EFFECT OF ROAD ROUGHNESS ON VEHICLE STEERING

B. E. Quinn, Purdue University; and
S. E. Hildebrand, International Harvester Company

The roughness of a pavement influences the steering behavior of a vehicle by producing variations in the normal forces between the tires and the pavement that in turn affect the lateral forces needed to control the vehicle. A simple mathematical model of a passenger car is used to compute the position of the car relative to a set of axes fixed in the pavement as the vehicle executes different maneuvers. Pavement roughness is introduced indirectly by using, as inputs to the model, the actual normal tire forces that were measured experimentally on a smooth and a rough pavement. For vehicle paths having large radii of curvature and for low vehicle velocities, the lateral forces required to control the vehicle are relatively small. Under these conditions pavement roughness is relatively unimportant. For vehicle paths having small radii of curvature and for high vehicle velocities, the required lateral forces can be quite high. Developing these forces may not be possible if the pavement is too rough, and this can cause loss of control of the vehicle. Such a condition may exist on a rough road when an overtaking vehicle changes lanes at a high velocity to pass a slower vehicle and then is suddenly forced to return to the original driving lane because of oncoming traffic. Safe vehicle handling can thus be adversely influenced by pavement roughness.

•MANY FACTORS influence the steering behavior of a vehicle. In designing the vehicle the manufacturer makes decisions relative to the length of the wheelbase, the steering linkage geometry, and other properties that influence the handling characteristics of the car. In addition, the tire manufacturer imparts certain properties to the tire that will greatly affect the steering characteristics. One such property, the cornering stiffness of the tire, is of considerable importance in the study of vehicle steering characteristics. Moreover, the driver can also influence the behavior of the vehicle by deciding how the vehicle is to be loaded. Different steering characteristics will be produced if a large proportion of the vehicle weight is on the rear tires than if the same proportion of weight is on the front tires. The characteristics of the pavement on which the vehicle is operated will also influence the handling of the vehicle. If the pavement is very slippery, it may be quite difficult to control the vehicle.

The property of the pavement of primary concern in this paper is that of the pavement roughness, which imparts a vertical motion to the vehicle tires and is independent of the slipperiness of the pavement. The task of providing a vehicle with safe handling characteristics is thus the responsibility of many groups. This paper is primarily concerned with pavement roughness as a factor influencing safe vehicle handling characteristics.

LATERAL TIRE FORCES

Lateral tire forces are needed to control the motion of a vehicle. These are the forces that act on the tread of the tire parallel to the surface of the road and at right angles to the wheel plane. Figure 1 shows a top view of a wheel moving in the direction

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shown by the arrow. It should be noted that the direction of motion is not parallel to the wheel plane but is rather at the angle α, which is indicated as the slip angle.

As a consequence of this motion, a lateral force is developed on the tire. This is a horizontal force exerted by the road on the tire perpendicular to the plane of the wheel for the motion as indicated. The magnitude of this force depends on the slip angle α and the normal force. In general this is a nonlinear relation.

Figure 1 does not show the normal tire force. This force would be acting on the bottom of the tire and is perpendicular to the plane of the paper.

The relation among the normal force, the lateral tire force, and the slip angle for a typical tire is shown in Figure 2 in which the lateral force is plotted as a function of normal force for various slip angles. Information of this type is obtained experimentally and is usually shown in the form of carpet plots (1) rather than as in Figure 2.

In obtaining the information shown in Figure 2, a flat surface representative of a pavement is used. A reasonable coefficient of friction exists between the tire and the flat surface. The effect of a slippery pavement would be to greatly reduce the lateral forces that can be developed for a given normal force and a given slip angle. In this paper it is assumed that slipperiness is not a factor in the behavior of the vehicle.

Of particular interest is the nonlinear relation shown in Figure 2. For a normal force of 1,000 lb and a slip angle of 6 deg, the corresponding lateral force is 760 lb. If the normal force is reduced by 300 lb, the lateral force is reduced by 160 lb. If, however, the normal force is increased by 300 lb, the lateral force is only increased by 140 lb.

