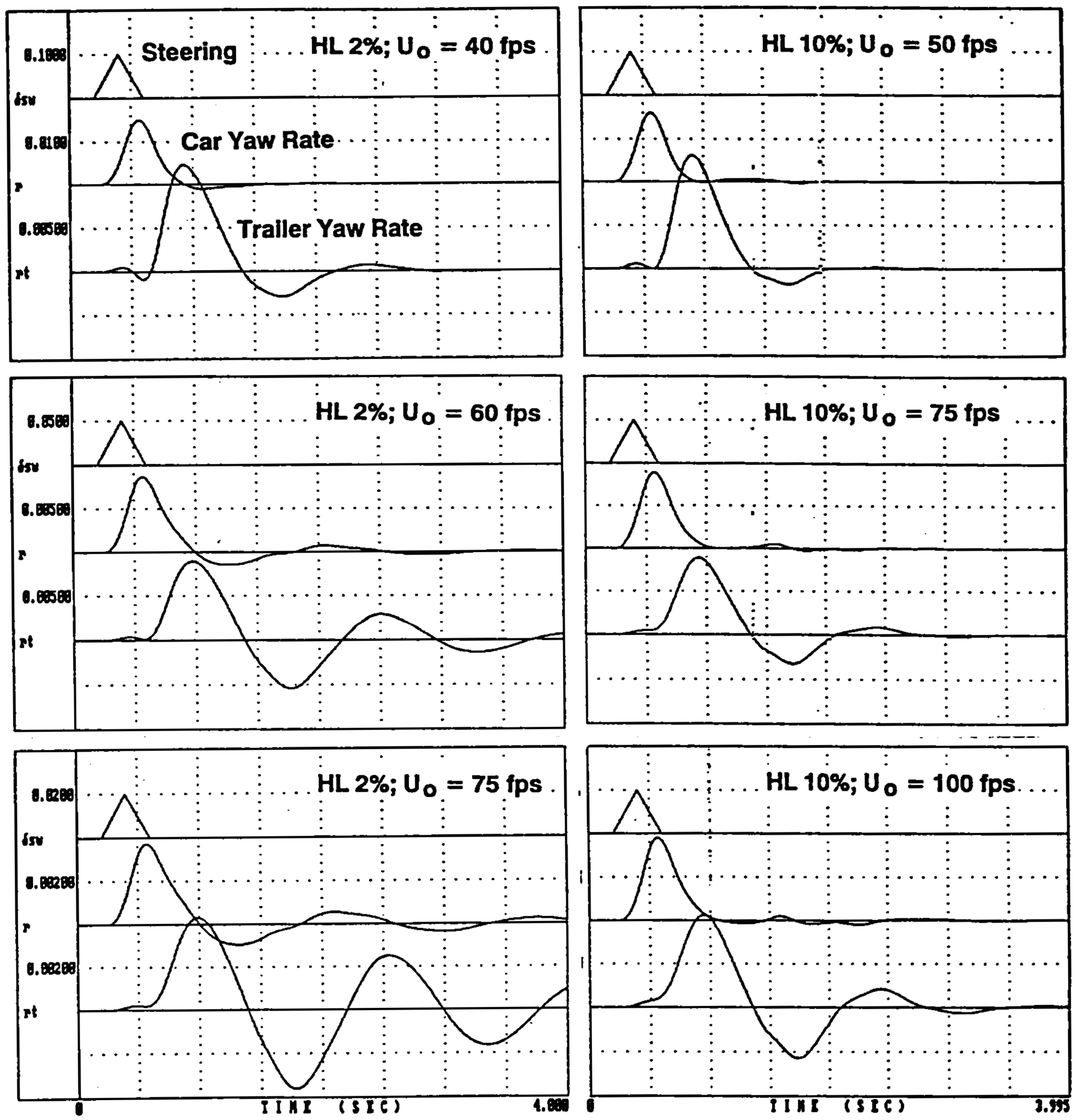



Figure 15. Car/Trailer Transient Responses at Several Combinations of Speed and Hitch Load

Fig. 16, where the nonlinear simulation results are compared with linear control theory analysis (19). This comparison points out the fact that linear analysis and simulation may be useful for some dynamic analysis applications. In cases where tire force saturation and trailer jackknife are of concern, however, nonlinear simulation would be required.

