

Vehicle Dynamics Terminology

SAE J670b

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Handbook Supplement

Vehicle Dynamics Terminology

SAE J670b

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FOREWORD

This revision of "Vehicle Dynamics Terminology, SAE J670b" has been expanded by the Vehicle Dynamics Committee to encompass terminology related to directional control of vehicles. Revisions have also been made to update the original terminology, and an alphabetical index has been appended to facilitate location of definitions.

The function of uniform terminology is to promote understandable and exact communication. A great deal of effort has been expended to make these definitions suit this purpose. It is recognized that this terminology, like other dictionaries, must be revised periodically to reflect current usage and changing needs. The Vehicle Dynamics Committee therefore solicits suggestions for improvements and additions to be considered in future revisions. Comments should be directed to SAE Headquarters.

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VEHICLE DYNAMICS TERMINOLOGY

NOTE: Italicized words and phrases appearing in a definition are themselves defined elsewhere in this Terminology.

1. MECHANICAL VIBRATION-QUALITATIVE TERMINOLOGY

1.1 VIBRATION (OSCILLATION), GENERAL - Vibration is the variation with time of the displacement of a body with respect to a specified reference dimension when the displacement is alternately greater and smaller than the reference. (Adapted from ANS Z24.1-1951, item 1.040.)

1.2 FREE VIBRATION - Free Vibration of a system is the *vibration* during which no variable force is externally applied to the system. (Adapted from ANS Z24.1-1951, item 2.135.)

1.3 FORCED VIBRATION - Forced vibration of a system is *vibration* during which variable forces outside the system determine the *period* of the vibration. (Adapted from ANS Z24.1-1951, item 2.130.)

1.3.1 Resonance - A *forced vibration* phenomenon which exists if any small change in *frequency* of the applied force causes a decrease in the *amplitude* of the vibrating system. (Adapted from ANS Z24.1, item 2.105.)

1.4 SELF-EXCITED VIBRATION - *Vibrations* are termed self-excited if the vibratory motion produces cyclic forces which sustain the *vibration*.

1.5 SIMPLE HARMONIC VIBRATION - *Vibration* at a point in a system is simple harmonic when the displacement with respect to time is described by a simple sine function.

1.6 STEADY STATE VIBRATION - Steady state vibration exists in a system if the displacement at each point recurs for equal increments of time. (Adapted from ANS Z24.1-1951, items 11.005 and 1.045.)

1.7 PERIODIC VIBRATION - Periodic vibration exists in a system when recurring *cycles* take place in equal time intervals.

1.8 RANDOM VIBRATION - Random vibration exists in a system when the *oscillation* is sustained but irregular both as to *period* and *amplitude*.

1.9 TRANSIENT VIBRATION - Transient vibration exists in a system when one or more component *oscillations* are discontinuous.

2. MECHANICAL VIBRATION-QUANTITATIVE TERMINOLOGY

2.1 PERIOD - Period of an *oscillation* is the smallest increment of time in which one complete sequence of variation in displacement occurs. (Adapted from ANS Z24.1-1951, item 1.050.)

2.2 CYCLE - Cycle of *oscillation* is the complete sequence of variations in displacement which occur during a *period*. (Adapted from ANS Z24.1-1951, item 1.055.)

2.3 FREQUENCY - Frequency of *vibration* is the number of *periods* occurring in unit time. (Adapted from ANS Z24.1-1951, item 1.060.)

2.3.1 *Natural Frequency* - Natural frequency of a body or system is a frequency of free vibration. (Same as ANS Z24.1-1951, item 2.140.)

2.3.2 *Exciting Frequency* - Exciting frequency is the *frequency* of variation of the exciting force.

2.3.3 *Frequency Ratio* - The ratio of *exciting frequency* to the *natural frequency*.

2.3.4 *Resonant Frequency* - *Frequency* at which *resonance* exists. (Same as ANS Z24.1-1951, item 2.110.)

2.4 AMPLITUDE - Amplitude of displacement at a point in a *vibrating system* is the largest value of displacement that the point attains with reference to its equilibrium position. (Adapted from ANS Z24.1-1951, item 1.070.)