This observation is of utmost importance because it means that, if the normal force fluctuates, the resulting average value of the lateral force for an average value of 1,000 lb will not be 760 lb but less.

Figure 2 shows the mechanism whereby pavement roughness influences the ability to control a vehicle. Pavement roughness causes variations in the normal tire force. On a relatively smooth pavement these variations are very small, but on a rough pavement these variations can be quite large. The net result as far as the lateral force is concerned is that there is a reduction in the average value of the lateral force available to control the vehicle. For those situations in which large lateral forces are necessary, this loss of force may mean loss of control of the vehicle.

The mechanism shown in Figure 2 is important for 2 reasons: It provides an explanation for the loss of lateral force when there is a variation in the normal tire force, and it provides a basis for defining the following 3 terms in a theoretical context.

1. Rough road is a road that causes a variation in the normal tire forces (and consequently a variation in the lateral forces).
2. Road having no roughness is a road that does not cause any variation in the normal tire forces (the normal tire forces are always equal to the static wheel loads) but that has a coefficient of friction such that the lateral forces shown in Figure 2 can be developed.
3. Slippery road is a road having a low coefficient of friction such that the lateral forces shown in Figure 2 cannot be developed.

From a practical viewpoint a road having no roughness does not exist, but this concept is useful in theoretical studies.

PREDICTING VEHICLE BEHAVIOR

The problem of predicting vehicle-handling characteristics has been of great concern to the automotive industry. Not only normal steering characteristics but also problems dealing with instability have been studied. Milliken (2), Bundorf (3), and many others have done research in this area. Various mathematical techniques have been developed, and mathematical vehicle models of varying degrees of complexity have been employed.

In this investigation a very simple model of the vehicle, known as the bicycle model (4), was employed. In this model, shown in Figure 3, the 2 front wheels of an automobile have been replaced by a single wheel and the 2 rear wheels have also been replaced

Figure 1. Tire slip angle.

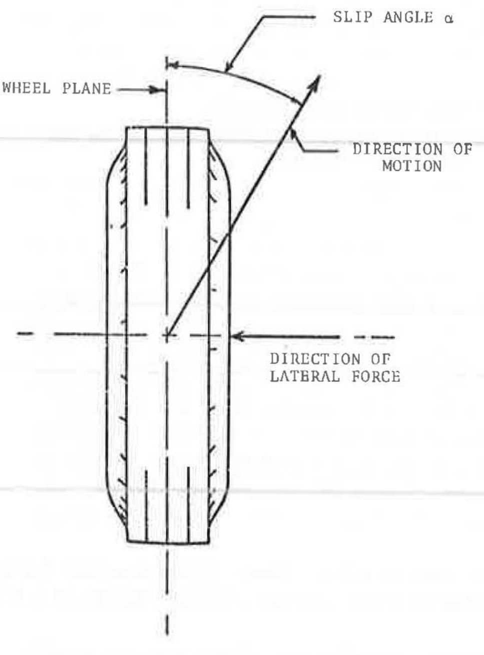


Figure 2. Tire force characteristics.

