Side Friction for Superelevation on Horizontal Curves

Appendices A - G
Volume III

C. C. MacAdam
P. S. Fancher
L. Segel

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   The basic objective of this study has been to address the issue of how  
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   focused on this and related questions by combining computer analysis and  
   full-scale vehicle testing. Simple-to-use models for predicting the fric-  
   tion factor requirements at individual wheel locations were first  
   developed and applied to the steady-turning condition. An existing com-  
   prehensive computer model used for predicting transient or nonsteady  
   maneuvering situations was also employed to analyze friction demand while  
   maneuvering along superelevated curves. Highway tests were then performed  
   for two passenger cars and a five-axle tractor-semitrailer to collect repre-  
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Appendix A

STEADY TURNING MODEL EQUATIONS: TWO-AXLE VEHICLE

The equations presented here represent the steady turning motion of a two-axle vehicle moving along a circular path while resting upon a road surface which contains both superelevation and grade. The two-axle vehicle model is described by four degrees of freedom for the sprung mass element (vehicle body): roll, pitch, yaw, and bounce. Front and rear unsprung mass elements (suspension masses) are also represented but are located at a fixed height above the road plane (no vertical tire compliance). Solution of the model equations produces the steady state values for vehicle sideslip velocity, roll angle, pitch angle, vertical bounce, front wheel steer angle, and tire drive thrust required for traversing a curve of specified geometry at a given speed. The six equations describing the model are three force equilibrium equations and three moment equilibrium equations applied to the vehicle with respect to a body axis system whose origin is located along the vehicle centerline at a distance $d_f$ aft of the front axle. All rotations and displacements of the sprung mass are with respect to a static reference condition defined by the vehicle at rest on a horizontal plane which is normal to the gravity vector. Normal SAE sign conventions apply [7].

The next section of this appendix contains a list of definitions for symbols appearing in the equations which are then presented in the final section. The equations are in the form $A x = b$, where $A$ is a 6 by 6 matrix, and $b$ is a 6 by 1 vector. Each of these two arrays contains various vehicle and highway geometric parameters. The 6 by 1 solution vector, $x$, is obtained by computing the matrix inverse of $A$ and multiplying it by the $b$ vector:

$$x = A^{-1} b$$

A two- or three-stage iterative solution is required since a few terms in the $A$ and $b$ arrays contain components of $x$ as weak nonconstant influences. The
six elements of \( x \) are the solution quantities noted above and are also defined in the following nomenclature listing. The first three model equations represent force equilibrium conditions acting in the longitudinal, lateral, and vertical directions. The last three model equations represent moment equilibrium conditions about the roll, pitch, and yaw axes.

Lastly, equations defining the lateral and vertical tire forces, suspension forces, and friction factors at each wheel location are included.

**Nomenclature**

- \( C_{af} \) front tire cornering stiffness \((<0)\)
- \( C_{ar} \) rear \((<0)\)
- \( C_D \) aerodynamic drag coefficient
- \( C_{LO} \) lift coefficient at trim pitch angle \((p = p_r)\)
- \( C_r \) rolling resistance percentage / 100
- \( d_f \) distance from front axle to vehicle body-axis origin \((\text{arbitrary})\)
- \( d_r \) rear \((L - d_f)\)
- \( e \) highway superelevation
- \( F_{XTf} \) front tire traction force, \( x(6) \)
- \( F_{XTr} \) rear tire traction force
- \( g \) acceleration of gravity
- \( h \) height above ground of sprung mass c.g.
- \( h_A \) height above ground of the aerodynamic center of pressure
- \( h_r \) arbitrary height above ground of reference axis system origin
- \( K_f \) front suspension stiffness
- \( K_r \) rear
- \( L \) vehicle wheelbase
- \( m_s \) mass of sprung weight \((\text{body})\)
- \( m_{uf} \) front unsprung mass
- \( m_{ur} \) rear
\begin{align*}
N_{sf} & \quad \text{front static axle load} \\
N_{sr} & \quad \text{rear} \\
p & \quad \text{vehicle sprung mass pitch angle relative to the horizontal plane normal to the gravity vector, } x(4) \\
p_r & \quad \text{highway grade} \\
q & \quad \text{aerodynamic force } = \left[ \left( \text{density of air} \right) \left( \text{reference area} \right) U^2 / 2 \right] \\
R & \quad \text{highway curve radius} \\
s_L & \quad \text{slope of aerodynamic lift coefficient with respect to pitch} \\
s_Y & \quad \text{slope of aerodynamic side force with respect to sideslip angle} \\
T_F & \quad \text{front suspension spread} \\
T_R & \quad \text{rear} \\
T_{Tf} & \quad \text{front tire track} \\
T_{Tr} & \quad \text{rear} \\
U & \quad \text{vehicle speed} \\
v & \quad \text{vehicle sideslip velocity at the body-axis origin, } x(1) \\
W_T & \quad \text{total vehicle weight} \\
X_A & \quad \text{distance of aerodynamic center of pressure ahead of body-axis origin} \\
X_C & \quad \text{distance of sprung mass center ahead of body-axis origin} \\
z & \quad \text{vehicle sprung mass displacement normal to the road surface (relative to the static reference condition), } x(2) \\
z_f & \quad \text{height above ground of front suspension roll center} \\
z_r & \quad \text{rear} \\
\delta_{FW} & \quad \text{vehicle front wheel steer angle, } x(5) \\
\theta & \quad \text{vehicle sprung mass roll angle relative to the horizontal plane normal to the gravity vector, } x(3) 
\end{align*}
Two-Axle Model Equations: $Ax = b$

\[
A = \begin{bmatrix}
U W_T / (R g) & 0 & 0 & 0 & 0 & 2 \\
[2(C_{af} + C_{ar})] & 0 & 0 & 0 & -2C_{af} & 2\partial FW \\
-q S_y I / U & 0 & 0 & 0 & 0 & 0 \\
0 & -2(K_f + K_r) & 2(C_{ar} d_r - C_{af} d_f)/R & 2(d_r K_f + U^2 W_T / (R g) - d_r K_r) & -2(C_{af} + C_{ar}) v/U & +q S_L \\
2(C_{ar} (z_f - h_r) + C_{af} (z_r - h_r))/U & 0 & -T_r^2 K_f/2 -N_{ar}(z_r - h_r) & 0 & -2C_{af} (z_f - h_r) & 2\partial FW (z_f - h_r) \\
U(m_3 (h_r - h) + m_{ur} (h_r - z_r) + m_{ur} (h_r - z_r)/R & 2(C_{ard_f} - C_{ard'_f})^2 /R & m_3 g (h_r - h_r) + m_{ur} g (z_r - h_r) & 0 & -2(z_r - h_r) \\
+2(\partial FW (z_r - z_r) & -d_r m_{ur} / R & -2d_r^2 K_r - N_{ar} (z_r - h_r) & +2(C_{ard_f} - C_{ard'_f}) v/U & -N_{af} (z_r - h_r) & +q S_L \\
-2C_{ard_f} & 2\partial FW & 0 & 2\partial FW (z_f - z_r) & -2C_{ard'_f} & 2d_r \partial FW \\
2(C_{af} d_f - C_{ar} d_r)/U & 2\partial FW & 0 & 2\partial FW (z_f - z_r) & -2C_{af} d_f & 2d_r \partial FW \\
\end{bmatrix}
\]

\[
\mathbf{x} = [v, z, \theta, p, \partial FW, F_{XT}]^T
\]
The boldface terms, \( \mathbf{v} \) and \( \mathbf{a}_{FW} \), appearing in the \( \mathbf{A} \) and \( \mathbf{b} \) arrays represent the \( x \) components contributing to weak nonlinear terms.
Lateral Tire Forces

Front Tires: \[ F_{Yf} = C_{af}(\alpha_f) \]
\[ = C_{af} \left( \frac{v}{U} + d_f/R - \delta_{FW} \right) \]

Rear Tires: \[ F_{Yr} = C_{ar}(\alpha_f) \]
\[ = C_{ar} \left( \frac{v}{U} - d_r/R \right) \]

Front Suspension Forces

Left Side: \[ F_{sfL} = [-T_F(\theta - e)/2 - d_f(p - p_r) + z]K_f \]

Right Side: \[ F_{sfR} = [T_F(\theta - e)/2 - d_f(p - p_r) + z]K_f \]

Rear Suspension Forces

Left Side: \[ F_{srL} = [-T_R(\theta - e)/2 + d_r(p - p_r) + z]K_r \]

Right Side: \[ F_{srR} = [T_R(\theta - e)/2 + d_r(p - p_r) + z]K_r \]

Front Vertical Tire Forces

Left Side: \[ F_{zfL} = N_{sf}/2 + (F_{sfL} + F_{sfR})/2 - T_F(F_{sfR} - F_{sfL})/(2TT_f) \]
\[ + F_{Yf} z_f / TT_f \]

Right Side: \[ F_{zfR} = N_{sf}/2 + (F_{sfL} + F_{sfR})/2 + T_F(F_{sfR} - F_{sfL})/(2TT_f) \]
\[ - F_{Yf} z_f / TT_f \]

Rear Vertical Tire Forces

Left Side: \[ F_{zrL} = N_{sr}/2 + (F_{srL} + F_{srR})/2 - T_R(F_{srR} - F_{srL})/(2TT_r) \]
\[ + F_{Yr} z_r / TT_r \]

Right Side: \[ F_{zrR} = N_{sr}/2 + (F_{srL} + F_{srR})/2 + T_R(F_{srR} - F_{srL})/(2TT_r) \]
\[ - F_{Yr} z_r / TT_r \]
Friction Factors

Front Left Side: \( ff_1 = \frac{F_{yL}}{F_{zL}} \)
Front Right Side: \( ff_2 = \frac{F_{yR}}{F_{zR}} \)
Rear Left Side: \( ff_3 = \frac{F_{yL}}{F_{zL}} \)
Rear Right Side: \( ff_4 = \frac{F_{yR}}{F_{zR}} \)
Appendix B

STEADY TURNING MODEL EQUATIONS: TRACTOR-SEMITRAILER

The equations presented in this appendix represent the steady turning motion of a multiple axle tractor-semitrailer moving along a circular path while resting upon a road surface which contains both superelevation and grade. In this model, the semitrailer and rear end of the tractor are treated as a single unit (full-trailer) with articulation acting as the "steer" angle for the full-trailer. Following solution of the full-trailer steady turning equations, the front wheel steer angle of the tractor is solved with the requirement that the tractor front axle tire forces support and counterbalance its share of the centripetal force deriving from the tractor sprung and unsprung masses during steady turning motion. The vehicle model is described by four degrees of freedom for the sprung mass element (semitrailer body): roll, pitch, yaw, and bounce. Tractor and semitrailer unsprung mass elements (suspension masses) are also represented but are located at a fixed height above the road plane (no vertical tire compliance). Solution of the model equations produces the steady state values for semitrailer sideslip velocity, roll angle, pitch angle, vertical bounce, articulation angle, and tractor tire drive thrust required for traversing a curve of specified geometry at a given speed. The six equations describing the model are three force equilibrium equations and three moment equilibrium equations applied to the vehicle with respect to a body axis system whose origin is located along the trailer centerline at a distance \( d_f \) aft of the tractor rear suspension centerline. All rotations and displacements of the trailer sprung mass are with respect to a static reference condition defined by the vehicle at rest on a horizontal plane which is normal to the gravity vector. Normal SAE sign conventions apply [7].

The tractor front axle lateral tire forces, steer angle, and sideslip angle are obtained from the required yaw moment equilibrium condition about the kingpin, the calculated articulation angle, and the specified turning conditions. The tractor sprung mass is assumed constrained to the semitrailer for roll motions. The tractor pitch angle is calculated as equal to the semitrailer pitch angle, modified by pitch moment effects deriving from centripetal forces during
turning. The tractor sprung mass vertical position is the vertical displacement of the tractor sprung mass c.g. relative to the kinpin and due only to tractor pitch angle.

The next section contains a list of definitions for symbols appearing in the equations which are then presented in the final section. The equations are in the form $A \mathbf{x} = \mathbf{b}$, where $A$ is a 6 by 6 matrix, and $\mathbf{b}$ is a 6 by 1 vector. Each of these two arrays contains various vehicle and highway geometric parameters. The 6 by 1 solution vector, $\mathbf{x}$, is obtained by computing the matrix inverse of $A$ and multiplying it by the $\mathbf{b}$ vector:

$$\mathbf{x} = A^{-1} \mathbf{b}$$

A two- or three-stage iterative solution is required since a few terms in the $A$ and $\mathbf{b}$ arrays contain components of $\mathbf{x}$ as weak non-constant influences. The six elements of $\mathbf{x}$ are the solution quantities noted above and are also defined in the following nomenclature listing. The first three model equations represent force equilibrium conditions acting in the longitudinal, lateral, and vertical directions of the trailer. The last three model equations represent moment equilibrium conditions about the roll, pitch, and yaw axes of the trailer.

Lastly, equations defining the lateral and vertical tire forces, suspension forces, and friction factors at each wheel location are included. Expressions for calculating the tractor steer angle, sideslip, pitch angle, and vertical bounce are also shown.

**Nomenclature**

- $b_T$: distance from tractor sprung mass c.g. to rear suspension centerline (set at 0.8 $L_T$)
- $C_{a1}$: tractor front tire cornering stiffness ($<0$)
- $C_{aj}$: tractor rear tire cornering stiffness ($<0$)
- $C_{ak}$: semitrailer rear ($<0$)
- CD: aerodynamic drag coefficient
CLO aerodynamic lift coefficient at trim pitch angle \((p = pr)\)

\(C_r\) rolling resistance percentage \(/ 100\)

\(d_f\) distance from semitrailer kinpin to semitrailer body-axis origin (arbitrary)

\(d_r\) rear suspension centerline to \((L - d_f)\)

\(d_j\) distance from tractor rear axle \(j\) to semitrailer body-axis origin

\(d_r\) semitrailer rear axle \(k\) to \(L\)

\(e\) highway superelevation

\(F_{pz}\) static semitrailer kingpin load applied to tractor

\(F_{xtf}\) tractor rear tire traction force, \(x(6)\)

\(F_{xtt}\) tire traction force

\(g\) acceleration of gravity

\(h\) height above ground of semitrailer sprung mass c.g.