2.4.1 *Peak-to-Peak Amplitude (Double Amplitude)* - Peak-to-Peak amplitude of displacement at a point in a *vibrating system* is the sum of the extreme values of displacement in both directions from the equilibrium position. (Adapted from ANS Z24.1-1951, item 1.075.)

2.4.2 *Static Amplitude* - Static amplitude in *forced vibration* at a point in a system is that displacement of the point from its specified equilibrium position which would be produced by a static force equal to the maximum value of exciting force.

2.4.3 *Amplitude Ratio (Relative Magnification Factor)* - The ratio of a *forced vibration* amplitude to the *static amplitude*.

2.5 VELOCITY - Velocity of a point in a *vibrating system* is the time rate of change of its displacement. (Adapted from ANS Z24.1-1951, item 1.345.)

In *simple harmonic vibration*, the maximum velocity,

$$v_m = \omega x$$

where:

$$\omega = 2\pi f$$

f = frequency

x = amplitude

2.6 ACCELERATION - Acceleration of a point is the time rate of change of the *velocity* of the point. (Same as ANS Z24.1-1951, item 1.355.)

In *simple harmonic vibration*, the maximum acceleration,

$$a_m = \omega^2 x$$

2.7 Jerk - "Jerk" is a concise term used to denote the time rate of change of *acceleration* of a point.

In *simple harmonic motion*, the maximum jerk,

$$j_m = \omega^3 x$$

2.8 TRANSMISSIBILITY - Transmissibility in *forced vibration* is the ratio of the transmitted force to the applied force.

3. VIBRATING SYSTEMS

3.1 DEGREE OF FREEDOM - The number of degrees of freedom of a *vibrating system* is the sum total of all ways in which the masses of the system can be independently displaced from their respective equilibrium positions.

EXAMPLES: A single rigid body constrained to move only vertically on supporting springs is a system of one degree of freedom. If the same mass is also permitted angular displacement in one vertical plane, it has two degrees of freedom: one being vertical displacement of the center of gravity; the other, angular displacement about the center of gravity.

3.2 LINEAR - Linear *vibrating systems* are those in which all the variable forces are directly proportional to the displacement, or to the derivatives of the displacement, with respect to time.

3.3 NONLINEAR - Nonlinear *vibrating systems* are those in which any of the variable forces are not directly proportional to the displacement, or to its derivatives, with respect to time.

EXAMPLE: A system having a variable *spring rate*.

3.4 UNDAMPED - Undamped systems are those in which there are no forces opposing the vibratory motion to dissipate energy.

3.5 DAMPED - Damped systems are those in which energy is dissipated by forces opposing the vibratory motion.

Any means associated with a *vibrating system* to balance or modulate exciting forces will reduce the vibratory motion, but are not considered to be in the same category as damping. The latter term is applied to an inherent characteristic of the system without reference to the nature of the excitation.

3.5.1 *Viscous Damping* - Damping in which the force opposing the motion is proportional and opposite in direction to the *velocity*.

3.5.2 *Critical Damping* - The minimum amount of *viscous damping* required in a *linear system* to prevent the displacement of the system from passing the equilibrium position upon returning from an initial displacement.

3.5.3 *Damping Ratio* - The ratio of the amount of *viscous damping* present in a system to that required for *critical damping*.

3.5.4 *Coulomb Damping* - Damping in which a constant force opposes the vibratory motion.

3.5.5 *Complex Damping* - Damping in which the force opposing the vibratory motion is variable, but not proportional, to the *velocity*.

In the field of aircraft flutter and vibration, complex damping is also used to denote a specific type of damping in which the damping force is assumed to be *harmonic* and in phase

with the *velocity* but to have an *amplitude* proportional to the *amplitude* of displacement.

4. COMPONENTS AND CHARACTERISTICS OF SUSPENSION SYSTEMS

4.1 VIBRATING MASS AND WEIGHT -

4.1.1 *Sprung Weight* - All weight which is supported by the suspension, including portions of the weight of the suspension members.

In the case of most vehicles, the sprung weight is commonly defined as the total weight less the weight of *unsprung parts*.

4.1.2 *Sprung Mass* - Considered to be a rigid body having equal mass, the same center of gravity, and the same moments of inertia about identical axes as the total *sprung weight*.