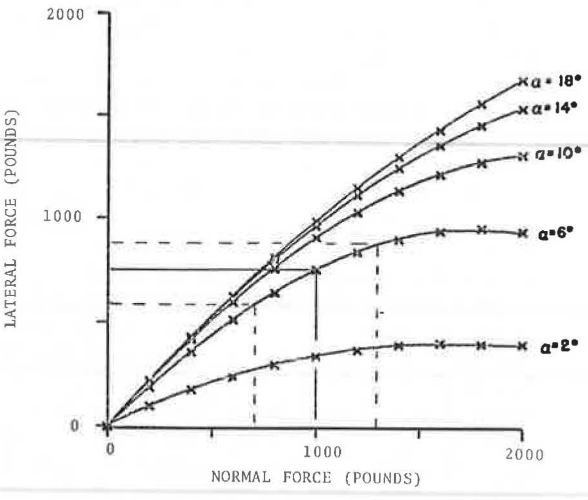
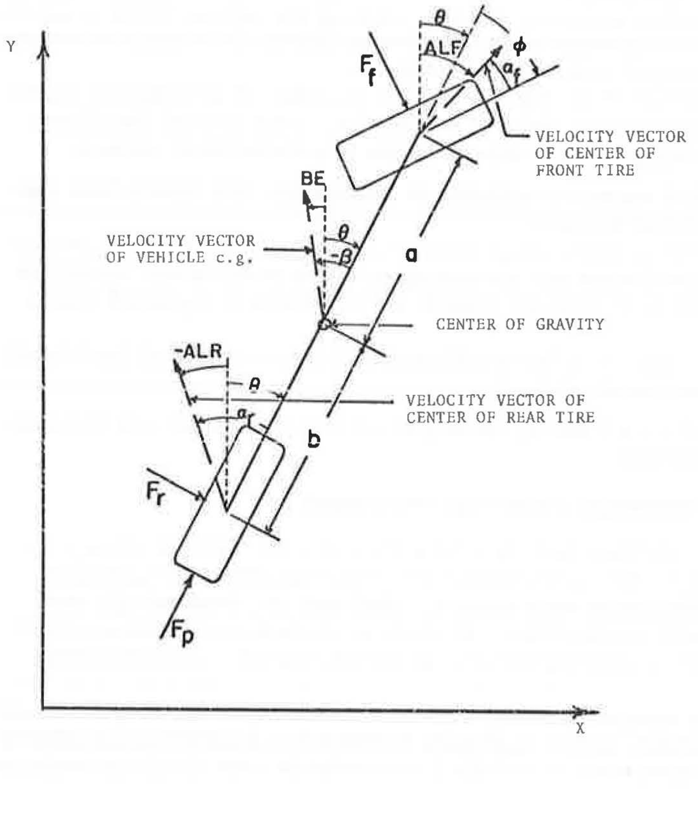


Figure 3. Bicycle model of automobile.



by a single wheel. The single front tire is therefore assumed to have the property of the 2 front tires on the actual vehicle, and the single rear tire is assumed to have the properties of the 2 rear tires.

In this model the wheelbase is the same as in the actual vehicle. The same weight is used, and the fore and aft location of the center of gravity is the same as in the prototype vehicle. In addition, the mass moment of inertia about a vertical axis through the center of gravity and perpendicular to the plane of the paper (Fig. 3) is assumed to be the same as that of the actual vehicle.

The use of this model immediately imposes limitations on the quantities that can be considered. Using this simple model makes it impossible to include the effect of pitching of the vehicle or to consider any of the riding qualities.

Moreover, no rolling of the actual automobile can be considered, and thus the transfer of load from the inner to the outer wheels cannot be introduced in a model of this simplicity. In brief, the effects of the suspension system of the vehicle cannot be taken into account with this model as it is normally employed.

This model does permit a consideration of yaw (rotation about an axis perpendicular to the paper as shown in Figure 3). In addition it is possible to consider the x and y locations of the center of gravity of the model relative to a set of X and Y axes that are always fixed in the pavement. It is possible to compute the coordinates of the path of the center of gravity of the vehicle and to compute the angular position of the vehicle relative to the axes. In brief, the motion of the vehicle as seen from above can be approximated by using this technique.

The derivation of the equations necessary for making these calculations is given in the Appendix.

The question may be asked as to how the effect of pavement roughness can be introduced when such a simple model is employed, particularly since it is impossible to introduce a road profile into the calculations because neither the springs nor the shock absorbers of the suspension system are included.

In this investigation the effect of road roughness was introduced in the following manner. The dynamic tire forces (normal forces) were measured experimentally by using an actual passenger vehicle operated over both a rough and a smooth road at various speeds. These normal tire forces were obtained as time-varying quantities.