**Driver High Side Slip Steering**

Controlling a vehicle at high side-slip angle amounts to maintaining the directional mode in an unstable condition. This is illustrated in Fig. 17, which shows a vehicle cornering under low and high side-slip conditions and displays the required operating points on the tire lateral force versus slip angle curve. Under the high side-slip cornering condition, the rear axle is clearly operating in the region that results in directional instability (i.e., side force decreases with increasing slip angle) while countersteer brings the front axle into the normal steering region of the tire curve.

A complex driver model was developed to control a vehicle under high side-slip conditions, as illustrated in Fig. 18. This model operates in two modes:

1) Throttle input and feedback to break away the rear axle and capture the slip angle at a large slip operating condition
2) Steering control to maintain path position.

The model response is compared against field test data in Fig. 19. Here, we see that the model maintains the same operating condition as the field test driver, although the model operates quite smoothly, while the real driver exhibits a significant amount of stochastic variation.

The above example provides the highest degree of complexity of any considered here. Both the vehicle and the driver models are complex and nonlinear. Previously, the complex vehicle model response has been validated against field test data for spin out conditions (20). Here, we illustrate that a nonlinear driver model is capable of controlling a vehicle under unstable high side-slip conditions, which amounts to very experienced behavior. This degree of model complexity is required in order to operate and control a vehicle under unstable high side-slip conditions.

## CONCLUDING REMARKS

Vehicle dynamics simulation models have a wide variety of applications that result in a range of requirements and implementations. It is important to establish the requirements for a given application based on the vehicle response behavior that is of interest. The models can be linear or nonlinear and can range in complexity from simple transfer functions to very complex nonlinear equations. Nominal maneuvering dynamics can be modeled with relatively simple linear equations, while limit performance maneuvering requires more complex dynamics and a fairly complex, nonlinear tire model.

Complete vehicle dynamics model specification also involves consideration of parameter requirements and system command and disturbance inputs that are necessary to produce realistic operational scenarios. Parameter and input requirements can add significant complexity to an overall vehicle dynamics system simulation. When considering model complexity requirements significant attention should be devoted to minimizing the size of the parameter data base.

Applications for vehicle dynamics models will become more prevalent as efficient models are developed and validated. Current applications include computer simulations for stability and handling analysis, as well as real-time models for driver and hardware-in-the-loop simulations. Future applications may include computer-aided assessment of vehicle and roadway designs, automated vehicle control concepts, automated highway concepts, etc.

## NOMENCLATURE

**Subscripts**

| | |
|---|---|
| 1 | Left front |
| 2 | Right front |
| 3 | Left rear |
| 4 | Right rear |
| F | Front |
| LF | Left Front |
| LR | Left Rear |
| R | Rear or Right |
| RF | Right Front |
| RR | Right Rear |
| S | Sprung mass |
| U | Unsprung mass |
| UF | Unsprung mass Front |
| UR | Unsprung mass Rear |

**Variables**

| | |
|---|---|
| $a$ | Longitudinal distance from the vehicle's front axle to the center of gravity (ft) |
| $a_x$ | Longitudinal acceleration |
| $a_y$ | Lateral acceleration |
| $a_z$ | Vertical acceleration |
| $b$ | Longitudinal distance from the vehicle's rear axle to the center of gravity (ft) |
| $F_{RA}$ | Bushing force between the sprung and unsprung masses |