\(h_a\) height above ground of the aerodynamic center of pressure

\(h_r\) arbitrary height above ground of reference axis system origin

\(i\) subscript denoting all of the rear tractor and semitrailer axles

\(j\) subscript denotes one of possibly several tractor rear axles

\(k\) semitrailer rear axles

\(K_1\) spring rate of tractor front suspension (one side)

\(K_j\) tractor rear suspension stiffness

\(K_k\) semitrailer rear

\(L_T\) tractor wheelbase

\(L\) semitrailer wheelbase

\(m_1\) mass of tractor front unsprung mass

\(m_2\) total mass of tractor rear suspension (rear unsprung masses)

\(m_j\) tractor rear unsprung mass

\(m_k\) semitrailer rear

\(m_s\) mass of sprung weight (semitrailer body + payload)
\( N_{sj} \) tractor rear static load of axle j
\( N_{sk} \) semitrailer static load of axle k
\( N_1 \) static load on tractor front axle
\( N_2 \) total static load on tractor rear axles
\( n_d \) number of tractor rear drive axles
\( n_s \) number of tractor rear axles
\( p \) semitrailer sprung mass pitch angle relative to the horizontal plane normal to the gravity vector, \( x(4) \)
\( p_r \) highway grade
\( p_T \) tractor pitch angle
\( q \) aerodynamic force = \( ((\text{density of air})(\text{reference area})\ U^2 / 2) \)
\( R \) highway curve radius
\( s_L \) slope of aerodynamic lift coefficient with respect to pitch
\( s_Y \) slope of aerodynamic side force with respect to sideslip angle
\( T_j \) tractor rear suspension spread
\( T_k \) semitrailer rear spread
\( T{T}_j \) tractor rear tire track
\( T{T}_k \) semitrailer rear spread
\( U \) vehicle speed
\( v \) semitrailer sideslip velocity at the body-axis origin, \( x(1) \)
\( W_T \) total combination vehicle weight
\( W_1 \) weight of tractor sprung mass
\( x_A \) distance of aerodynamic center of pressure ahead of body-axis origin
\( x_C \) distance of semitrailer sprung mass center ahead of body-axis origin
\( z \) semitrailer sprung mass displacement normal to the road surface (relative to the static reference condition), \( x(2) \)
\( z_1 \) vertical displacement of tractor sprung mass c.g. (positive downward)
\( z_j \) height above ground of tractor rear suspension roll center
\( z_k \) height above ground of semitrailer suspension roll center

\( \beta \) sideslip angle of tractor at sprung mass c.g. location

\( \delta_{FW} \) tractor front steer angle

\( \Delta \) kingpin offset ahead of tractor rear axle centerline

\( f_5 \) variation in kingpin vertical load due to steady turning (positive downward)

\( \theta \) semitrailer sprung mass roll angle relative to the horizontal plane normal to the gravity vector, \( x(3) \)

\( \Pi \) articulation angle between tractor and semitrailer, \( x(5) \)
Tractor-semi-trailer Model Equations: $A \mathbf{x} = \mathbf{b}$

$$A = \begin{bmatrix}
U W_T / (R \, g) & 0 & 0 & 0 & 0 & 2n_u \\
2 \Sigma C_{ai} / U & 0 & 0 & 0 & -2 \Sigma C_{ai} & 2 \Pi \\
2 \Sigma \left( C_{ai} / U \right) & -2 \Sigma K_i & 2 \Sigma C_{ai} d_i / R & 2 \Sigma K_i d_i & 0 & 0 \\
-\sigma_S y / U & 0 & -2 \Sigma C_{ai} v / U & + U^2 W_T / (R) & + U^2 v / \sigma_L & -2 \Sigma C_{ai} v / U \\
0 & -2 \Sigma k_i & 2 \Sigma C_{ai} d_i / \sigma_L & 2 \Sigma K_i d_i & 0 & 0 \\
2 \Sigma C_{ai} (h_i - h_p) / U & 0 & +\Sigma m_i g (z_i - h_p) & 0 & -2 \Sigma C_{ai} (z_i - h_p) & 2 \Pi \Sigma (z_i - h_p) \\
- (h_A - h_p) h_v / U & -2 \Sigma m_i (z_i - h_p) & 0 & -2 \Sigma C_{ai} (z_i - h_p) & 2 \Pi \Sigma (z_i - h_p) \\
0 & -2 \Sigma \left( C_{ai} / U \right) & 2 \Sigma m_i g (h - h_p) & m_i g (h - h_p) & 0 & -2 \Sigma (z_i - h_p) \\
2 \Sigma m_i (h_i - h) & -2 \Sigma C_{ai} d_i^2 \, \text{sgn}(d_i) / R & -U^2 \Sigma m_i d_i / R & \Sigma m_i g (z_i - h_p) & 0 & -2 \Sigma (z_i - h_p) \\
+\Sigma m_i (h_i - z_i) / R & -2 \Sigma K_i d_i^2 / \sigma_L & -2 \Sigma k_i d_i^2 & -2 \Sigma C_{ai} d_i / \sigma_L & + x_A \sigma s_L & -2 \Sigma C_{ai} d_i / \sigma_L \\
2 \Sigma C_{ai} d_i / U & 2 \Pi & 0 & 2 \Pi \Sigma (z_i - h_p) & -2 \Sigma C_{ai} d_i & 2 d_f \Pi \\
-\sigma_s y / U & 0 & 0 & 0 & 0 & 2n_d \\
\end{bmatrix}$$

$\mathbf{x} = [ v, z, e, p, \Pi, FxT ]^T$
The boldface terms, \( \mathbf{v} \) and \( \mathbf{\Pi} \), appearing in the \( \mathbf{A} \) and \( \mathbf{b} \) arrays represent the \( x \) components contributing to weak nonlinear terms.
Tractor Response Variables

**Tractor Front Axle Steer Angle:**
\[ \delta_{FW} = \frac{v}{U} - \Pi + \frac{(d_f + L_T)}{R} + \left[ \frac{(v^2/R - e)(F_{pz} \Delta/g + W_1 b_T/g + m_1 L_T)}{(2L_T C_{a1})} \right] \]

**Tractor Sideslip Angle:**
\[ \beta = \frac{v}{U} + \frac{(d_f - \Delta + b_T)}{R} - \Pi \]

**Tractor Pitch Angle:**
\[ \rho_T = \frac{p - \Delta f_s}{(2 K_1 L_T^2)} \]

**Tractor Bounce (vertical displacement):**
\[ z = - \rho_T b_T \]

where,
\[ \Delta = \frac{(N_1 - m_1 g - b_T) L_T}{F_{pz}} \]
\[ F_{pz} = N_1 + N_2 - W_1 - m_1 g - m_2 g \]
\[ b_T = 0.80 L_T \]

**Lateral Tire Forces**

Tractor Front Tire: \( F_{y1} = C_{a1} (\alpha f) \)
\[ = C_{a1} \left( \frac{(v/U + d_f/R - \Pi)}{R} + \frac{(L_T - \Delta)}{R} - \delta_{FW} \right) \]

Tractor Rear Tires: \( F_{yj} = C_{aj} (\alpha f) \)
\[ = C_{aj} \left( \frac{(v/U + d_j/R - \Pi)}{R} \right) \quad ; j \text{ denotes tractor rear axle} \]

Rear Tires: \( F_{yk} = C_{ak} (\alpha f) \)
\[ = C_{ak} \left( \frac{(v/U - d_k/R)}{R} \right) \quad ; k \text{ denotes semitrailer rear axle} \]

**Tractor Front Suspension Forces**

Left Side: \( F_{SL1} = \left[ -T_1(\alpha - e)/2 - (L_T - \Delta)(p - p_f) \right] K_1 \)

Right Side: \( F_{SL2} = \left[ T_1(\alpha - e)/2 - (L_T - \Delta)(p - p_f) \right] K_1 \)
Tractor Rear Suspension Forces

Left Side: $F_{SLj} = [-T_j(a - e)/2 - d_j(p - p_r) + z]K_j$
Right Side: $F_{SRj} = [T_j(a - e)/2 - d_j(p - p_r) + z]K_j$

; $j$ denotes tractor rear axle

Semitrailer Rear Suspension Forces

Left Side: $F_{SLk} = [-T_k(a - e)/2 + d_k(p - p_r) + z]K_k$
Right Side: $F_{SRk} = [T_k(a - e)/2 + d_k(p - p_r) + z]K_k$

; $k$ denotes semitrailer rear axle

Tractor Front Vertical Tire Forces

Left Side: $F_{zL1} = N_{s1}/2 + (F_{SL1} + F_{SR1})/2 - T_1(F_{SR1} - F_{SL1})/(2TT_1)
+ F_{y1} z_1 / TT_1$
Right Side: $F_{zR1} = N_{s1}/2 + (F_{SL1} + F_{SR1})/2 + T_1(F_{SR1} - F_{SL1})/(2TT_1)
- F_{y1} z_1 / TT_1$

Tractor Rear Vertical Tire Forces

Left Side: $F_{zLj} = N_{sj}/2 + (F_{SLj} + F_{SRj})/2 - T_j(F_{SRj} - F_{SLj})/(2TT_j)
+ F_{yj} z_j / TT_j$
Right Side: $F_{zRj} = N_{sj}/2 + (F_{SLj} + F_{SRj})/2 + T_j(F_{SRj} - F_{SLj})/(2TT_j)
- F_{yj} z_j / TT_j$

Semitrailer Rear Vertical Tire Forces

Left Side: $F_{zLk} = N_{sk}/2 + (F_{SLk} + F_{SRk})/2 - T_k(F_{SRk} - F_{SLk})/(2TT_k)
+ F_{yk} z_k / TT_k$
Right Side: $F_{zRk} = N_{sk}/2 + (F_{SLk} + F_{SRk})/2 + T_k(F_{SRk} - F_{SLk})/(2TT_k)
- F_{yk} z_k / TT_k$
FRICITION FACTORS:

Tractor Front Left Side: \( f_{FFL1} = \frac{F_{yL1}}{F_{zL1}} \)

Tractor Front Right Side: \( f_{FFR1} = \frac{F_{yR1}}{F_{zR1}} \)

Tractor Rear Left Side: \( f_{FFLj} = \frac{F_{yLj}}{F_{zLj}} \)

Tractor Rear Right Side: \( f_{FFRj} = \frac{F_{yRj}}{F_{zRj}} \) ; \( j \) denotes rear tractor axle

Semitrailer Rear Left Side: \( f_{FFLk} = \frac{F_{yLk}}{F_{zLk}} \)

Semitrailer Rear Right Side: \( f_{FFRk} = \frac{F_{yRk}}{F_{zRk}} \) ; \( k \) denotes rear semitrailer axle
INDEPENDENT SUSPENSION ADDITION TO THE PHASE 4 MODEL

An independent wheel suspension was added to the Phase 4 computer model [5] to permit improved simulation of typical passenger car suspension behavior. Section 3.4 (volume II) of this report provides a general description of the modifications to the Phase 4 computer model performed during the project. The material in this appendix supplements that description with more detailed information.

Reference to figure C-1 (or figure 12) shows the basic kinematic layout of the independent suspension which is seen to be very similar to a McPherson strut assembly. The strut, of nominal length $L_s$, is allowed to vary in length and pivot about its end points. The strut contains a spring and damper having force characteristics which vary linearly with strut displacement and velocity. The lateral link of length $a$ locates the lower endpoint of the strut. On an actual vehicle the upper endpoint, at lateral displacement $c$ from the vehicle centerline, is not readily known. Accordingly, input to the model for defining the angular orientation of the strut assembly is provided by specifying the lateral displacement of the strut, $c$, coincident with the top of the tire. The static tire radius, $R_T$, is normally entered as one of the "Tires and Wheels" data in the Phase 4 model.

Knowledge of the tire half track dimension, $b$, in addition to $c$ and $R_T$, permits the model to calculate the linkage motions shown in figure C-1. The tire track parameter $= 2b$, is normally entered in the Phase 4 model under the category of "Suspension and Axle Parameters." The parameter $c$ is selected by the current model version to cause the strut centerline to intersect the center of the tire contact patch at the road surface. However, the wheel axle assembly is assumed to always remain parallel to the road surface. That is, as vehicle roll/bounce motions and tire bounce motions occur, the axle (tire) will not roll (camber) according to the kinematics depicted in figure C-1. To accommodate tire cambering and steering in response to suspension motion (deriving from vehicle bounce and roll motions), two parameters are entered by the model user to specify these
Input Parameters:

- $b$  tire track dimension
- $c$  spacing of upper strut pivot
- $R_T$  static tire radius
- $L_s$  steer-bounce coefficient
- $k$  camber-bounce coefficient

Figure C-1. Independent suspension model (Phase 4).
relationships. The first such parameter is the camber-bounce coefficient which causes the tire to camber an amount proportional to the relative bounce motion of the suspension. The second parameter is the steer-bounce coefficient which causes the tire to steer in direct proportion to the bounce motion of the suspension. In this implementation, the tire camber relationship to suspension motion is not limited to just that seen in figure C-1. Instead, different camber-bounce and steer-bounce relationships, as obtained, for example, from laboratory suspension measurements, may be represented as well. However, the key element to remember is that all tire camber motion is provided by the first of these parameters. No tire camber motion occurs, although it is suggested, by the kinematics depicted in figure C-1.

To use the independent suspension option in the Phase 4 model, the following instructions should be followed during preparation of a Phase 4 data set:

- Under the category of "Suspension and Axle Parameters," when entering the spring rate for a particular wheel location, follow the right-side spring rate entry with any positive number in F10.3 format. This will key the program to interpret subsequent numerical input for that wheel location as parametric data for the independent suspension. This should be performed at each wheel location requiring an independent suspension.

- Three lines later, where the "Axle Roll Moment of Inertia" is usually entered, instead enter the independent suspension camber/bounce coefficient value in units of degrees/inch.

- Two lines after this, where the "Roll Steer Coefficient" is usually entered, instead enter the independent suspension steer/bounce coefficient value in units of degrees/inch.