The equations given in the Appendix were solved numerically by using time as the independent variable. The time was increased by small increments, and at each interval of time it was necessary to obtain values for the lateral forces at the front and back wheels. Because the normal tire forces were available as functions of time, it was possible to obtain values for these forces from the available records. Having these normal forces and knowing the slip angles, it was then possible to compute the corresponding lateral forces from the tire characteristics shown in Figure 2. The x and y coordinates of the center of gravity and the corresponding angular position θ of the vehicle were then computed. In all cases the vehicle speed was maintained at a constant value during the maneuver.

The smooth road used in this investigation had a BPR roughometer rating of 62 in./mile, and the rough road had a BPR roughometer rating of 122 in./mile.

EFFECTS OF PAVEMENT ROUGHNESS

To summarize the effects of pavement roughness on the steering properties of a vehicle is difficult. This is because the resulting motion of a vehicle can be quite complex, and no simple criteria are available for discussing whether the vehicle has satisfactorily executed a particular maneuver. Because of this difficulty, results are depicted in different ways in an attempt to describe the effect of pavement roughness on the vehicle-handling characteristics.

Step-Steer Input

One way of evaluating vehicle steering behavior is to subject the vehicle to identical steering conditions for pavements having different amounts of roughness. Accordingly, the steer angle of the vehicle (see Appendix) was suddenly increased at x = 0, y = 0, and

Figure 6. Effect of roughness on vehicle path at 30 mph.

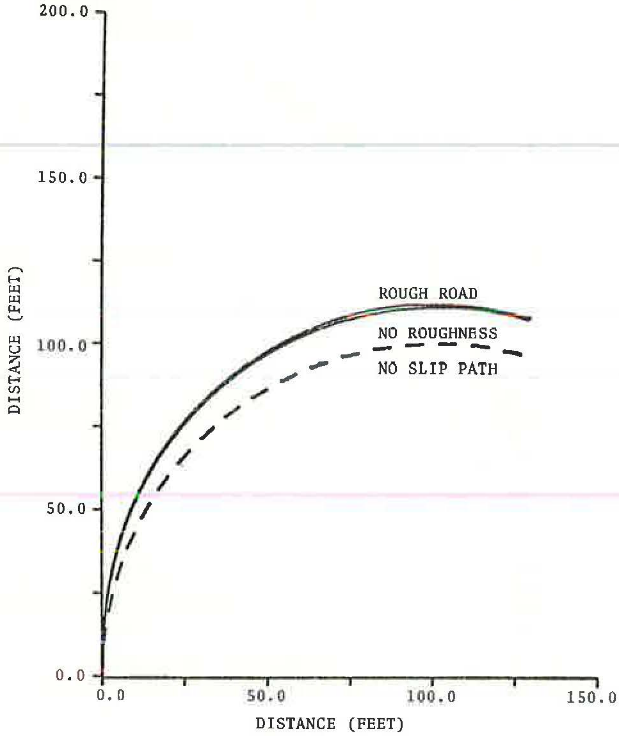
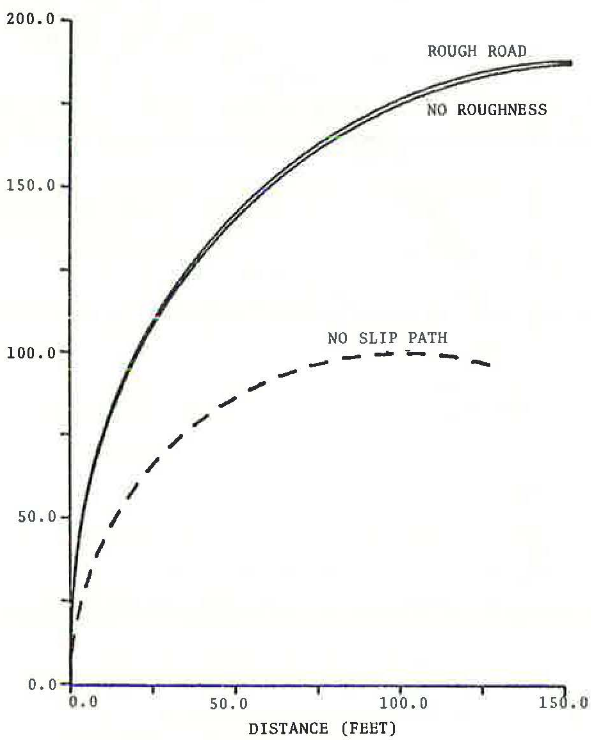


Figure 7. Effect of roughness on vehicle path at 50 mph.