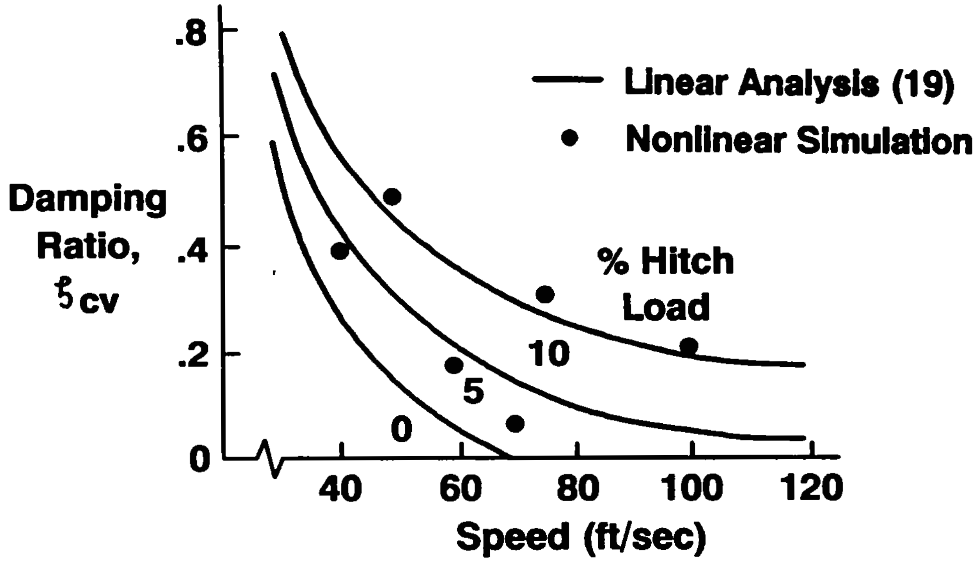



Figure 16. Trailer Mode Damping as a Function of Speed and Hitch Load

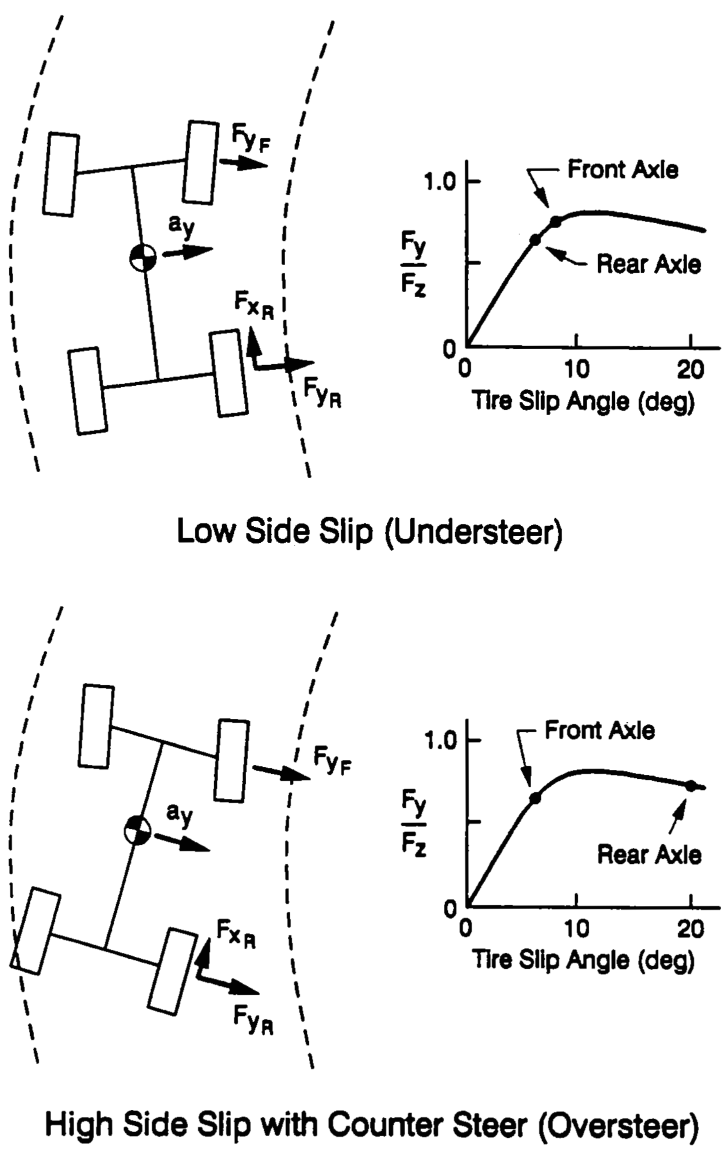
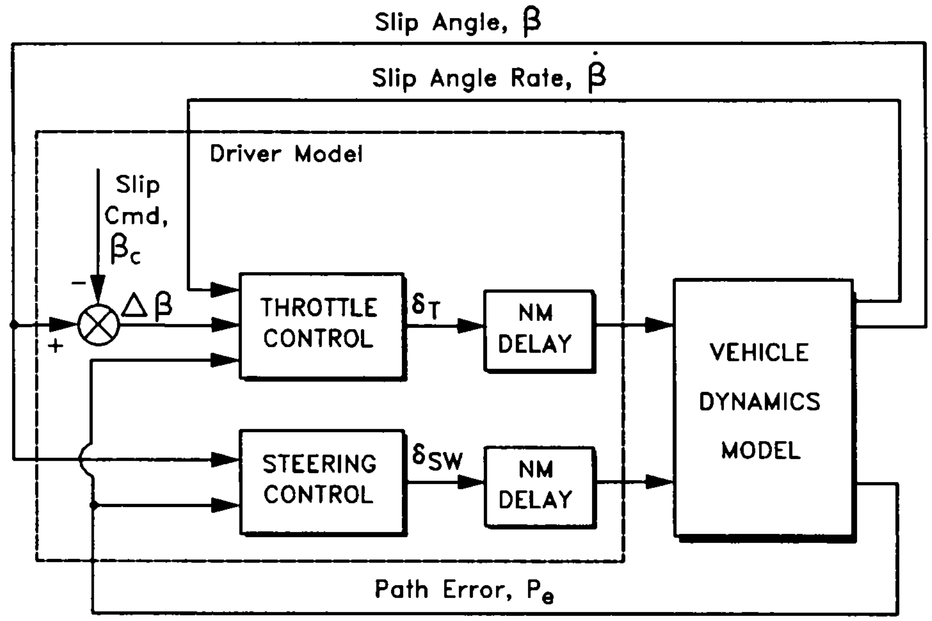