At the start of execution of the Phase 4 program an "echo" of vehicle parameters occurs and any independent suspension parameters entered as described above will be accurately identified at this point (figure C-2). If
## Truck Parameters

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<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Value 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheelbase - distance from front axle to center of rear suspension (in)</td>
<td>100.30</td>
<td>100.00</td>
</tr>
<tr>
<td>Base vehicle curb weight on front suspension (lb)</td>
<td>1800.00</td>
<td>1800.00</td>
</tr>
<tr>
<td>Base vehicle curb weight on rear suspension (lb)</td>
<td>1400.00</td>
<td>1400.00</td>
</tr>
<tr>
<td>Springs mass CG height (in, above ground)</td>
<td>25.00</td>
<td>25.00</td>
</tr>
<tr>
<td>Springs mass roll moment of inertia (in-lb-sec(^2))</td>
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<td>1000.00</td>
</tr>
<tr>
<td>Springs mass yaw moment of inertia (in-lb-sec(^2))</td>
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<td>8000.00</td>
</tr>
<tr>
<td>Payload weight (lb)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td><strong>Note:</strong> Five payload description parameters are not entered ***</td>
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<td></td>
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## Truck Front Suspension and Axle Parameters

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</tr>
</thead>
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<td>Suspension spring rate (lb/in(side/axle))</td>
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<td>230.00</td>
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<tr>
<td>Suspension viscous damping (lb-sec/in(side/axle))</td>
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<td>10.00</td>
</tr>
<tr>
<td>Coulomb friction (lb(side/axle))</td>
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<td>0.0</td>
</tr>
<tr>
<td>Roll center height (in, above ground)</td>
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<tr>
<td>Independent suspension steer/bounce coefficient (deg/lin)</td>
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<tr>
<td>Auxiliary roll stiffness (in-lb/deg/axle)</td>
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<td>97.00</td>
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<tr>
<td>Lateral distance between suspension springs (in)</td>
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<td>0.0</td>
</tr>
<tr>
<td>Track width (in)</td>
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<td>100.00</td>
</tr>
<tr>
<td>Unsprung weight (lb)</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Steering gear ratio (deg steering wheel/deg road wheel)</td>
<td>90.00</td>
<td>90.00</td>
</tr>
<tr>
<td><strong>Note:</strong> Negative or zero entry indicates no steering system ***</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Note:</strong> Steering system parameters not to be entered ***</td>
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<td></td>
</tr>
</tbody>
</table>

## Truck Front Tires and Wheels

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<tr>
<th>Parameter</th>
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<td>Cornering stiffness (lb/deg/tire)</td>
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<td>-1.00</td>
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<td><strong>Note:</strong> Negative entry indicates table entered ***</td>
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<td></td>
</tr>
<tr>
<td><strong>Note:</strong> Echo will appear on table index page ***</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Longitudinal stiffness (lb/deg/tire)</td>
<td>5000.00</td>
<td>5000.00</td>
</tr>
<tr>
<td>Camber stiffness (lb/deg/tire)</td>
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<td>0.0</td>
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<tr>
<td>Aligning moment (in-lb/deg/tire)</td>
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<td>0.0</td>
</tr>
<tr>
<td>Tire spring rate (lb/in/tire)</td>
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<td>1000.00</td>
</tr>
<tr>
<td>Tire Load radius (in)</td>
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<td>12.00</td>
</tr>
<tr>
<td>Polar moment of inertia (in-lb-sec(^2)/tire)</td>
<td>20.00</td>
<td>20.00</td>
</tr>
</tbody>
</table>

**Figure G-2.** Independent suspension output "echo"; Phase 4 model.
they are not, then a check of the data set should be performed to see that the independent suspension key following the spring rates was entered properly (Item 1 above). If this fails, then a check to see that the most recent version of the Phase 4 model, containing the independent suspension model developed under this project, is being used.
Appendix D

STEADY TURNING MODEL PREDICTIONS

The steady turning model printouts seen in this appendix correspond in order and vehicle type to the steady turning test results seen in appendix E and the corresponding model/measurement comparisons seen in chapter 5 (volume II). The steady turning model predictions seen in chapter 5 (volume II) are taken directly from the printouts shown in this appendix. The first set of microcomputer model predictions are for the tractor-semitrailer vehicle (test vehicle C); the second set of model predictions are for the front wheel drive passenger car (test vehicle A); and the final set of predictions correspond to the rear wheel drive passenger car (test vehicle B). For example, the first two pages of the tractor-semitrailer predictions represent a single microcomputer run and show input values for path radius, vehicle speed, and superelevation rate of 1273 ft (388 m), 47.6 mph (76.6 km/h), and 6.7 percent. These conditions correspond to the test data for the tractor-semitrailer at curve site 1 and repeat 1. The model output results follow beginning with values of vehicle response variables such as tractor sideslip (0.06 degrees), tractor vertical bounce (0), and tractor roll angle (3.23 degrees). Each microcomputer result concludes with a plan view of the vehicle showing the friction factor values for each wheel location and the c.g. (point-mass) location. All model predictions shown here are for right hand turns. (Most of the test results are for left hand turns and therefore require a sign change for certain variables when model/test result comparisons are performed, as in chapter 5.)

A User's Guide for operating the microcomputer models appears at the end of this appendix.
Vehicle C

5-Axle Tractor-Semitrailer
FHWA / UMTRI TRACTOR-SEMITRAILER, STEADY TURNING VEHICLE MODEL

NUMBER OF AXLES ON TRACTOR REAR SUSPENSION: 2
NUMBER OF AXLES ON SEMITRAILER SUSPENSION: 2

AXLE 1 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 650
AXLE 2 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1280
AXLE 3 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1280
AXLE 4 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1460
AXLE 5 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1460

AXLE 1 SPRING RATE (LB/IN/SIDE): 1200
AXLE 2 SPRING RATE (LB/IN/SIDE): 5000
AXLE 3 SPRING RATE (LB/IN/SIDE): 5000
AXLE 4 SPRING RATE (LB/IN/SIDE): 6000
AXLE 5 SPRING RATE (LB/IN/SIDE): 6000

TRACTOR REAR SUSPENSION AXLE SPACING (IN): 50
SEMITRAILER SUSPENSION AXLE SPACING (IN): 48
TRACTOR WHEELBASE (IN): 142
SEMITRAILER WHEELBASE (IN): 410
SUPERELEVATION: .067
GRADE: 0
FORWARD VELOCITY (MPH): 47.6
PATH RADIUS (FT): 1273
AXLE 1 STATIC LOAD (LB): 10300
AXLE 2 STATIC LOAD (LB): 15710
AXLE 3 STATIC LOAD (LB): 15710
AXLE 4 STATIC LOAD (LB): 16900
AXLE 5 STATIC LOAD (LB): 16900
TRACTOR SPRUNG MASS WEIGHT (LB): 9700
TRACTOR REAR ROLL CENTER HEIGHT (IN): 29
TRACTOR FRONT ROLL CENTER HEIGHT (IN): 23
SEMITRAILER SPRUNG MASS WEIGHT (LB): 70
SEMITRAILER SPRUNG MASS C.G. HEIGHT (IN): 44
FIFTH WHEEL HEIGHT (IN): 48
TRACTOR SPRUNG MASS C.G. HEIGHT (IN): 48
TRACTOR FRAME HEIGHT (IN): 36
TRACTOR FRONT SPRING SPACING (IN): 32
TRACTOR REAR SPRING SPACING (IN): 38
SEMITRAILER SPRING SPACING (IN): 38
TRACTOR FRONT TRACK (IN): 81
TRACTOR REAR TRACK (IN): 73
SEMITRAILER TRACK (IN): 73
AXLE 1 UNSPRUNG WEIGHT (LB): 1200
AXLE 2 UNSPRUNG WEIGHT (LB): 2300
AXLE 3 UNSPRUNG WEIGHT (LB): 2300
AXLE 4 UNSPRUNG WEIGHT (LB): 1500
AXLE 5 UNSPRUNG WEIGHT (LB): 1500
PERCENT ROLLING RESISTANCE: 1

**** OUTPUT ****

TRACTOR SIDESLIP ANGLE (DEG): .06
TRACTOR VERTICAL BOUNCE (IN): 0

25
TRACTOR ROLL ANGLE (DEG): 3.23
TRACTOR PITCH ANGLE (DEG): -0.01
TRACTOR STEER ANGLE (DEG): .57
TRACTOR TOTAL DRIVE THRUST (LB): 298.4
SEMITRAILER SIDESLIP ANGLE (DEG): .42
SEMITRAILER VERTICAL BOUNCE (IN): .01
SEMITRAILER ROLL ANGLE (DEG): 3.23
SEMITRAILER PITCH ANGLE (DEG): -0.01
ARTICULATION ANGLE (DEG): 1.57
HORIZ LATERAL ACCEL (G'S): .118
FRICITION FACTORS:
LEFT    RIGHT    AXLE
.049    .054    1
.035    .041    2
.062    .075    3
.031    .037    4
.059    .072    5
POINT MASS VALUE = .051
VERTICAL TIRE LOADS (LB):
5427.9   4885.1  1
8541.3   7270.1  2
9638.5   7174.6  3
9247.5   7774.2  4
9351.8   7669.6  5
LATERAL TIRE FORCES (LB):
267.2    267.2  1
300.6    300.6  2
540.6    540.6  3
292.1    292.1  4
555      555   5
** FRICTION FACTORS: **
.054 .041 .075 .037 .072
.051
C.G.
.049 .035 .062 .031 .059
TRACTOR    SEMITRAILER
26
FHWA / UMTRI TRACTOR-SEMITRAILER, STEADY TURNING VEHICLE MODEL

NUMBER OF AXLES ON TRACTOR REAR SUSPENSION: 2
NUMBER OF AXLES ON SEMITRAILER SUSPENSION: 2

AXLE 1 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 650
AXLE 2 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1280
AXLE 3 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1460

AXLE 1 SPRING RATE (LB/IN/SIDE): 1200
AXLE 2 SPRING RATE (LB/IN/SIDE): 5000
AXLE 3 SPRING RATE (LB/IN/SIDE): 5000
AXLE 4 SPRING RATE (LB/IN/SIDE): 6000
AXLE 5 SPRING RATE (LB/IN/SIDE): 6000

TRACTOR REAR SUSPENSION AXLE SPACING (IN): 50
SEMITRAILER SUSPENSION AXLE SPACING (IN): 48

TRACTOR WHEELBASE (IN): 142
SEMITRAILER WHEELBASE (IN): 410

SAG ELEVATION: .067

GRADE: 0
FORWARD VELOCITY (MPH): 45.5
PATH RADIUS (FT): 1273

AXLE 1 STATIC LOAD (LB): 10500
AXLE 2 STATIC LOAD (LB): 15710
AXLE 3 STATIC LOAD (LB): 15710
AXLE 4 STATIC LOAD (LB): 16900
AXLE 5 STATIC LOAD (LB): 16900

TRACTOR SPRUNG MASS WEIGHT (LB): 9700
TRACTOR FRONT ROLL CENTER HEIGHT (IN): 23
TRACTOR REAR ROLL CENTER HEIGHT (IN): 29
SEMITRAILER ROLL CENTER HEIGHT (IN): 29
TRACTOR SPRUNG MASS C.G. HEIGHT (IN): 44
SEMITRAILER SPRUNG MASS C.G. HEIGHT (IN): 70

FIFTH WHEEL HEIGHT (IN): 48
TRACTOR FRAME HEIGHT (IN): 36
TRACTOR FRONT SPRING SPACING (IN): 32
TRACTOR REAR SPRING SPACING (IN): 38
SEMITRAILER SPRING SPACING (IN): 38
TRACTOR FRONT TRACK (IN): 8
TRACTOR REAR TRACK (IN): 78
SEMITRAILER TRACK (IN): 78

AXLE 1 UNSPRUNG WEIGHT (LB): 1200
AXLE 2 UNSPRUNG WEIGHT (LB): 2300
AXLE 3 UNSPRUNG WEIGHT (LB): 2300
AXLE 4 UNSPRUNG WEIGHT (LB): 1500
AXLE 5 UNSPRUNG WEIGHT (LB): 1500

PERCENT ROLLING RESISTANCE: 1

**** OUTPUT ****

TRACTOR SIDE SLIP ANGLE (DEG): .12
TRACTOR VERTICAL BOUNCE (IN): 0

27
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<td>Tractor Steer Angle (deg)</td>
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<td>Semitrailer Sideslip Angle (deg)</td>
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<td>Left</td>
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**Friction Factors:**

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<td>0.022</td>
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**C.G.**

Tractor  Semitrailer
FHWA / UMTRI TRACTOR-SEMITRAILER, STEADY TURNING VEHICLE MODEL

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tr>
<td>Number of axles on tractor rear suspension</td>
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<tr>
<td>Number of axles on semitrailer suspension</td>
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</tr>
<tr>
<td>Axle 1 tire cornering stiffness (lb/deg/side)</td>
<td>650</td>
</tr>
<tr>
<td>Axle 2 tire cornering stiffness (lb/deg/side)</td>
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<tr>
<td>Axle 3 tire cornering stiffness (lb/deg/side)</td>
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</tr>
<tr>
<td>Axle 4 tire cornering stiffness (lb/deg/side)</td>
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<tr>
<td>Axle 5 tire cornering stiffness (lb/deg/side)</td>
<td>1460</td>
</tr>
<tr>
<td>Axle 1 spring rate (lb/in/side)</td>
<td>1200</td>
</tr>
<tr>
<td>Axle 2 spring rate (lb/in/side)</td>
<td>5000</td>
</tr>
<tr>
<td>Axle 3 spring rate (lb/in/side)</td>
<td>5000</td>
</tr>
<tr>
<td>Axle 4 spring rate (lb/in/side)</td>
<td>6000</td>
</tr>
<tr>
<td>Axle 5 spring rate (lb/in/side)</td>
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</tr>
<tr>
<td>Tractor rear suspension axle spacing (in)</td>
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<td>Semitrailer suspension axle spacing (in)</td>
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<td>Tractor wheelbase (in)</td>
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<td>Semitrailer wheelbase (in)</td>
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<td>Super-elevation</td>
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<td>Tractor rear roll center height (in)</td>
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<td>Semitrailer roll center height (in)</td>
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<td>Tractor sprung mass c.g. height (in)</td>
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<td>Semitrailer sprung mass c.g. height (in)</td>
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<td>Fifth wheel height (in)</td>
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<td>Tractor frame height (in)</td>
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<td>Tractor front spring spacing (in)</td>
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<td>Percent rolling resistance</td>
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**** OUTPUT ****

Tractor sideslip angle (deg): .1
Tractor vertical bounce (in): 0
TRACTOR ROLL ANGLE (DEG): 3.31
TRACTOR PITCH ANGLE (DEG): -0.01
TRACTOR STEER ANGLE (DEG): 0.56
TRACTOR TOTAL DRIVE THRUST (LB): 297.4
SEMIRAILER SIDESLIP ANGLE (DEG): 0.46
SEMIRAILER VERTICAL BOUNCE (IN): 0
SEMIRAILER ROLL ANGLE (DEG): 3.31
SEMIRAILER PITCH ANGLE (DEG): 0
ARTICULATION ANGLE (DEG): 1.57
HORIZ LATERAL ACCEL (G'S): 0.112
FRICITION FACTORS:

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POINT MASS VALUE = 0.045

VERTICAL TIRE LOADS (LB):

| 5392.3 | 4919.5 |
| 8455.1 | 7549   |
| 8550.7 | 7253.9 |
| 9147.8 | 7869.8 |
| 9252.5 | 7765.6 |

LATERAL TIRE FORCES (LB):

| 231.8  | 231.8  |
| 246.5  | 246.5  |
| 488.5  | 488.5  |
| 233.8  | 233.8  |
| 496.7  | 496.7  |

**FRICITION FACTORS:**

| 0.047 | 0.033 | 0.067 | 0.029 | 0.063 |

\[ \text{TRACTOR} \quad \text{SEMIRAILER} \]

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<td>Fifth wheel height (in)</td>
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<tr>
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<td>Axle 5 unsprung weight (lb)</td>
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<tr>
<td>Percent rolling resistance</td>
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**** Output ****

Tractor sideslip angle (deg): -0.08
Tractor vertical bounce (in): 0

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<td>Tractor Steer Angle (deg)</td>
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**Friction Factors:**

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**Point Mass Value** = 0.074

**Vertical Tire Loads (lb):**

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**Lateral Tire Forces (lb):**

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**Inside of Turn Friction Factors:**

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**Diagram:**

- Tractor
- Semitrailer

-C.G.