Lane-Change Maneuver

In the previous figures, a constant steer angle was used to control the vehicle. At this point a different approach is taken. In the work that follows, the path that the vehicle is to travel is specified, and the steer angles necessary to accomplish this maneuver are computed together with the associated sideslip angles. This is a more complex condition and requires a modification of the techniques used for solving the equations given in the Appendix. These details will be omitted, however, in the interest of brevity.

If a path is selected for a vehicle to follow, there will be a theoretical relation between the steer angle and the position of the vehicle on the path. If the vehicle moves at very low velocities and the steer angle is varied in the theoretical fashion, the center of gravity of the vehicle will follow the desired path. As the speed of the vehicle is increased, it is necessary to change the steer angle at different points along the path in order to develop the necessary lateral forces to keep the vehicle moving in the desired path. Under certain circumstances, it is possible that no value of the steer angle will produce lateral forces sufficient to control the vehicle in the desired manner. When this point is reached, it is assumed in this investigation that control of the vehicle has been lost, and the calculations are not continued beyond this point.

The sideslip angle is another criterion for evaluating the behavior of a vehicle during a maneuver. As shown in Figure 3, this is the angle between the centerline of the vehicle and the velocity of the center of gravity. When this angle is equal to 0 deg, the vehicle is pointed in the direction that the center of gravity is moving; when this angle is equal to 90 deg, the vehicle is sliding sideways. Figure 5 shows a situation in which the sideslip angle becomes excessive.

For the maneuvers shown in Figures 8 and 9, the sideslip angles are compared with those that would exist if these maneuvers were executed at very low velocities.

Consider the lane-change maneuver shown in Figure 8. This occurs when a vehicle overtakes a slower moving vehicle and swings out in the adjacent lane to pass. The following equation was used to describe the desired path:

$$y = A \tan^{-1} (x/B)$$

where

x = x coordinate of path, ft; and
y = y coordinate of path, ft.

The constants A and B can be varied to change the severity of the maneuver. For this analysis, A was set equal to 4 ft and B was set equal to 30 ft.

The broken-line curves shown in Figure 9 indicate the values for the steer angle and the sideslip angle that are required for the vehicle to follow the path shown in Figure 8 at a very low velocity and with no variation in the normal tire forces (no pavement roughness).

When this maneuver is executed at 30 mph on the smooth pavement section, the required steer angles and sideslip angles are virtually identical to those obtained for a very low velocity and no pavement roughness.

When the rough pavement section is considered, the associated steer angles and sideslip angles are indicated by the solid lines shown in Figure 9. At 30 mph on the rough pavement, there is virtually no difficulty encountered in executing the passing maneuver. The same can be said, of course, for the smooth pavement.

Ninety-Degree Turn

Another common maneuver required in highway driving is that of going around a turn of changing radius. The desired path is shown in Figure 10 and is described by the following equation:

$$y = k/x$$

Figure 11. Ninety-degree turn on smooth road at 30 mph.