Figure 17. Vehicle Operating Conditions for Low and High Side-Slip Cornering




**Driver Control Laws**

$$\delta_T = K_1\left(T_\beta \Delta\beta + \int \Delta\beta dt\right) + K_2\dot{\beta} + K_T\left(T_L P_e + \int P_e dt\right)$$

- Use $\Delta\beta$, $\dot{\beta}$ phase plane for capture
- $P_e$ crossfeed helps keep path error small

$$\delta_{SW} = K_P\left(T_L P_e + \int P_e dt\right) + K_\beta \beta$$

- $\beta$ crossfeed maintains front axle slip angle at desired tire curve operating point

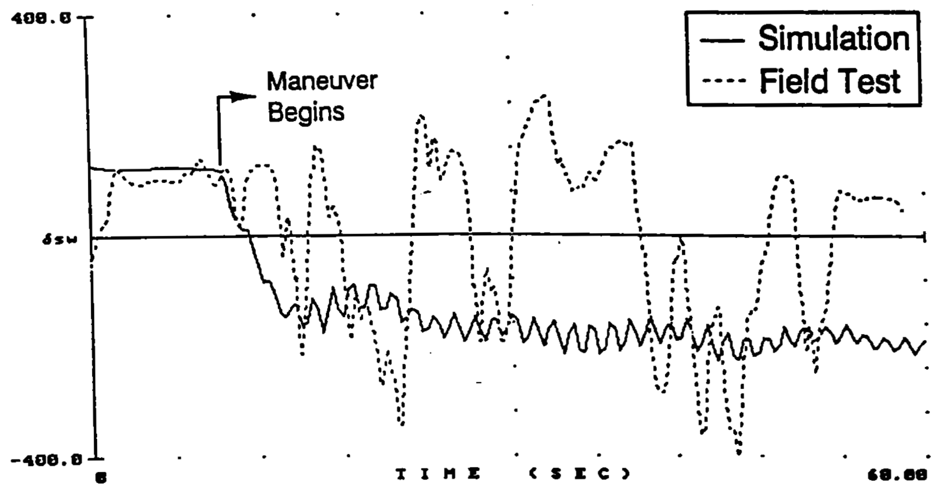
**Gain Scheduling**

- Reduce $K_1$ after first $\Delta\beta$ zero crossing
- Switching ON $K_2$ after first $\dot{\beta}$ zero crossing