4.1.3 *Dynamic Index* - (k^2/ab ratio) is the square of the radius of gyration (k) of the *sprung mass* about a transverse axis through the center of gravity, divided by the product of the two longitudinal distances (a and b) from the center of gravity to the front and rear *wheel centers*.

4.1.4 *Unsprung Weight* - All weight which is not carried by the suspension system, but is supported directly by the tire or wheel, and considered to move with it.

4.1.5 *Unsprung Mass* - The unsprung masses are the equivalent masses which reproduce the inertia forces produced by the motions of the corresponding unsprung parts.

4.2 SPRING RATE - The change of load of a spring per unit deflection, taken as a mean between loading and unloading at a specified load.

4.2.1 *Static Rate* - Static rate of an elastic member is the rate measured between successive stationary positions at which the member has settled to substantially equilibrium condition.

4.2.2 *Dynamic Rate* - Dynamic rate of an elastic member is the rate measured during rapid deflection where the member is not allowed to reach static equilibrium.

4.3 RESULTANT SPRING RATE -

4.3.1 *Suspension Rate (Wheel Rate)* - The change of wheel load, at the *center of tire contact*, per unit vertical displacement of the *sprung mass* relative to the wheel at a specified load.

If the *wheel camber* varies, the displacement should be measured relative to the lowest point on the rim centerline.

4.3.2 *Tire Rate (Static)* - The *static rate* measured by the change of wheel load per unit vertical displacement of the wheel relative to the ground at a specified load and inflation pressure.

4.3.3 *Ride Rate* - The change of wheel load, at the *center of tire contact*, per unit vertical displacement of the *sprung mass* relative to the ground at a specified load.

4.4 STATIC DEFLECTION -

4.4.1 *Total Static Deflection* - Total static deflection of a loaded suspension system is the overall deflection under the static load from the position at which all elastic elements are free of load.

4.4.2 *Effective Static Deflection* - Effective static deflection of a loaded suspension system equals the static load

divided by the *spring rate* of the system at that load.

Total *static deflection* and effective static deflection are equal when the *spring rate* is constant.

4.4.3 *Spring Center* - The vertical line along which a vertical load applied to the *sprung mass* will produce only uniform vertical displacement.

4.4.3.1 Parallel Springing - Describes the suspension of a vehicle in which the *effective static deflections* of the two ends are equal; that is, the *spring center* passes through the center of gravity of the *sprung mass*.

4.5 DAMPING DEVICES - As distinct from specific types of damping, damping devices refer to the actual mechanisms used to obtain damping of suspension systems.

4.5.1 *Shock Absorber* - A generic term which is commonly applied to hydraulic mechanisms for producing damping of suspension systems.

4.5.2 *Snubber* - A generic term which is commonly applied to mechanisms which employ dry friction to produce damping of suspension systems.

5. VIBRATIONS OF VEHICLE SUSPENSION SYSTEMS

5.1 SPRUNG MASS VIBRATIONS -

5.1.1 *Rigid Body Modes* -

5.1.1.1 Bounce - The *oscillation* of the *sprung mass* which consists primarily of vertical displacement.

5.1.1.2 Pitch - The *oscillation* of the *sprung mass* which consists primarily of angular displacement about a transverse axis.

5.1.1.3 Roll - Angular displacement of the *sprung mass* about a central longitudinal axis with respect to its static position.

5.1.2 *Structural Modes (Shake)* - A mode of *vibration* of the entire *sprung mass* as a flexible body occurring generally in the *frequency* of 5-25 cps.

5.1.2.1 Torsional Shake - A mode of *vibration* of the entire *sprung mass* involving predominately twisting deformation of the structure.

5.1.2.2 Beaming - A mode of *vibration* of the entire *sprung mass* involving predominately bending deformation of the entire structure.

5.2 UNSPRUNG MASS VIBRATIONS -

5.2.1 *Wheel Vibration Modes* -

5.2.1.1 Hop - The vertical oscillatory motion of a wheel between the road surface and the *sprung mass*.

5.2.1.1.1 Parallel hop is the form of wheel hop in which a pair of wheels hop in phase.

5.2.1.1.2 Tramp is the form of wheel hop in which a pair of wheels hop in opposite phase.

5.2.1.2 Brake Hop - An oscillatory hopping motion of a single wheel or of a pair of wheels which occurs when brakes are applied in forward or reverse motion of the vehicle.