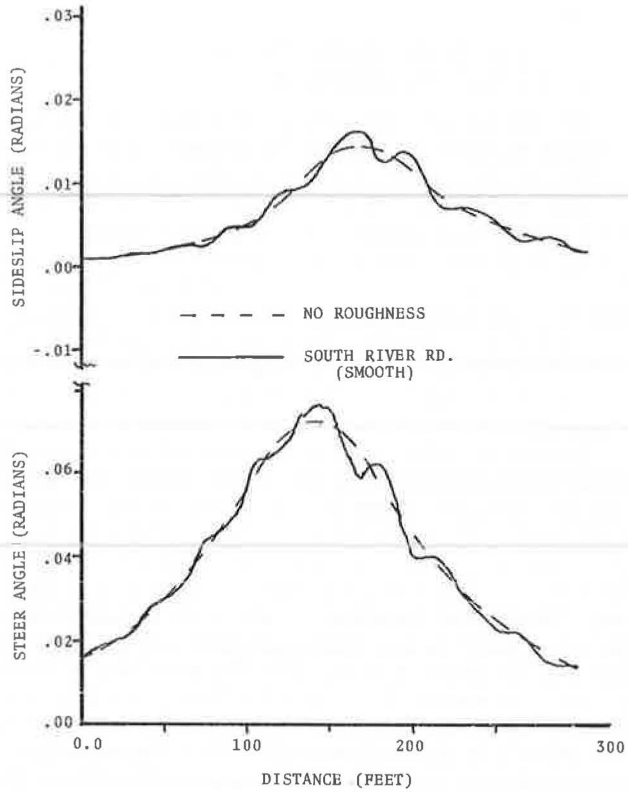
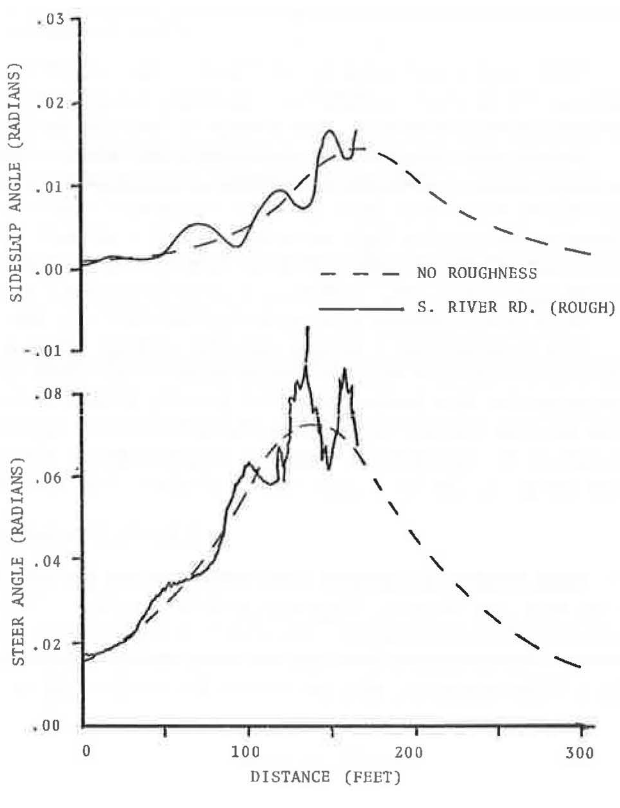


Figure 12. Ninety-degree turn on rough road at 30 mph.



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APPENDIX

DERIVATION OF MATHEMATICAL MODEL OF VEHICLE FOR STEP-STEER INPUT

Figure 3 shows the bicycle model of an automobile and the forces acting upon it in the x-y plane. The position of the vehicle is described by the x and y coordinates of the center of gravity, and the orientation of the vehicle is described by the absolute angular rotation θ. The variables shown in Figure 3 are defined as follows:

a = distance from vehicle center of gravity to front tire;
b = distance from vehicle center of gravity to rear tire;
F_f = front tire lateral force;
F_r = rear tire lateral force;
F_p = rear tire propulsion force;
x = abscissa of vehicle center of gravity;
y = ordinate of vehicle center of gravity;
θ = angle between +y axis and vehicle centerline measured clockwise;
ϕ = steer angle measured clockwise from vehicle centerline to centerline of front tire;
ALF = angle measured clockwise between +y axis and velocity vector of front tire;
ALR = angle measured clockwise between +y axis and velocity vector of rear tire;
α_f = front tire slip angle;
α_r = rear tire slip angle;
BE = angle measured clockwise between +y axis and velocity vector of vehicle center of gravity; and
β = vehicle sideslip angle.