32
FHWA / UMTRI TRACTOR-SEMITRAILER, STEADY TURNING VEHICLE MODEL

NUMBER OF AXLES ON TRACTOR REAR SUSPENSION: 2
NUMBER OF AXLES ON SEMITRAILER SUSPENSION: 2

AXLE 1 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 650
AXLE 2 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1280
AXLE 3 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1280
AXLE 4 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1460
AXLE 5 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1460

AXLE 1 SPRING RATE (LB/IN/SIDE): 1200
AXLE 2 SPRING RATE (LB/IN/SIDE): 5000
AXLE 3 SPRING RATE (LB/IN/SIDE): 5000
AXLE 4 SPRING RATE (LB/IN/SIDE): 6000
AXLE 5 SPRING RATE (LB/IN/SIDE): 6000

TRACTOR REAR SUSPENSION AXLE SPACING (IN): 50
SEMITRAILER SUSPENSION AXLE SPACING (IN): 48
TRACTOR WHEELBASE (IN): 142
SEMITRAILER WHEELBASE (IN): 410
SUPERELEVATION: .067
GRADE: 0

FORWARD VELOCITY (MPH): 57.5
PATH RADIUS (FT): 1273

AXLE 1 STATIC LOAD (LB): 10300
AXLE 2 STATIC LOAD (LB): 15710
AXLE 3 STATIC LOAD (LB): 15710
AXLE 4 STATIC LOAD (LB): 16900
AXLE 5 STATIC LOAD (LB): 16900

TRACTOR SPRUNG MASS WEIGHT (LB): 19700
TRACTOR FRONT ROLL CENTER HEIGHT (IN): 23
TRACTOR REAR ROLL CENTER HEIGHT (IN): 29
SEMITRAILER ROLL CENTER HEIGHT (IN): 29
TRACTOR SPRUNG MASS C.G. HEIGHT (IN): 44
SEMITRAILER SPRUNG MASS C.G. HEIGHT (IN): 70
FIFTH WHEEL HEIGHT (IN): 48
TRACTOR FRAME HEIGHT (IN): 36
TRACTOR FRONT SPRING SPACING (IN): 32
TRACTOR REAR SPRING SPACING (IN): 38
SEMITRAILER SPRING SPACING (IN): 38
TRACTOR FRONT TRACK (IN): 81
TRACTOR REAR TRACK (IN): 73
SEMITRAILER TRACK (IN): 73

AXLE 1 UNSPRUNG WEIGHT (LB): 1200
AXLE 2 UNSPRUNG WEIGHT (LB): 2300
AXLE 3 UNSPRUNG WEIGHT (LB): 2300
AXLE 4 UNSPRUNG WEIGHT (LB): 1500
AXLE 5 UNSPRUNG WEIGHT (LB): 1500

PERCENT ROLLING RESISTANCE: 1

***** OUTPUT *****

TRACTOR SIDESLIP ANGLE (DEG): -.28
TRACTOR VERTICAL BOUNCE (IN): 0

33
TRACTOR ROLL ANGLE (DEG): 2.67
TRACTOR PITCH ANGLE (DEG): -.01
TRACTOR STEER ANGLE (DEG): .67
TRACTOR TOTAL DRIVE THRUST (LB): 316.8

SEMITRAILER SIDESLIP ANGLE (DEG): .1
SEMITRAILER VERTICAL BOUNCE (IN): .01
SEMITRAILER ROLL ANGLE (DEG): 2.67
SEMITRAILER PITCH ANGLE (DEG): -.01
ARTICULATION ANGLE (DEG): 1.59

HORIZ LATERAL ACCEL (G'S): .173

FRICTION FACTORS:
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POINT MASS VALUE = .106

VERTICAL TIRE LOADS (LB):

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LATERAL TIRE FORCES (LB):

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**FRICTION FACTORS:**

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<td>C.G.</td>
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**FHWA / UMTRI TRACTOR-SEMIFAILE, STEADY TURNING VEHICLE MODEL**

<table>
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<th>Parameter</th>
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<td>Number of axles on semitrailer suspension</td>
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<td>Axle 1 tire cornering stiffness (lb/deg/side)</td>
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***** OUTPUT *****

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TRACTOR ROLL ANGLE (DEG): 1.59
TRACTOR PITCH ANGLE (DEG): -0.02
TRACTOR STEER ANGLE (DEG): 3.08
TRACTOR TOTAL BRAKING FORCE (LB): -114.8
SEMIRAILER SIDESLIP ANGLE (DEG): 2.69
SEMIRAILER VERTICAL BOUNCE (IN): .02
SEMIRAILER ROLL ANGLE (DEG): 1.59
SEMIRAILER PITCH ANGLE (DEG): -0.02
ARTICULATION ANGLE (DEG): 8.71
HORIZ LATERAL ACCEL (G'S): .295

FRICTION FACTORS:
LEFT       RIGHT       AXLE
.182       .287       1
.11        .208       2
.222       .49        3
.097       .202       4
.216       .325       5

POINT MASS VALUE = .225

VERTICAL TIRE LOADS (LB):
6356.2  4047.1  1
10852.8  5736.4  2
11317.2  5145.1  3
11286.9  5416.1  4
11791.7  4765    5

LATERAL TIRE FORCES (LB):
1161.6  1161.6  1
1194.9  1194.9  2
2523.6  2523.6  3
1095.5  1095.5  4
2550.4  2550.4  5

FRICTION FACTORS:
INSIDE OF TURN
.287  .208  .498  .202  .333
.225
.6

TRACTOR    SEMIRAILER
1.16  1.10  2.22  0.97  0.216

36
FHWA / UMTRI TRACTOR-SEMITRAILER, STEADY TURNING VEHICLE MODEL

NUMBER OF AXLES ON TRACTOR REAR SUSPENSION: 2
NUMBER OF AXLES ON SEMITRAILER SUSPENSION: 2

AXLE 1 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 650
AXLE 2 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1280
AXLE 3 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1280
AXLE 4 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1460
AXLE 5 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 1460

AXLE 1 SPRING RATE (LB/IN/SIDE): 1200
AXLE 2 SPRING RATE (LB/IN/SIDE): 5000
AXLE 3 SPRING RATE (LB/IN/SIDE): 5000
AXLE 4 SPRING RATE (LB/IN/SIDE): 6000
AXLE 5 SPRING RATE (LB/IN/SIDE): 6000
TRACTOR REAR SUSPENSION AXLE SPACING (IN): 50
SEMITRAILER SUSPENSION AXLE SPACING (IN): 48
TRACTOR WHEELBASE (IN): 142
SEMITRAILER WHEELBASE (IN): 410
SUPERELEVATION: .07

GRADE: 0
FORWARD VELOCITY (MPH): 32.1
PATH RADIUS (FT): 230
AXLE 1 STATIC LOAD (LB): 10300
AXLE 2 STATIC LOAD (LB): 15710
AXLE 3 STATIC LOAD (LB): 15710
AXLE 4 STATIC LOAD (LB): 16900
AXLE 5 STATIC LOAD (LB): 16900
TRACTOR SPRUNG MASS WEIGHT (LB): 9700
TRACTOR FRONT ROLL CENTER HEIGHT (IN): 23
TRACTOR REAR ROLL CENTER HEIGHT (IN): 29
SEMITRAILER ROLL CENTER HEIGHT (IN): 29
TRACTOR SPRUNG MASS C.G. HEIGHT (IN): 44
SEMITRAILER SPRUNG MASS C.G. HEIGHT (IN): 70
FIFTH WHEEL HEIGHT (IN): 48
TRACTOR FRAME HEIGHT (IN): 36
TRACTOR FRONT SPRING SPACING (IN): 32
TRACTOR REAR SPRING SPACING (IN): 38
SEMITRAILER SPRING SPACING (IN): 38
TRACTOR FRONT TRACK (IN): 81
TRACTOR REAR TRACK (IN): 73
SEMITRAILER TRACK (IN): 73
AXLE 1 UNSPRUNG WEIGHT (LB): 1200
AXLE 2 UNSPRUNG WEIGHT (LB): 2300
AXLE 3 UNSPRUNG WEIGHT (LB): 2300
AXLE 4 UNSPRUNG WEIGHT (LB): 1500
AXLE 5 UNSPRUNG WEIGHT (LB): 1500
PERCENT ROLLING RESISTANCE: 1

**** OUTPUT ****

TRACTOR SIDESLIP ANGLE (DEG): .68
TRACTOR VERTICAL BOUNCE (IN): .03
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<td>Tractor Steer Angle (deg)</td>
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<td>0.210</td>
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<td>0.548</td>
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**Diagram:**

- Tractor
- Semitrailer
- Point Mass Value = 0.229
- Articulation Angle = 8.71 deg
- Friction Factors: Inside of Turn
  - Left: 0.293
  - Right: 0.214
  - Axle: 0.500
  - 0.210
  - 0.548

38
Vehicle A

Front-Wheel-Drive Passenger Car
FHW / UMTRI SINGLE-UNIT, STEADY TURNING VEHICLE MODEL

***** INPUT PARAMETERS *****

NUMBER OF AXLES ON FRONT SUSPENSION: 1
NUMBER OF AXLES ON REAR SUSPENSION: 1
AXLE 1 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 210
AXLE 1 SPRING RATE (LB/IN/SIDE): 220
AXLE 2 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 191
AXLE 2 SPRING RATE (LB/IN/SIDE): 300
WHEELBASE (IN): 100.3
SUPERELEVATION: .067
GRADE: 0
FORWARD VELOCITY (MPH): 56.7
PATH RADIUS (FT): 1273
AXLE 1 STATIC LOAD (LB): 1800
AXLE 2 STATIC LOAD (LB): 1400
FRONT ROLL CENTER HEIGHT (IN): 1
REAR ROLL CENTER HEIGHT (IN): 6
SPRUNG MASS C.G. HEIGHT (IN): 25
FRONT SPRING SPACING (IN): 57
REAR SPRING SPACING (IN): 40
FRONT TRACK (IN): 57
REAR TRACK (IN): 57.6
AXLE 1 UNSPRUNG WEIGHT (LB): 100
AXLE 2 UNSPRUNG WEIGHT (LB): 100
PERCENT ROLLING RESISTANCE: 1

***** OUTPUT *****

SIDESLIP ANGLE (DEG): -.16
VERTICAL BOUNCE (IN): .02
ROLL ANGLE (DEG): 3.12
PITCH ANGLE (DEG): 0
STEER ANGLE (DEG): .43
TOTAL DRIVE THRUST (LB): 34
HORIZ LATERAL ACCEL (G'S): .168
FRICITION FACTORS:
LEFT  RIGHT  AXLE
.092   .11    1
.092   .109   2

POINT MASS VALUE = .101

VERTICAL TIRE LOADS (LB):
985.4  825.1  1
769.4  650.1  2
LATERAL TIRE FORCES (LB):

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INSIDE OF TURN

FRONT

REAR

C.G.

**FRICITION FACTORS:**

- Inside of turn:
  - 0.110
  - 0.109

- Front:
  - 0.101

- Rear C.G.:
  - 0.092
  - 0.092

41
FHWA / UMTRI SINGLE-UNIT, STEADY TURNING VEHICLE MODEL

*** INPUT PARAMETERS ***

NUMBER OF AXLES ON FRONT SUSPENSION: 1
NUMBER OF AXLES ON REAR SUSPENSION: 1
AXLE 1 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 210
AXLE 2 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 191
AXLE 1 SPRING RATE (LB/IN/SIDE): 220
AXLE 2 SPRING RATE (LB/IN/SIDE): 300
WHEELBASE (IN): 100.3
SUPERELEVATION: .067
GRADE: 0
FORWARD VELOCITY (MPH): 57
PATH RADIUS (FT): 1273
AXLE 1 STATIC LOAD (LB): 1800
AXLE 2 STATIC LOAD (LB): 1400
FRONT ROLL CENTER HEIGHT (IN): 1
REAR ROLL CENTER HEIGHT (IN): 6
SPRUNG MASS C.G. HEIGHT (IN): 25
FRONT SPRING SPACING (IN): 57
REAR SPRING SPACING (IN): 40
FRONT TRACK (IN): 57
REAR TRACK (IN): 57.6
AXLE 1 UNSPRUNG WEIGHT (LB): 100
AXLE 2 UNSPRUNG WEIGHT (LB): 100
PERCENT ROLLING RESISTANCE: 1

*** OUTPUT ***

SIDESLIP ANGLE (DEG): - .17
VERTICAL BOUNCE (IN): .02
ROLL ANGLE (DEG): 3.1
PITCH ANGLE (DEG): 0
STEER ANGLE (DEG): .43
TOTAL DRIVE THRUST (LB): 34
HORIZ LATERAL ACCEL (G'S): .17
FRICTION FACTORS:
LEFT RIGHT AXLE
.094 .112 1
.094 .111 2
POINT MASS VALUE = .103
VERITCAL TIRE LOADS (LB):
986.9 823.8 1
770.6 649.2 2
LATERAL TIRE FORCES (LB):

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<td>72.4</td>
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**INSIDE OF TURN**

- FRONT: 0.112
- C.G.: 0.111
- REAR: 0.111

- FRONT: 0.094
- C.G.: 0.094
- REAR: 0.094

**FRICTION FACTORS:**

```
**FRICION FACTORS:**
```
FHWA / UMTRI SINGLE-UNIT, STEADY TURNING VEHICLE MODEL

**** INPUT PARAMETERS ****

NUMBER OF AXLES ON FRONT SUSPENSION: 1
NUMBER OF AXLES ON REAR SUSPENSION: 1
AXLE 1 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 210
AXLE 2 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 191
AXLE 1 SPRING RATE (LB/IN/SIDE): 220
AXLE 2 SPRING RATE (LB/IN/SIDE): 300
WHEELBASE (IN): 100.3
SUF'ERELEVATION: .067
GRADE: 0
FORWARD VELOCITY (MPH): 56.4
PATH RADIUS (FT): 1273
AXLE 1 STATIC LOAD (LB): 1800
AXLE 2 STATIC LOAD (LB): 1400
FRONT ROLL CENTER HEIGHT (IN): 1
REAR ROLL CENTER HEIGHT (IN): 6
SPRUNG MASS C.G. HEIGHT (IN): 25
FRONT SPRING SPACING (IN): 37
REAR SPRING SPACING (IN): 40
FRONT TRACK (IN): 57
REAR TRACK (IN): 57.6
AXLE 1 UNSPRUNG WEIGHT (LB): 100
AXLE 2 UNSPRUNG WEIGHT (LB): 100
PERCENT ROLLING RESISTANCE: 1

**** OUTPUT ****

SIDESLIP ANGLE (DEG): -.16
VERTICAL BOUNCE (IN): .02
ROLL ANGLE (DEG): 3.13
PITCH ANGLE (DEG): 0
STEER ANGLE (DEG): .43
TOTAL DRIVE THRUST (LB): 33.8
HORIZ LATERAL ACCEL (G'S): .166

FRICITION FACTORS:
LEFT RIGHT AXLE
.091 .108 1
.091 .107 2

POINT MASS VALUE = .099

VERTICAL TIRE LOADS (LB):
983.9 826.4 1
768.2 651.1 2
LATERAL TIRE FORCES (LB):

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<th>Inside of Turn</th>
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<td>99.8</td>
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INSIDE OF TURN

FRONT [C.G.] REAR

FRICITION FACTORS: 