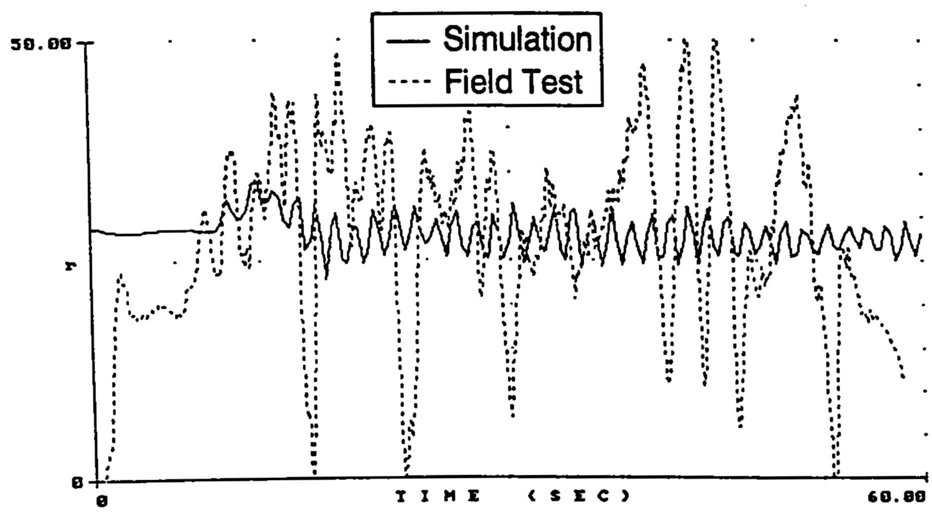
**Command**

- $\beta_c$ input initiates maneuver

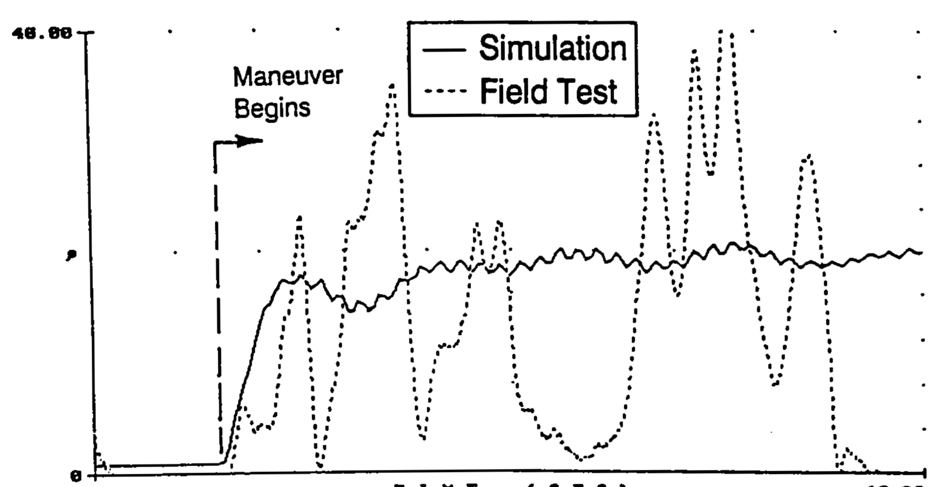
Figure 18. Nonlinear Driver Model Required for High Slip Maneuvering




a) Steering




b) Yaw Rate




c) Body Slip Angle

Figure 19. Driver/Vehicle Response During Steady-State High Slip (20 deg) Cornering

$F_{SQ}$ Squat/lift suspension forces acting on the sprung and unsprung masses

$F_{SUSP}$ Suspension forces acting on the sprung and unsprung masses

$F_X$ Longitudinal force generated at the tires

$F_Y$ Lateral force generated at the tires

$F_Z$ Vertical (normal) tire load

$I_{FW}$ Steer axis wheel inertia

$I_W$ Wheel rotational inertia

$K_{LT}$ Lateral compliance rate of tire, wheel, and suspension

m Body mass

$M_Z$ Tire aligning moment

p Roll rate

q Pitch rate

r Yaw rate

S Tire longitudinal slip ratio

T/2 Half of the vehicle's track width

T Torques

$T_B$ Brake torque

$T_E$ Engine torque

$T_F$ Drive-train torque that is sent from the center differential to the front axle

$T_P$ Drive-train power torque

$T_R$ Drive-train torque that is sent from the center differential to the rear axle

$T_T$ Torque produced by the transmission

$T_{TC}$ Torque exiting the torque converter

u Longitudinal velocity

v Lateral velocity

w Vertical velocity

x Longitudinal position

y Lateral position

z Vertical position

$Z_{SUSP}$ Suspension vertical deflections

$\alpha$ Tire slip angle

$\beta$ Vertical body slip angle

$\delta_{SW}$ Steering wheel angle

$\delta_W$ Front wheel steer angle

$\delta_T$ Throttle position

$\gamma$ Wheel camber angle

$\phi$ Roll angle

$\theta$ Pitch angle

$\omega$ Angular velocity

$\omega_c$ Torque converter angular velocity

$\omega_E$ Engine's angular velocity

$\omega_T$ Transmission angular velocity

$\psi$ Heading angle

$\dot{\psi}$ Yaw rate

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