Because the position of the center of gravity of the vehicle is determined by the coordinates x and y and the angular orientation of the vehicle is determined by the angle θ, then

$\dot{x}$ = velocity of vehicle center of gravity in +x direction,
$\dot{y}$ = velocity of vehicle center of gravity in +y direction, and
$\dot{\theta}$ = angular velocity of vehicle.

Let

$\dot{x}_f$ = velocity of front tire in +x direction, and
$\dot{y}_f$ = velocity of front tire in +y direction.

From examination of Figure 3,

$$\dot{x}_f = \dot{x} + a\,\dot{\theta}\cos(\theta)$$
$$\dot{y}_f = \dot{y} - a\,\dot{\theta}\sin(\theta)$$

Also,

$$ALF = \tan^{-1}(\dot{x}_f/\dot{y}_f) \tag{1}$$

Therefore,

$$ALF = \tan^{-1}\left[\frac{\dot{x} + a\,\dot{\theta}\cos(\theta)}{\dot{y} - a\,\dot{\theta}\sin(\theta)}\right] \tag{2}$$

Similarly,

$$ALR = \tan^{-1}\left[\frac{\dot{x} - b\,\dot{\theta}\cos(\theta)}{\dot{y} + b\,\dot{\theta}\sin(\theta)}\right] \tag{3}$$

Also,

$$BE = \tan^{-1}(\dot{x}/\dot{y}) \tag{4}$$

The sum of the forces acting on the vehicle in the +x direction equals the product of the mass of the vehicle and the component of acceleration of the vehicle center of gravity in the +x direction.

$$\Sigma F_x = M\,\ddot{x} \tag{5}$$

or

$$F_f\cos(\theta + \phi) + F_r\cos(\theta) + F_p\sin(\theta) = M\,\ddot{x} \tag{6}$$

The sum of the forces acting on the vehicle in the +y direction equals the product of the mass of the vehicle and the component of acceleration of the vehicle center of gravity in the +y direction.

$$\Sigma F_y = M\,\ddot{y} \tag{7}$$

or

$$-F_f\sin(\theta + \phi) - F_r\sin(\theta) + F_p\cos(\theta) = M\,\ddot{y} \tag{8}$$

The sum of the moments acting on the vehicle about the center of gravity equals the product of the moment of inertia of the vehicle and its angular acceleration.

$$\Sigma M_{c.g} = I\,\ddot{\theta} \tag{9}$$

or

$$a\,F_f\cos(\phi) - b\,F_r = I\,\ddot{\theta} \tag{10}$$

In order for the vehicle to move at constant speed, the acceleration of the center of gravity of the vehicle in the direction of the velocity vector of the center of gravity must equal 0. For this to be true, the sum of the forces acting on the vehicle in this direction must equal 0.

$$F_p\cos(\beta) - F_r\sin(-\beta) - F_f\sin(\phi - \beta) = 0 \tag{11}$$

$$F_p = \frac{F_r \sin(-\beta) + F_f \sin(\phi - \beta)}{\cos(\beta)} \tag{12}$$

The lateral tire forces F_f and F_r are determined from α_f, α_r, and the normal tire forces by using the tire characteristics as shown in Figure 2. Because each tire used in this model replaced 2 tires on an actual vehicle, it is necessary to double the lateral tire force obtained from the tire characteristic curves.

The tire slip angles α_f and α_r can be determined as follows (Fig. 3):

$$\alpha_f = \theta + \phi - \mathrm{ALF} \tag{13}$$

$$\alpha_r = \theta - \mathrm{ALR} \tag{14}$$

Because of the nonlinearities involved in these equations, a numerical technique was used to obtain a solution.

Various numerical methods for solving equations of this type are available (5), and further details of solution are omitted in this paper.