.108 .099 .107 .091 .091
FHWA / UMTRI SINGLE-UNIT, STEADY TURNING VEHICLE MODEL

**** INPUT PARAMETERS ****

NUMBER OF AXLES ON FRONT SUSPENSION: 1
NUMBER OF AXLES ON REAR SUSPENSION: 1
AXLE 1 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 210
AXLE 2 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 191
AXLE 1 SPRING RATE (LB/IN/SIDE): 220
AXLE 2 SPRING RATE (LB/IN/SIDE): 300
WHEELBASE (IN): 100.5
SUPERELEVATION: .07
GRADE: 0
FORWARD VELOCITY (MPH): 57.8
PATH RADIUS (FT): 1273
AXLE 1 STATIC LOAD (LB): 1800
AXLE 2 STATIC LOAD (LB): 1400
FRONT ROLL CENTER HEIGHT (IN): 1
REAR ROLL CENTER HEIGHT (IN): 6
SPRUNG MASS C.G. HEIGHT (IN): 25
FRONT SPRING SPACING (IN): 57
REAR SPRING SPACING (IN): 40
FRONT TRACK (IN): 57
REAR TRACK (IN): 57.6
AXLE 1 UNSPRUNG WEIGHT (LB): 100
AXLE 2 UNSPRUNG WEIGHT (LB): 100
PERCENT ROLLING RESISTANCE: 1

**** OUTPUT ****

SIDESLIP ANGLE (DEG): -.18
VERTICAL BOUNCE (IN): .03
ROLL ANGLE (DEG): 3.26
PITCH ANGLE (DEG): 0
STEER ANGLE (DEG): .44
TOTAL DRIVE THRUST (LB): 34.2
HORIZ LATERAL ACCEL (G'S): .175
FRICITION FACTORS:
LEFT RIGHT AXLE
.095 .115
.095 .115

POINT MASS VALUE = .105

VERTICAL TIRE LOADS (LB):

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46
LATERAL TIRE FORCES (LB):

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INSIDE OF TURN

**FRICITION FACTORS:**
FHWA / UMTRI SINGLE-UNIT, STEADY TURNING VEHICLE MODEL

**** INPUT PARAMETERS ****

NUMBER OF AXLES ON FRONT SUSPENSION: 1
NUMBER OF AXLES ON REAR SUSPENSION: 1
AXLE 1 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 210
AXLE 2 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 191
AXLE 1 SPRING RATE (LB/IN/SIDE): 220
AXLE 2 SPRING RATE (LB/IN/SIDE): 300
WHEELBASE (IN): 100.3
SUPERELEVATION: .067
GRADE: 0
FORWARD VELOCITY (MPH): 57.9
PATH RADIUS (FT): 1273
AXLE 1 STATIC LOAD (LB): 1800
AXLE 2 STATIC LOAD (LB): 1400
FRONT ROLL CENTER HEIGHT (IN): 1
REAR ROLL CENTER HEIGHT (IN): 6
SPRUNG MASS C.G. HEIGHT (IN): 25
FRONT SPRING SPACING (IN): 57
REAR SPRING SPACING (IN): 40
FRONT TRACK (IN): 57
REAR TRACK (IN): 57.6
AXLE 1 UNSPRUNG WEIGHT (LB): 100
AXLE 2 UNSPRUNG WEIGHT (LB): 100
PERCENT ROLLING RESISTANCE: 1

**** OUTPUT ****

SIDESLIP ANGLE (DEG): -.19
VERTICAL BOUNCE (IN): .03
ROLL ANGLE (DEG): .07
PITCH ANGLE (DEG): 0
STEER ANGLE (DEG): .44
TOTAL DRIVE THRUST (LB): 34.2
HORIZONTAL LATERAL ACCEL (G'S): .175
FRICITION FACTORS:
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POINT MASS VALUE = .108

VERTICAL TIRE LOADS (LB):

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INSIDE OF TURN

FRONT  REAR

C.G.

**FRICTION FACTORS:** **
FHWA / UMTRI SINGLE-UNIT, STEADY TURNING VEHICLE MODEL

**** INPUT PARAMETERS ****

NUMBER OF AXLES ON FRONT SUSPENSION: 1
NUMBER OF AXLES ON REAR SUSPENSION: 1
AXLE 1 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 210
AXLE 2 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 191
AXLE 1 SPRING RATE (LB/IN/SIDE): 220
AXLE 2 SPRING RATE (LB/IN/SIDE): 300
WHEELBASE (IN): 100.3
SUPERELEVATION: .07
GRADE: 0
FORWARD VELOCITY (MPH): 28.8
PATH RADIUS (FT): 230
AXLE 1 STATIC LOAD (LB): 1800
AXLE 2 STATIC LOAD (LB): 1400
FRONT ROLL CENTER HEIGHT (IN): 1
REAR ROLL CENTER HEIGHT (IN): 6
SPRUNG MASS C.G. HEIGHT (IN): .25
FRONT SPRING SPACING (IN): 57
REAR SPRING SPACING (IN): 40
FRONT TRACK (IN): 57
REAR TRACK (IN): 57.6
AXLE 1 UNSPRUNG WEIGHT (LB): 100
AXLE 2 UNSPRUNG WEIGHT (LB): 100
PERCENT ROLLING RESISTANCE: 1

**** OUTPUT ****

SIDESLIP ANGLE (DEG): .55
VERTICAL BOUNCE (IN): .03
ROLL ANGLE (DEG): 2.8
PITCH ANGLE (DEG): -.03
STEER ANGLE (DEG): 2.18
TOTAL DRIVE THRUST (LB): 28.4
HORIZ LATERAL ACCEL (G'S): .24

FRICTION FACTORS:
LEFT AXLE
.146
.148
RIGHT AXLE
.196
.198

POINT MASS VALUE = .17

VERTICAL TIRE LOADS (LB):

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LATERAL TIRE FORCES (LB):

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**INSIDE OF TURN**

**FRICION FACTORS**

[Diagram showing friction factors at Inside of Turn]
FHWA / UMTRI SINGLE-UNIT, STEADY TURNING VEHICLE MODEL

**** INPUT PARAMETERS ****

NUMBER OF AXLES ON FRONT SUSPENSION: 1
NUMBER OF AXLES ON REAR SUSPENSION: 1
AXLE 1 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 210
AXLE 2 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 191
AXLE 1 SPRING RATE (LB/IN/SIDE): 220
AXLE 2 SPRING RATE (LB/IN/SIDE): 300
WHEELBASE (IN): 100.3
SUPERELEVATION: .07
GRADE: 0
FORWARD VELOCITY (MPH): 28.6
PATH RADIUS (FT): 230
AXLE 1 STATIC LOAD (LB): 1800
AXLE 2 STATIC LOAD (LB): 1400
FRONT ROLL CENTER HEIGHT (IN): 1
REAR ROLL CENTER HEIGHT (IN): 6
SPRUNG MASS C.G. HEIGHT (IN): 25
FRONT SPRING SPACING (IN): 57
REAR SPRING SPACING (IN): 40
FRONT TRACK (IN): 57
REAR TRACK (IN): 57.6
AXLE 1 UNSPRUNG WEIGHT (LB): 100
AXLE 2 UNSPRUNG WEIGHT (LB): 100
PERCENT ROLLING RESISTANCE: 1

**** OUTPUT ****

SIDESLIP ANGLE (DEG): .56
VERTICAL BOUNCE (IN): .03
ROLL ANGLE (DEG): 2.82
PITCH ANGLE (DEG): -.03
STEER ANGLE (DEG): 2.18
TOTAL DRIVE THRUST (LB): 28.4
HORIZONTAL LATERAL ACCEL (G'S): .237
FRICITION FACTORS:
LEFT    RIGHT    AXLE
.143    .192    1
.146    .193    2

POINT MASS VALUE = .167

VERTICAL TIRE LOADS (LB):

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>1044.9</td>
<td>780.8</td>
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<tr>
<td>801.3</td>
<td>604.9</td>
<td>2</td>
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52
LATERAL TIRE FORCES (LB):

<p>| | | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
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<td>117.3</td>
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FRICITION FACTORS:

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</thead>
<tbody>
<tr>
<td>.192</td>
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<tr>
<td>.167</td>
<td>.167</td>
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<tr>
<td>.143</td>
<td>.143</td>
</tr>
<tr>
<td>.146</td>
<td>.146</td>
</tr>
</tbody>
</table>
FHWA / UMTRI SINGLE-UNIT, STEADY TURNING VEHICLE MODEL

***** INPUT PARAMETERS *****

NUMBER OF AXLES ON FRONT SUSPENSION: 1
NUMBER OF AXLES ON REAR SUSPENSION: 1
AXLE 1 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 210
AXLE 2 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 191
AXLE 1 SPRING RATE (LB/IN/SIDE): 220
AXLE 2 SPRING RATE (LB/IN/SIDE): 300
WHEELBASE (IN): 100.3
SUPERELEVATION: .07
GRADE: 0
FORWARD VELOCITY (MPH): 28.9
PATH RADIUS (FT): 230
AXLE 1 STATIC LOAD (LB): 1800
AXLE 2 STATIC LOAD (LB): 1400
FRONT ROLL CENTER HEIGHT (IN): 1
REAR ROLL CENTER HEIGHT (IN): 6
SPRUNG MASS C.G. HEIGHT (IN): 25
FRONT SPRING SPACING (IN): 57
REAR SPRING SPACING (IN): 40
FRONT TRACK (IN): 57
REAR TRACK (IN): 57.6
AXLE 1 UNSPRUNG WEIGHT (LB): 100
AXLE 2 UNSPRUNG WEIGHT (LB): 100
PERCENT ROLLING RESISTANCE: 1

***** OUTPUT *****

SIDESLIP ANGLE (DEG): .54
VERTICAL BOUNCE (IN): .03
ROLL ANGLE (DEG): 2.79
PITCH ANGLE (DEG): -.03
STEER ANGLE (DEG): 2.18
TOTAL DRIVE THRUST (LB): 28.6
HORIZ LATERAL ACCEL (G'S): .242
FRICITION FACTORS:
LEFT     RIGHT
.147     .199
.15      .2
POINT MASS VALUE = .172
VERTICAL TIRE LOADS (LB):
1049.3   777.4   1
804.3    602     2
LATERAL TIRE FORCES (LB):

<table>
<thead>
<tr>
<th>Inside</th>
<th>Inside</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>154.7</td>
<td>154.7</td>
<td>1</td>
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<tr>
<td>120.8</td>
<td>120.8</td>
<td>2</td>
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</tbody>
</table>

INSIDE OF TURN

<table>
<thead>
<tr>
<th>.199</th>
<th>.200</th>
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<tbody>
<tr>
<td>FRONT</td>
<td>C.G.</td>
</tr>
<tr>
<td>.147</td>
<td>.172</td>
</tr>
</tbody>
</table>

**FRICITION FACTORS: **
Vehicle B

Rear-Wheel-Drive Passenger Car
FHWA / UMTRI SINGLE-UNIT. STEADY TURNING VEHICLE MODEL

**** INPUT PARAMETERS ****

NUMBER OF AXLES ON FRONT SUSPENSION: 1
NUMBER OF AXLES ON REAR SUSPENSION: 1
AXLE 1 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 207
AXLE 2 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 216
AXLE 1 SPRING RATE (LB/IN/SIDE): 250
AXLE 2 SPRING RATE (LB/IN/SIDE): 200
WHEELBASE (IN): 105.6
SUPERELEVATION: .067
GRADE: 0
FORWARD VELOCITY (MPH): 56.2
PATH RADIUS (FT): 1273
AXLE 1 STATIC LOAD (LB): 1925
AXLE 2 STATIC LOAD (LB): 1675
FRONT ROLL CENTER HEIGHT (IN): 1
REAR ROLL CENTER HEIGHT (IN): 6
SPRUNG MASS C.S. HEIGHT (IN): 25
FRONT SPRING SPACING (IN): 57
REAR SPRING SPACING (IN): 57
FRONT TRACK (IN): 57
REAR TRACK (IN): 57
AXLE 1 UNSPRUNG WEIGHT (LB): 100
AXLE 2 UNSPRUNG WEIGHT (LB): 100
PERCENT ROLLING RESISTANCE: 1

**** OUTPUT ****

SIDESLIP ANGLE (DEG): -.22
VERTICAL BOUNCE (IN): .04
ROLL ANGLE (DEG): 3.12
PITCH ANGLE (DEG): .02
STEER ANGLE (DEG): .48
TOTAL DRIVE THRUST (LB): 38.2
HORIZ LATERAL ACCEL (G'S): .177
FRICITION FACTORS:
LEFT RIGHT AXLE
.1 .121 1
.099 .12 2
POINT MASS VALUE = .11
VERTICAL TIRE LOADS (LB):

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>1060.1</td>
<td>879.3</td>
<td>1</td>
</tr>
<tr>
<td>931.9</td>
<td>770.8</td>
<td>2</td>
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</table>
LATERAL TIRE FORCES (LB):

<table>
<thead>
<tr>
<th>Inside of Turn</th>
<th>Front</th>
<th>Rear</th>
</tr>
</thead>
<tbody>
<tr>
<td>106.4</td>
<td>106.4</td>
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<tr>
<td>92.7</td>
<td>92.7</td>
<td>121</td>
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</tbody>
</table>

**FRICION FACTORS:**

- Inside of Turn: .120
- Front: .110
- C.G.: .100
- Rear: .099
FHWA / UMTRI SINGLE-UNIT, STEADY TURNING VEHICLE MODEL

**** INPUT PARAMETERS ****

NUMBER OF AXLES ON FRONT SUSPENSION: 1
NUMBER OF AXLES ON REAR SUSPENSION: 1
AXLE 1 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 207
AXLE 2 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 216
AXLE 1 SPRING RATE (LB/IN/SIDE): 250
AXLE 2 SPRING RATE (LB/IN/SIDE): 200
WHEELBASE (IN): 105.6
SUNPERELEVATION: 0.067
GRADE: 0
FORWARD VELOCITY (MPH): 58.3
PATH RADIUS (FT): 1273
AXLE 1 STATIC LOAD (LB): 1925
AXLE 2 STATIC LOAD (LB): 1675
FRONT ROLL CENTER HEIGHT (IN): 1
REAR ROLL CENTER HEIGHT (IN): 6
SPRUNG MASS C.G. HEIGHT (IN): 25
FRONT SPRING SPACING (IN): 57
REAR SPRING SPACING (IN): 57
FRONT TRACK (IN): 57
REAR TRACK (IN): 57
AXLE 1 UNSPRUNG WEIGHT (LB): 100
AXLE 2 UNSPRUNG WEIGHT (LB): 100
PERCENT ROLLING RESISTANCE: 1

**** OUTPUT ****

SIDESLIP ANGLE (DEG): -0.22
VERTICAL BOUNCE (IN): 0.04
ROLL ANGLE (DEG): 3.12
PITCH ANGLE (DEG): 0.02
STEER ANGLE (DEG): 0.48
TOTAL DRIVE THRUST (LB): 38.2
HORIZONTAL LATERAL ACCEL (G'S): 0.178
FRICITION FACTORS:
LEFT  RIGHT  AXLE
.1     .121    1
.1     .121    2

POINT MASS VALUE = 0.111

VERTICAL TIRE LOADS (LB):
1060.6  878.9  1
932.4  770.4  2
LATERAL TIRE FORCES (LB):

<table>
<thead>
<tr>
<th>Inside of Turn</th>
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<th>107</th>
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</thead>
<tbody>
<tr>
<td>95.2</td>
<td>93.2</td>
<td>93.2</td>
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</tbody>
</table>

**FRICTION FACTORS:**

- Inside of Turn
- Front
- Rear

**C.G.**
FHWA / UMTRI SINGLE-UNIT, STEADY TURNING VEHICLE MODEL

#### INPUT PARAMETERS ####

NUMBER OF AXLES ON FRONT SUSPENSION: 1
NUMBER OF AXLES ON REAR SUSPENSION: 1
AXLE 1 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 207
AXLE 2 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 216
AXLE 1 SPRING RATE (LB/IN/SIDE): 250
AXLE 2 SPRING RATE (LB/IN/SIDE): 200
WHEELBASE (IN): 105.6
SUPERELEVATION: .067
GRADE: 0
FORWARD VELOCITY (MPH): 56
PATH RADIUS (FT): 1273
AXLE 1 STATIC LOAD (LB): 1925
AXLE 2 STATIC LOAD (LB): 1675
FRONT ROLL CENTER HEIGHT (IN): 1
REAR ROLL CENTER HEIGHT (IN): 6
SPRUNG MASS C.G. HEIGHT (IN): 25
FRONT SPRING SPACING (IN): 57
REAR SPRING SPACING (IN): 57
FRONT TRACK (IN): 57
REAR TRACK (IN): 57
AXLE 1 UNSPRUNG WEIGHT (LB): 100
AXLE 2 UNSPRUNG WEIGHT (LB): 100
PERCENT ROLLING RESISTANCE: 1

#### OUTPUT ####

SIDESLIP ANGLE (DEG): -.17
VERTICAL BOUNCE (IN): .04
ROLL ANGLE (DEG): 3.21
PITCH ANGLE (DEG): .02
STEER ANGLE (DEG): .47
TOTAL DRIVE THRUST (LB): 37.6
HORIZONTAL LATERAL ACCEL (G'S): .164
FRICION FACTORS:
<table>
<thead>
<tr>
<th>LEFT</th>
<th>RIGHT</th>
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</thead>
<tbody>
<tr>
<td>.089</td>
<td>.105</td>
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<tr>
<td>.088</td>
<td>.104</td>
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</tbody>
</table>
AXLE 1 1
AXLE 2 2

POINT MASS VALUE = .097
VERTICAL TIRE LOADS (LB):

<table>
<thead>
<tr>
<th>POINT LOAD (LB)</th>
<th>FRONT AXLE</th>
<th>REAR AXLE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1048.6</td>
<td>.889</td>
<td>1</td>
</tr>
<tr>
<td>921.7</td>
<td>.779</td>
<td>2</td>
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</table>

61
LATERAL TIRE FORCES (LB):

<p>| | | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
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<td>1</td>
</tr>
<tr>
<td>81.7</td>
<td>81.7</td>
<td>2</td>
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**FRICTION FACTORS:**

<table>
<thead>
<tr>
<th>Inside of Turn</th>
<th>.105</th>
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<tbody>
<tr>
<td>Front</td>
<td>.097</td>
</tr>
<tr>
<td>C.G.</td>
<td>.009</td>
</tr>
<tr>
<td>Rear</td>
<td>.080</td>
</tr>
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</table>

**FRICTION FACTORS:**

---

62
FHWA / UMTRI SINGLE-UNIT, STEADY TURNING VEHICLE MODEL

**INPUT PARAMETERS**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Number of axles on front suspension</td>
<td>1</td>
</tr>
<tr>
<td>Number of axles on rear suspension</td>
<td>1</td>
</tr>
<tr>
<td>Axle 1 tire cornering stiffness (lb/deg/side)</td>
<td>207</td>
</tr>
<tr>
<td>Axle 2 tire cornering stiffness (lb/deg/side)</td>
<td>216</td>
</tr>
<tr>
<td>Axle 1 spring rate (lb/in/side)</td>
<td>250</td>
</tr>
<tr>
<td>Axle 2 spring rate (lb/in/side)</td>
<td>200</td>
</tr>
<tr>
<td>Wheelbase (in)</td>
<td>105.6</td>
</tr>
<tr>
<td>Super elevation</td>
<td>0.07</td>
</tr>
<tr>
<td>Forward velocity (mph)</td>
<td>57.2</td>
</tr>
<tr>
<td>Path radius (ft)</td>
<td>1273</td>
</tr>
<tr>
<td>Axle 1 static load (lb)</td>
<td>1925</td>
</tr>
<tr>
<td>Axle 2 static load (lb)</td>
<td>1675</td>
</tr>
<tr>
<td>Front roll center height (in)</td>
<td>1</td>
</tr>
<tr>
<td>Rear roll center height (in)</td>
<td>6</td>
</tr>
<tr>
<td>Sprung mass c.g. height (in)</td>
<td>25</td>
</tr>
<tr>
<td>Front spring spacing (in)</td>
<td>57</td>
</tr>
<tr>
<td>Rear spring spacing (in)</td>
<td>57</td>
</tr>
<tr>
<td>Front track (in)</td>
<td>57</td>
</tr>
<tr>
<td>Rear track (in)</td>
<td>57</td>
</tr>
<tr>
<td>Axle 1 unsprung weight (lb)</td>
<td>100</td>
</tr>
<tr>
<td>Axle 2 unsprung weight (lb)</td>
<td>100</td>
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<tr>
<td>Percent rolling resistance</td>
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**OUTPUT**

<table>
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<tr>
<th>Parameter</th>
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<tbody>
<tr>
<td>Sideslip angle (deg)</td>
<td>-0.19</td>
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<tr>
<td>Vertical bounce (in)</td>
<td>0.04</td>
</tr>
<tr>
<td>Roll angle (deg)</td>
<td>3.35</td>
</tr>
<tr>
<td>Pitch angle (deg)</td>
<td>0.02</td>
</tr>
<tr>
<td>Steer angle (deg)</td>
<td>0.47</td>
</tr>
<tr>
<td>Total drive thrust (lb)</td>
<td>37.8</td>
</tr>
<tr>
<td>Horizontal lateral accel (g's)</td>
<td>0.171</td>
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<tr>
<td>Friction factors:</td>
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<tr>
<td>Left axle</td>
<td>0.092</td>
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<tr>
<td>Right axle</td>
<td>0.109</td>
</tr>
<tr>
<td>Total</td>
<td>0.11</td>
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<tr>
<td>Point mass value</td>
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<td>Vertical tire loads (lb)</td>
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<td>1052.9</td>
<td>886.9</td>
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<tr>
<td>925.5</td>
<td>777.5</td>
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63
LATERAL TIRE FORCES (LB):

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<tbody>
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<td>97.7</td>
<td>97.7</td>
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<tr>
<td>85.1</td>
<td>85.1</td>
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</tr>
</tbody>
</table>

**FRICTION FACTORS: **

- INSIDE OF TURN: 0.109
- FRONT C.G.: 0.101
- REAR C.G.: 0.092

**FRICITION FACTORS: **
FHWA / UMTRI SINGLE-UNIT. STEADY TURNING VEHICLE MODEL

**** INPUT PARAMETERS ****

NUMBER OF AXLES ON FRONT SUSPENSION: 1
NUMBER OF AXLES ON REAR SUSPENSION: 1
AXLE 1 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 207
AXLE 2 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 216
AXLE 1 SPRING RATE (LB/IN/SIDE): 250
AXLE 2 SPRING RATE (LB/IN/SIDE): 200
WHEELBASE (IN): 105.6
SUPERELEVATION: .067
GRADE: 0
FORWARD VELOCITY (MPH): 55.9
PATH RADIUS (FT): 1273
AXLE 1 STATIC LOAD (LB): 1925
AXLE 2 STATIC LOAD (LB): 1675
FRONT ROLL CENTER HEIGHT (IN): 1
REAR ROLL CENTER HEIGHT (IN): 6
SPRUNG MASS C.G. HEIGHT (IN): 25
FRONT SPRING SPACING (IN): 57
REAR SPRING SPACING (IN): 57
FRONT TRACK (IN): 57
REAR TRACK (IN): 57
AXLE 1 UNSPRUNG WEIGHT (LB): 100
AXLE 2 UNSPRUNG WEIGHT (LB): 100
PERCENT ROLLING RESISTANCE: 1

**** OUTPUT ****

SIDESLIP ANGLE (DEG): -.17
VERTICAL BOUNCE (IN): .04
ROLL ANGLE (DEG): 3.21
PITCH ANGLE (DEG): .02
STEER ANGLE (DEG): .47
TOTAL DRIVE THRUST (LB): 37.6
HORIZ LATERAL ACCEL (G'S): .163
FRICITION FACTORS:
LEFT RIGHT AXLE
.088 .104 1
.088 .104 2

POINT MASS VALUE = .096

VERTICAL TIRE LOADS (LB):
1048.1 889.8 1
921.2 780.1 2
LATERAL TIRE FORCES (LB):

<table>
<thead>
<tr>
<th>Inside of Turn</th>
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<tbody>
<tr>
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<tr>
<td>81.2</td>
<td>81.2</td>
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</tbody>
</table>

**FRICTION FACTORS:**

- Inside of Turn: .104
- Front: .096
- Rear: .096
- C.G.: .088

**FRICTION FACTORS:**

- Inside of Turn: .104
- Front: .096
- Rear: .096
- C.G.: .088
FHWA / UMTRI SINGLE-UNIT, STEADY TURNING VEHICLE MODEL

**** INPUT PARAMETERS ****

NUMBER OF AXLES ON FRONT SUSPENSION: 1
NUMBER OF AXLES ON REAR SUSPENSION: 1
AXLE 1 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 207
AXLE 2 TIRE CORNERING STIFFNESS (LB/DEG/SIDE): 216
AXLE 1 SPRING RATE (LB/IN/SIDE): 250
AXLE 2 SPRING RATE (LB/IN/SIDE): 200
WHEELBASE (IN): 105.6
SUPERELEVATION: .07
GRADE: 0
FORWARD VELOCITY (MPH): 30.7
PATH RADIUS (FT): 230
AXLE 1 STATIC LOAD (LB): 1925
AXLE 2 STATIC LOAD (LB): 1675
FRONT ROLL CENTER HEIGHT (IN): 1
REAR ROLL CENTER HEIGHT (IN): 6
SPRUNG MASS C.G. HEIGHT (IN): 25
FRONT SPRING SPACING (IN): 57
REAR SPRING SPACING (IN): 57
FRONT TRACK (IN): 57
REAR TRACK (IN): 57
AXLE 1 UNSPRUNG WEIGHT (LB): 100
AXLE 2 UNSPRUNG WEIGHT (LB): 100
PERCENT ROLLING RESISTANCE: 1

**** OUTPUT ****

SIDESLIP ANGLE (DEG): .38
VERTICAL BOUNCE (IN): .08
ROLL ANGLE (DEG): 2.7
PITCH ANGLE (DEG): -.01
STEER ANGLE (DEG): 2.34
TOTAL DRIVE THRUST (LB): 28.6
HORIZ LATERAL ACCEL (G'S): .273
FRICITION FACTORS:
LEFT  RIGHT  AXLE
.17   .239  1
.17   .241  2

POINT MASS VALUE = .203

VERTICAL TIRE LOADS (LB):
1149.6  817.1  1
1002.2  705.7  2

67
LATERAL TIRE FORCES (LB):

<p>| | | |</p>
<table>
<thead>
<tr>
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</thead>
<tbody>
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<td>195.5</td>
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</tr>
<tr>
<td>170.0</td>
<td>170.0</td>
<td>2</td>
</tr>
</tbody>
</table>

INSIDE OF TURN

FRONT  .239  .203  .170  C.G.
REAR   .241

**FRICTION FACTORS:**

68
### Input Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of axles on front suspension</td>
<td>1</td>
</tr>
<tr>
<td>Number of axles on rear suspension</td>
<td>1</td>
</tr>
<tr>
<td>Axle 1 tire cornering stiffness (lb/deg/side)</td>
<td>207</td>
</tr>
<tr>
<td>Axle 2 tire cornering stiffness (lb/deg/side)</td>
<td>216</td>
</tr>
<tr>
<td>Axle 1 spring rate (lb/in/side)</td>
<td>250</td>
</tr>
<tr>
<td>Axle 2 spring rate (lb/in/side)</td>
<td>200</td>
</tr>
<tr>
<td>Wheelbase (in)</td>
<td>105.6</td>
</tr>
<tr>
<td>Super elevation</td>
<td>0.07</td>
</tr>
<tr>
<td>Grade</td>
<td>0</td>
</tr>
<tr>
<td>Forward velocity (mph)</td>
<td>26.8</td>
</tr>
<tr>
<td>Path radius (ft)</td>
<td>230</td>
</tr>
<tr>
<td>Axle 1 static load (lb)</td>
<td>1925</td>
</tr>
<tr>
<td>Axle 2 static load (lb)</td>
<td>1675</td>
</tr>
<tr>
<td>Front roll center height (in)</td>
<td>1</td>
</tr>
<tr>
<td>Rear roll center height (in)</td>
<td>6</td>
</tr>
<tr>
<td>Sprung mass c.g. height (in)</td>
<td>25</td>
</tr>
<tr>
<td>Front spring spacing (in)</td>
<td>57</td>
</tr>
<tr>
<td>Rear spring spacing (in)</td>
<td>57</td>
</tr>
<tr>
<td>Front track (in)</td>
<td>57</td>
</tr>
<tr>
<td>Rear track (in)</td>
<td>57</td>
</tr>
<tr>
<td>Axle 1 unsprung weight (lb)</td>
<td>100</td>
</tr>
<tr>
<td>Axle 2 unsprung weight (lb)</td>
<td>100</td>
</tr>
<tr>
<td>Percent rolling resistance</td>
<td>1</td>
</tr>
</tbody>
</table>

### Output

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sideslip angle (deg)</td>
<td>0.63</td>
</tr>
<tr>
<td>Vertical bounce (in)</td>
<td>0.06</td>
</tr>
<tr>
<td>Roll angle (deg)</td>
<td>3.12</td>
</tr>
<tr>
<td>Pitch angle (deg)</td>
<td>0</td>
</tr>
<tr>
<td>Steer angle (deg)</td>
<td>2.29</td>
</tr>
<tr>
<td>Total drive thrust (lb)</td>
<td>27</td>
</tr>
<tr>
<td>Horiz lateral accel (g's)</td>
<td>0.208</td>
</tr>
<tr>
<td>Friction factors:</td>
<td></td>
</tr>
<tr>
<td>Left axle</td>
<td></td>
</tr>
<tr>
<td>Right axle</td>
<td></td>
</tr>
<tr>
<td>0.121</td>
<td>0.153</td>
</tr>
<tr>
<td>0.121</td>
<td>0.154</td>
</tr>
<tr>
<td>Point mass value = 0.138</td>
<td></td>
</tr>
<tr>
<td>Vertical tire loads (lb):</td>
<td></td>
</tr>
<tr>
<td>1.091</td>
<td>0.865</td>
</tr>
<tr>
<td>0.952</td>
<td>0.751</td>
</tr>
</tbody>
</table>
LATERAL TIRE FORCES (LB):

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>132.6</td>
<td>132.8</td>
<td>1</td>
</tr>
<tr>
<td>110</td>
<td>110</td>
<td>2</td>
</tr>
</tbody>
</table>

INSIDE OF TURN

FRONT  C.G.  REAR

**FRICTION FACTORS:**
INTRODUCTION

This guide is intended to serve as an informal user's manual, or aid, for operating the microcomputer-based vehicle models developed by the University of Michigan Transportation Research Institute (UMTRI) for the Federal Highway Administration (FHWA). These models were developed under the FHWA project entitled, "Side Friction for Superelevation on Horizontal Curves." Users' comments and suggestions for improving the use of the programs, their input/output format, and additions or deletions are welcomed and solicited. Please direct such comments to:

C. C. MacAdam
or
P. S. Fancher
at
The Transportation Research Institute
The University of Michigan
2901 Baxter Road
Ann Arbor, Michigan 48109

The computer models described in this guide are intended for use in studying the side-friction requirements of different types of vehicles operating, in a steady-turning manner, along highway curves of specified radii, superelevation, and grade. Operation of the models requires entering data which describes the characteristics of the vehicle and the roadway. (Parametric data may be entered directly from the keyboard or read from a specified text file which contains the parameter values.) The
model then calculates the steady-state solution satisfying that combination of vehicle characteristics and roadway geometry. The output from the model is a set of numbers describing the orientation of the vehicle in space, the required steer angle, and individual tire forces. The tire forces are in turn converted to friction factor requirements at each wheel location and summarized in both tabular and graphical form.

To accommodate the study of a variety of different types of vehicles, two separate vehicle models are employed. The first model, referred to as the "single-unit" model, is used to represent passenger cars, straight trucks, and full trailers. The second model is used for representing an articulated vehicle comprised of two units, such as a tractor semitrailer, and is accordingly referred to as the "tractor-semitrailer" model.

The following table describes and defines the input parameters necessary for running the single-unit computer model. The order of parameters appearing in the table is the same as that required by the model. The first column describes the parameter; the second column shows the required physical units for the numerical value of the parameter; the third column lists a "typical" passenger car value for each parameter; the fourth column lists a "typical" heavy truck value (fully loaded condition).

**INPUT PARAMETER LIST: SINGLE-UNIT MODEL**

<table>
<thead>
<tr>
<th>Parameter Description</th>
<th>Units</th>
<th>Car</th>
<th>Truck</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Number of axles on front suspension</td>
<td>-</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2 Number of axles on rear suspension</td>
<td>-</td>
<td>1</td>
<td>1-5</td>
</tr>
<tr>
<td>3 Axle 1 tire cornering stiffness</td>
<td>lb/deg/side</td>
<td>175</td>
<td>600</td>
</tr>
<tr>
<td>4 Axle 2 tire cornering stiffness</td>
<td>-</td>
<td>175</td>
<td>1200</td>
</tr>
<tr>
<td>(remaining cornering stiffnesses for axles 3-6 if specified)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 Axle 1 suspension spring rate</td>
<td>lb/in/side</td>
<td>200</td>
<td>1200</td>
</tr>
<tr>
<td>6 Axle 2 suspension spring rate</td>
<td>-</td>
<td>250</td>
<td>6000</td>
</tr>
<tr>
<td>(remaining spring rates for axles 3-6 if specified)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No.</td>
<td>Description</td>
<td>Unit(s)</td>
<td>Value</td>
</tr>
<tr>
<td>-----</td>
<td>------------------------------------------------------------------------------</td>
<td>---------</td>
<td>----------------</td>
</tr>
<tr>
<td>7</td>
<td>Fore-aft spread of axles on multi-axle susp</td>
<td>inches</td>
<td>48</td>
</tr>
<tr>
<td>8</td>
<td>Wheelbase; center to center susp distance</td>
<td>inches</td>
<td>102</td>
</tr>
<tr>
<td>9</td>
<td>Superelevation of road</td>
<td></td>
<td>&lt;0.15</td>
</tr>
<tr>
<td>10</td>
<td>Grade of road</td>
<td></td>
<td>&lt;0.15</td>
</tr>
<tr>
<td>11</td>
<td>Forward velocity</td>
<td>mph</td>
<td>55</td>
</tr>
<tr>
<td>12</td>
<td>Radius of turn</td>
<td>ft</td>
<td>1000</td>
</tr>
<tr>
<td>13</td>
<td>Axle 1 static load</td>
<td>lb</td>
<td>1500</td>
</tr>
<tr>
<td>14</td>
<td>Axle 2 static load</td>
<td>lb</td>
<td>1200</td>
</tr>
<tr>
<td></td>
<td>(static loads for axles 3-6 if specified)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Front suspension roll center height</td>
<td>inches</td>
<td>1</td>
</tr>
<tr>
<td>16</td>
<td>Rear suspension roll center height</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>17</td>
<td>Sprung mass (body) c.g. height</td>
<td></td>
<td>25</td>
</tr>
<tr>
<td>18</td>
<td>Front susp lateral distance between springs</td>
<td></td>
<td>40-55</td>
</tr>
<tr>
<td>19</td>
<td>Rear susp lateral distance between springs</td>
<td></td>
<td>40-55</td>
</tr>
<tr>
<td>20</td>
<td>Front track (distance between tires)</td>
<td></td>
<td>57</td>
</tr>
<tr>
<td>21</td>
<td>Rear track</td>
<td></td>
<td>57</td>
</tr>
<tr>
<td>22</td>
<td>Weight of axle assembly 1</td>
<td>lb</td>
<td>100</td>
</tr>
<tr>
<td>23</td>
<td>Weight of axle assembly 2</td>
<td>lb</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>(weights of axles 3-6 if specified)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>Percent rolling resistance</td>
<td>%</td>
<td>1</td>
</tr>
</tbody>
</table>

- Optional aerodynamic properties:

<table>
<thead>
<tr>
<th>No.</th>
<th>Description</th>
<th>Unit(s)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>Height of aero center of pressure</td>
<td>inches</td>
<td>30</td>
</tr>
<tr>
<td>26</td>
<td>Distance of center of press ahead of c.g.</td>
<td>inches</td>
<td>6</td>
</tr>
<tr>
<td>27</td>
<td>Frontal cross-sectional area</td>
<td>sq-ft</td>
<td>15</td>
</tr>
<tr>
<td>28</td>
<td>Drag coefficient</td>
<td>--</td>
<td>0.4</td>
</tr>
<tr>
<td>29</td>
<td>Lift coefficient</td>
<td>--</td>
<td>0.4</td>
</tr>
<tr>
<td>30</td>
<td>Slope of lift coeff vs. pitch angle</td>
<td>1/rad</td>
<td>3.0</td>
</tr>
<tr>
<td>31</td>
<td>Slope of side force vs. relative (wind) yaw</td>
<td>1/rad</td>
<td>3.0</td>
</tr>
</tbody>
</table>
The following table describes and defines the input parameters necessary for running the tractor‐semitrailer computer model. The order of parameters appearing in the table is the same as required by the model. The first column describes the parameter; the second column shows the required physical units of the parameter; the third column lists a "representative" tractor–semitrailer value for an empty condition; the fourth column lists a "representative" tractor–semitrailer value for a fully loaded condition.

### INPUT PARAMETER LIST: TRACTOR-SEMITRAILER MODEL

<table>
<thead>
<tr>
<th>Parameter Description</th>
<th>Units</th>
<th>Empty</th>
<th>Loaded</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Number of axles on tractor rear suspension</td>
<td>-</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>2 Number of axles on semitrailer suspension</td>
<td>-</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>3 Axle 1 tire cornering stiffness</td>
<td>lb/deg/side</td>
<td>500</td>
<td>600</td>
</tr>
<tr>
<td>4 Axle 2 tire cornering stiffness</td>
<td></td>
<td>900</td>
<td>1200</td>
</tr>
<tr>
<td>(remaining cornering stiffnesses for axles 3–6 if required)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 Axle 1 suspension spring rate</td>
<td>lb/in/side</td>
<td>1200</td>
<td>1200</td>
</tr>
<tr>
<td>6 Axle 2 suspension spring rate</td>
<td></td>
<td>4000</td>
<td>6000</td>
</tr>
<tr>
<td>(remaining spring rates for axles 3–6 if required)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 Fore-aft spread of axles on tractor susp</td>
<td>inches</td>
<td>48</td>
<td>48</td>
</tr>
<tr>
<td>8 Fore-aft spread of axles on semi susp</td>
<td>inches</td>
<td>48</td>
<td>48</td>
</tr>
<tr>
<td>9 Tractor wheelbase</td>
<td>inches</td>
<td>144</td>
<td>144</td>
</tr>
<tr>
<td>10 Semitrailer wheelbase</td>
<td>inches</td>
<td>432</td>
<td>432</td>
</tr>
<tr>
<td>11 Superelevation of road</td>
<td></td>
<td>&lt;0.15</td>
<td>&lt;0.15</td>
</tr>
<tr>
<td>12 Grade of road</td>
<td></td>
<td>&lt;0.15</td>
<td>&lt;0.15</td>
</tr>
<tr>
<td>13 Forward velocity</td>
<td>mph</td>
<td>55</td>
<td>55</td>
</tr>
<tr>
<td>14 Radius of turn</td>
<td>ft</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>15 Axle 1 static load</td>
<td>lb</td>
<td>8500</td>
<td>12000</td>
</tr>
<tr>
<td>16 Axle 2 static load</td>
<td>lb</td>
<td>5000</td>
<td>16000</td>
</tr>
<tr>
<td>(static loads for axles 3–6 if required)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17 Tractor sprung mass weight (body)</td>
<td>lb</td>
<td>9700</td>
<td>9700</td>
</tr>
<tr>
<td>18 Tractor front suspension roll center height</td>
<td>inches</td>
<td>23</td>
<td>23</td>
</tr>
<tr>
<td>19 Tractor rear suspension roll center height</td>
<td></td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>20 Semitrailer</td>
<td></td>
<td>29</td>
<td>29</td>
</tr>
<tr>
<td>No.</td>
<td>Description</td>
<td>Unit</td>
<td>Value1</td>
</tr>
<tr>
<td>-----</td>
<td>------------------------------------------------------------------------------</td>
<td>------</td>
<td>--------</td>
</tr>
<tr>
<td>21</td>
<td>Tractor sprung mass c.g. height (body)</td>
<td></td>
<td>44</td>
</tr>
<tr>
<td>22</td>
<td>Semitrailer c.g. height (body+payload)</td>
<td></td>
<td>60</td>
</tr>
<tr>
<td>23</td>
<td>Fifth Wheel height above ground</td>
<td></td>
<td>49</td>
</tr>
<tr>
<td>24</td>
<td>Tractor frame height above ground (center)</td>
<td></td>
<td>37</td>
</tr>
<tr>
<td>25</td>
<td>Tractor front susp distance between springs</td>
<td></td>
<td>32</td>
</tr>
<tr>
<td>26</td>
<td>Tractor rear susp distance between springs</td>
<td></td>
<td>38</td>
</tr>
<tr>
<td>27</td>
<td>Semi rear susp distance between springs</td>
<td></td>
<td>38</td>
</tr>
<tr>
<td>28</td>
<td>Tractor front track (distance between tires)</td>
<td></td>
<td>81</td>
</tr>
<tr>
<td>29</td>
<td>Tractor rear track</td>
<td></td>
<td>73</td>
</tr>
<tr>
<td>30</td>
<td>Semitrailer rear track</td>
<td></td>
<td>73</td>
</tr>
<tr>
<td>31</td>
<td>Tractor front axle assembly weight</td>
<td>lb</td>
<td>1200</td>
</tr>
<tr>
<td>32</td>
<td>Tractor rear assembly weight</td>
<td>lb</td>
<td>2300</td>
</tr>
<tr>
<td>33</td>
<td>Semi rear assembly weight</td>
<td>lb</td>
<td>1500</td>
</tr>
<tr>
<td></td>
<td>(weights of other axles if required)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>34</td>
<td>Percent rolling resistance (total vehicle)</td>
<td>%</td>
<td>1</td>
</tr>
</tbody>
</table>

- Optional aerodynamic properties:

<table>
<thead>
<tr>
<th>No.</th>
<th>Description</th>
<th>Unit</th>
<th>Value1</th>
<th>Value2</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>Height of aero center of pressure</td>
<td>inches</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>36</td>
<td>Distance of center of press ahead of c.g.</td>
<td>inches</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>37</td>
<td>Frontal cross-sectional area</td>
<td>sq-ft</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>38</td>
<td>Drag coefficient</td>
<td>--</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>39</td>
<td>Lift coefficient</td>
<td>--</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>40</td>
<td>Slope of lift coeff vs. pitch angle</td>
<td>1/rad</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>41</td>
<td>Slope of side force vs. relative (wind) yaw</td>
<td>1/rad</td>
<td>3.0</td>
<td>3.0</td>
</tr>
</tbody>
</table>
APPENDIX E

EXPERIMENTAL MEASUREMENTS

Appendix E is comprised of four sub-appendices (1 to 4) and contains experimental measurements of driver/vehicle test results (appendix E.1), flat bed tire force measurements (appendix E.2), and steering system measurements (appendix E.3). Appendix E.4 explains the estimation process for deriving individual wheel friction factors from the vehicle response measurements.
APPENDIX E.1

VEHICLE TEST RESULTS - TIME HISTORIES

STEADY TURNING

The time histories seen in this appendix are identified by channel numbers (Chan #2 .... Chan #16) which correspond to the data channels identified in table 3 (tractor-semitrailer; vehicle C) and table 4 (passenger cars A and B) of volume II. For example, tractor-semitrailer Chan #2 refers to vehicle speed (mph) and tractor-semitrailer Chan #16 is tractor yaw rate (deg/s). Likewise, passenger car A (Dodge Aries) Chan #8 is steering wheel angle (degrees) and Chan #10 is trolley angle (degrees).
Tractor-semitrailer

Curve #1

Repeat 1

Steady Turning
Tractor-semitrailer

Curve #1

Repeat 2

Steady Turning
Tractor-semi trailer

Curve #1

Repeat 3

Steady Turning
Chan # 2

Ave: 46.2

Chan # 3

Ave: -.116

Chan # 4
Tractor-semi trailer

Curve #2

Repeat 1

Steady Turning
Tractor-semitrailer

Curve #3

Repeat 1

Steady Turning
Tractor-semitrailer

Ramp

Repeat 1

Steady Turning
Chan # 8
Ave: 176

Chan # 9
Ave: 3.64

Chan # 10
Ave: 3.41
Tractor-semitrailer

Ramp

Repeat 2

Steady Turning
Chan # 2

Chan # 3

Chan # 4

Ave: 32.1

Ave: .301

Ave: 0
Dodge Aries

Curve #1

Repeat 1

Steady Turning
Dodge Aries
Curve #1
Repeat 2
Steady Turning
Dodge Aries

Curve #1

Repeat 3

Steady Turning
Dodge Aries

Curve #2

Repeat 1

Steady Turning
Dodge Aries

Curve #3

Repeat 1

Steady Turning
Dodge Aries

Ramp

Repeat 1

Steady Turning
Dodge Aries
Ramp
Repeat 2
Steady Turning
Chan 6

Ave: 10.2

Chan 6

Ave: 2.97

Chan 7
Dodge Aries
Ramp
Repeat 3
Steady Turning
Chan # 2
Ave: 28.9

Chan # 3
Ave: .251

Chan # 4
Ford LTD

Curve #1

Repeat 1

Steady Turning
Ford LTD

Curve #1

Repeat 2

Steady Turning
Ford LTD

Curve #1

Repeat 3

Steady Turning
Ford LTD

Curve #2

Repeat 1

Steady Turning
Ford LTD
Curve #3
Repeat 1
Steady Turning
Ford LTD

Ramp

Repeat 1

Steady Turning
Ford LTD

Ramp

Repeat 2

Steady Turning
Appendix E.2

Tire Force Measurements

This appendix contains seven sets of tire data (three for the tractor-semitrailer and two each for the passenger cars). All measurements seen here are lateral tire forces at 0° camber and were collected on the UMTRI flat-bed tire test machine.
Tractor Front Tire

4000 LB VERTICAL LOAD

5000 LB VERTICAL LOAD

6000 LB VERTICAL LOAD

SLIP ANGLE (DEG)
Trailer Tire

3000 LB VERTICAL LOAD

4000 LB VERTICAL LOAD

5000 LB VERTICAL LOAD

SLIP ANGLE (DEG)
Dodge Aries Tire Measurements - Front

700 lb Load

Force (lb)

-300  -200  -100   0   1   2   3   4

Slip Angle (deg)
Dodge Aries Tire Measurements - Front

**Force (lb)**

*900 lb Load*

**Slip Angle (deg)**
Dodge Aries Tire Measurements - Front

1100 lb Load

Force (lb)

Slip Angle (deg)
Dodge Aries Tire Measurements - Rear

500 lb Load

Force (lb)

-200
-100
0
1
2
3
4

Slip Angle (deg)
Dodge Aries Tire Measurements - Rear

700 lb Load

Force (lb)

Slip Angle (deg)
Dodge Aries Tire Measurements - Rear

900 lb Load

Force (lb)

-300
-200
-100
0
100
200
300
400
500
600
700

Slip Angle (deg)

0 1 2 3 4
Ford LTD Tire Measurements - Front

750 lb Load

Force (lb)

Slip Angle (deg)
Ford LTD Tire Measurements - Front

950 lb Load

Force (lb)

Slip Angle (deg)
Ford LTD Tire Measurements - Front

1150 lb Load

Force (lb)

Slip Angle (deg)
Ford LTD Tire Measurements - Rear

650 lb Load

Force (lb)

Slip Angle (deg)
Force (Ib)

Ford LTD Tire Measurements - Rear

850 lb Load

Slip Angle (deg)
Ford LTD Tire Measurements - Rear

1050 lb Load

Force (lb)

Slip Angle (deg)
Appendix E.3

Tractor Steering System Measurements

The measurements seen in the next two figures were performed on the tractor unit in its normally loaded condition ("Loaded") and with its front axle off the ground ("No Load"). The plots show measurements of left and right front wheel angles in response to displacements of the steering wheel (plus and minus 200° or so). The loaded plot indicates an effective steering gear ratio of approximately 50:1 while the no load measurements indicate an effective steering gear ratio of about 37:1. The level of hysteresis for the loaded measurements are about 30° - 40° at the steering wheel or about 0.7° at the front wheels. The hysteresis seen for the no load condition is about 15° at the steering wheel and about 0.3° at the front wheel. The no load measurements were performed primarily to examine the influence of vertical load changes on the degree of hysteresis and effective gear ratio observed during the more normal loaded condition.
DFW VS. DSW NO LOAD
Appendix E.4

Estimation of Individual Wheel Friction Factors from Vehicle Response Measurements
The methodology outlined here for estimating friction factors based upon vehicle response measurements is a summary of the discussion proposed as part of the "Validation Plan" used to guide the vehicle testing. The experimental estimates of individual wheel friction factors seen in Chapter 5 were obtained in the manner described here.

The term "friction factor" (or "normalized force") simply refers to the ratio of the lateral tire force requirement at a particular wheel location to the prevailing vertical tire load. The quantities of direct interest, then, are 1) the lateral tire force and 2) vertical tire load. Since the lateral tire force at a particular wheel location, when operating within the linear maneuvering regime, is simply the product of tire cornering stiffness and tire slip angle, knowledge of these two quantities are, in turn, needed. Cornering stiffness estimates were obtained from laboratory tire measurements (as seen in Appendix E.2). The slip angles at each wheel location can be obtained from knowledge of the geometric location of the wheel with respect to the vehicle c.g. and measurement of (a) vehicle sideslip, (b) yaw rate, (c) forward velocity, and (d) wheel steer angles. For example, the slip angle at the front axle of an automobile or truck is provided by the expression

\[ \beta_f = \beta + a \frac{r}{V} - \delta \]

where

- \( \beta_f \) is the slip angle of the front tire/axle
- \( a \) is the distance from the vehicle c.g. to the front axle
- \( \beta \) is the vehicle sideslip measurement at the c.g.
- \( r \) is the vehicle yaw rate measurement
- \( V \) is the forward speed measurement

and

- \( \delta \) is the front wheel steer angle measurement

Multiplying \( \beta_f \) by the measured cornering stiffness will provide the needed estimate of lateral tire force at that wheel location.
The vertical tire loads prevailing under steady turning conditions can be estimated from knowledge of the static (curb) axle loads, the level of vehicle lateral acceleration, vehicle c.g. height, and suspension properties (stiffness / spring spacing / wheel track). Since each of these items were measured or obtained from the technical literature, reasonable estimates of vertical tire loads could be expected. For example, the load transfer across an axle due to steady turning can be closely estimated by the expression

\[ \Delta F_z = W h (A_y - \phi) K / (T K_t) \]

where

- \( \Delta F_z \) is the side-to-side load transfer across an axle
- \( W \) is the total vehicle weight
- \( h \) is the vehicle c.g. height
- \( A_y \) is the steady turning lateral acceleration (horizontal plane)
- \( \phi \) is the vehicle roll angle relative to the gravity vector (includes highway superelevation)
- \( K \) is the axle roll stiffness
- \( K_t \) is the total vehicle roll stiffness
- \( T \) is the axle tire track

The prevailing tire load is then obtained by adding (or subtracting) the \( \Delta F_z \) quantity to the known (measured) static tire load. An estimate of the individual wheel friction factor is then obtained by a simple ratio of the aforementioned lateral force estimate and the above vertical tire force estimate.
Appendix F

COMPARISONS OF MODEL PREDICTION AND TEST RESULTS

This appendix contains model/test result comparisons which supplement the material presented in chapter 5 of volume II. Figures F-1 to F-6 show various vehicle response measurements and model predictions for each of the test vehicles at curve sites 2 and 3. Figures F-1 and F-2 apply to the 5-axle tractor-trailer (vehicle C); figures F-3 and F-4 apply to the front-wheel-drive passenger car (vehicle A); figures F-5 and F-6 apply to the rear-wheel-drive passenger car (vehicle B).
Figure F-1. Model/test comparisons; vehicle C.
Steer Angle (deg)

Test Results vs. Model Predictions

Tractor-semi

Roll Angle (deg)

Test Results vs. Model Predictions

Tractor-semi

Figure F-1 (cont)
Figure F-1 (cont)
Figure F-1 (cont)
Figure F-2. Model/test comparisons; vehicle C.
Ramp Site: Tractor-semi

Test Results  Model

Steer Angle (deg)

Roll Angle (deg)

Repeat #

Figure F-2 (cont)
Ramp Site: Tractor-semi

Test Results

Model

Sideslip Angle (deg)

Repeat #

Path Radius (ft)

Repeat #

Figure F-2 (cont)

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Ramp Site: Tractor-semi

Articulation Angle (deg)

Test Results

Model

Figure F-2 (cont)
Dodge Aries

Test Results  Model

Speed (mph)

2 3

Curve

Figure F-3. Model/test comparisons; vehicle A.
Dodge Aries

Test Results  Model

Path Radius (ft)

0 200 400 600 800 1000 1200 1400

Curve #

2 3

Dodge Aries

Test Results  Model Predictions

Sideslip Angle (deg)

0.00 -0.05 -0.10 -0.15 -0.20

Figure F-3 (cont)
Figure F-4. Model/test comparisons; Vehicle A.
Ramp Site: Dodge Aries

Test Results vs Model Predictions

Steer Angle (deg)

Roll Angle (deg)

Figure F-4 (cont)
Ramp Site: Dodge Aries

Path Radius (ft)

Test Results vs. Model

Repeat #

Sideslip Angle (deg)

Test Results vs. Model Predictions

Repeat #

Figure F-4 (cont)
Figure F-5. Model/test comparisons; Vehicle B.
Ford LTD

<table>
<thead>
<tr>
<th>Test Results</th>
<th>Model Predictions</th>
</tr>
</thead>
</table>

Steer Angle (deg)

- Curve 2: Test Results: 0.8, Model Predictions: 0.4
- Curve 3: Test Results: 0.9, Model Predictions: 0.5

Roll Angle (deg)

- Curve 2: Test Results: 2.1, Model Predictions: 3.2
- Curve 3: Test Results: 2.3, Model Predictions: 3.1

Figure F-5 (cont)
Ford LTD

Test Results  Model

Curve Radius (ft)

-0.05 Sideslip Angle -0.10
-0.15

Figure F-5 (cont)

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Ramp Site: Ford LTD

Test Results vs. Model Predictions

**Speed (mph)**

- Repeat 1
- Repeat 2

Ramp Site: Ford LTD

Test Results vs. Model Predictions

**Lateral Accel (g's)**

- Repeat 1
- Repeat 2

Figure F-6. Model/test comparisons; Vehicle B.
Ramp Site: Ford LTD

Test Results  Model Predictions

Steer Angle (deg)

Roll Angle (deg)

Repeat #

Figure F-6 (cont)
Ramp Site: Ford LTD

<table>
<thead>
<tr>
<th>Sideslip Angle (deg)</th>
<th>Test Results</th>
<th>Model Predictions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>0.3</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Repeat #

Figure F-6 (cont)
Appendix G

TRACTOR-SEMITRAILER PARAMETER SENSITIVITIES
(VEHICLE RESPONSE VARIABLES)

The graphs contained in this appendix supplement the material presented in chapter 6 of volume II. Vehicle response variables showing sensitivities to various parameter variations are seen for the five-axle tractor-semitrailer vehicle. Figures G-1 to G-8 illustrate vehicle sensitivity to changes in grade, suspension properties, fifth-wheel placement, center-of-gravity location, and wheelbase.
Figure G-1. Parameter sensitivities; vehicle C.
Baseline: $R = 1273\, \text{ft}$  \hspace{2mm} $V = 47.6\, \text{mph}$  \hspace{2mm} $e = 0.067\, \text{ft/ft}$

Tractor-semitrailer

| 3% Up Grade | Baseline | 3% Down Grade |

![Grade Variations](image)

Grade Variations

Figure G-1 (cont)
Baseline: \( R = 1273 \text{ ft} \), \( V = 47.6 \text{ mph} \), \( e = 0.067 \text{ ft/ft} \)

Tractor-semi trailer variability:

- Softened 30%
- Baseline
- Stiffened 30%

**Front Wheel Steer Angle**

Tractor Rear Suspension Variations

**Roll Angle**

Tractor Rear Suspension Variations

**Articulation Angle**

Tractor Rear Suspension Variations

Figure G-2. Parameter variations: vehicle C.
Baseline: $R = 1273$ ft, $V = 47.6$ mph, $e = 0.067$ ft/ft
Tractor-semitrailer

- Softened 30%
- Baseline
- Stiffened 30%

Tractor Rear Suspension Variations

Figure G-2 (cont)
Baseline: $R = 1273 \text{ ft}$, $V = 47.6 \text{ mph}$, $e = 0.067 \text{ ft/ft}$

Tractor-semitrailer

![Bar chart showing trailer suspension variations for different settings of front wheel steer angle, roll angle, and articulation angle.]

**Figure G-3. Parameter variations; vehicle C.**
Baseline: $R = 1273 \text{ ft}$, $V = 47.6 \text{ mph}$, $e = 0.067 \text{ ft/fl}$

Tractor-semitrailer

- **Tractor Sideslip Angle**
  - Baseline
  - Softened 30%
  - Stiffened 30%

- **Trailer Sideslip Angle**
  - Baseline
  - Softened 30%
  - Stiffened 30%

Figure G-3 (cont)
Figure G-4. Parameter variations; vehicle C.
Baseline: $R = 1273$ ft. $V = 47.6$ mph. $e = 0.067$ ft/ft

Tractor-semitrailer

![Graph showing Tractor Sideslip Angle variations with Baseline, Forward 8\°, and Aft 6\° settings.]

5th Wheel Fore/Aft Variations

Figure G-4 (cont)
Figure G-5. Parameter variations; vehicle C.
Baseline: $R = 1273\, \text{ft}$, $V = 47.6\, \text{mph}$, $e = 0.067\, \text{ft/ft}$

Tractor-semitrailer

- 20° Lower
- Baseline
- 20° Higher

C.G. Height Variations

Tractor Sideslip Angle

C.G. Height Variations

Baseline: $R = 1273\, \text{ft}$, $V = 47.6\, \text{mph}$, $e = 0.067\, \text{ft/ft}$

Tractor-semitrailer

- 20° Lower
- Baseline
- 20° Higher

C.G. Height Variations

Trailer Sideslip Angle

C.G. Height Variations

Figure G-5 (cont)
Baseline: \[ R = 1273 \text{ ft} \quad V = 47.6 \text{ mph} \quad e = 0.067 \text{ ft/ft} \]
Tractor-semi trailer

**Front Wheel Steer Angle**

- **Forward 35°**
- **Baseline**
- **Aft 35°**

**Payload Fore/Aft Variations**

**Roll Angle**

- **Forward 35°**
- **Baseline**
- **Aft 35°**

**Payload Fore/Aft Variations**

**Articulation Angle**

- **Forward 35°**
- **Baseline**
- **Aft 35°**

**Payload Fore/Aft Variations**

*Figure G-6. Parameter variations; vehicle C.*
Figure G-6 (cont)
Baseline: $R = 1273$ ft  $V = 47.6$ mph  $e = 0.067$ ft/ft

Tractor-semi-trailer

- 20° Shorter
- Baseline
- 20° Longer

### Front Wheel Steer Angle

![Front Wheel Steer Angle Bar Chart]

### Roll Angle

![Roll Angle Bar Chart]

### Articulation Angle

![Articulation Angle Bar Chart]

Figure G-7. Parameter variations; vehicle C.
Baseline: $R = 1273 \text{ ft}$  $V = 47.6 \text{ mph}$  $e = 0.067 \text{ ft/ft}$

Tractor-semi-trailer

- 20° Shorter
- Baseline
- 20° Longer

Tractor Wheelbase Variations

**Figure G-7 (cont)**
Baseline: $R = 1273$ ft $V = 47.6$ mph $e = 0.067$ ft/ft

Tractor-semi trailer

<table>
<thead>
<tr>
<th>60° Shorter</th>
<th>Baseline</th>
<th>60° Longer</th>
</tr>
</thead>
</table>

Front Wheel Steer Angle

Roll Angle

Articulation Angle

Figure G-8. Parameter variations; vehicle C.
Semitrailer Wheelbase Variations

Tractor Sideslip Angle

Figure G-8 (cont)