5.2.1.3 Power Hop - An oscillatory hopping motion of a single wheel or of a pair of wheels which occurs when *tractive force* is applied in forward or reverse motion of the vehicle.

5.2.2 *Axle Vibration Modes* -

5.2.2.1 Axle Side Shake - Oscillatory motion of an axle

which consists of transverse displacement.

5.2.2.2 Axle Fore- and- Aft Shake - Oscillatory motion of an axle which consists purely of longitudinal displacement.

5.2.2.3 Axle Yaw - Oscillatory motion of an axle around the vertical axis through its center of gravity.

5.2.2.4 Axle Windup - Oscillatory motion of an axle about the horizontal transverse axis through its center of gravity.

5.2.3 *Steering System Vibrations* -

5.2.3.1 Wheel Flutter - Forced *oscillation* of steerable wheels about their steering axes.

5.2.3.2 Wheel Wobble - A self-excited *oscillation* of steerable wheels about their steering axes, occurring without appreciable tramp.

5.2.3.3 Shimmy - A self-excited *oscillation* of a pair of steerable wheels about their steering axes, accompanied by appreciable *tramp*.

5.2.3.4 Wheelight - A rotary disturbance of the steering wheel produced by forces acting on the steerable wheels.

6. SUSPENSION GEOMETRY

6.1 KINGPIN GEOMETRY -

6.1.1 *Wheel Plane* - The central plane of the tire, normal to the *spin axis*.

6.1.2 *Wheel Center* - The point at which the *spin axis* of the wheel intersects the *wheel plane*.

6.1.3 *Center of Tire Contact* - The intersection of the *wheel plane* and the vertical projection of the *spin axis* of the wheel onto the road plane. (See Note 1.)

6.1.4 *Kingpin Inclination* - The angle in front elevation between the steering axis and the vertical.

6.1.5 *Kingpin Offset* - Kingpin offset at the ground is the horizontal distance in front elevation between the point where the steering axis intersects the ground and the *center of tire contact*.

The kingpin offset at the *wheel center* is the horizontal distance in front elevation from the *wheel center* to the steering axis.

6.2 WHEEL CASTER -

6.2.1 *Caster Angle* - The angle in side elevation between the steering axis and the vertical. It is considered positive when the steering axis is inclined rearward (in the upward direction) and negative when the steering axis is inclined forward.

6.2.2 *Rate of Caster Change* - The change in *caster angle* per unit vertical displacement of the *wheel center* relative to the *sprung mass*.

6.2.3 *Caster Offset* - The distance in side elevation between the point where the steering axis intersects the ground, and the *center of tire contact*. The offset is considered positive when the intersection point is forward of the tire contact center and negative when it is rearward.

6.2.4 *Centrifugal Caster* - The unbalance moment about the steering axis produced by a lateral acceleration equal to gravity acting at the combined center of gravity of all the steerable parts. It is considered positive if the combined center of gravity is forward of the steering axis and negative if rearward of the steering axis.

6.3 WHEEL CAMBER -

6.3.1 *Camber Angle* - The inclination of the *wheel plane* to the vertical. It is considered positive when the wheel leans outward at the top and negative when it leans inward.

6.3.2 *Rate of Camber Change* - The change of *camber angle* per unit vertical displacement of the *wheel center* relative to the *sprung mass*.

6.3.2.1 *Swing Center* - That instantaneous center in the transverse vertical plane through any pair of *wheel centers* about which the wheel moves relative to the *sprung mass*.

6.3.2.2 *Swing-Arm Radius* - The horizontal distance from the *swing center* to the *center of tire contact*.

6.3.3 *Wheel Track (Wheel Tread)* - The lateral distance between the *centers of tire contact* of a pair of wheels. For vehicles with dual wheels, it is the distance between the points centrally located between the *centers of tire contact* of the inner and outer wheels. (See SAE J693.)*

6.3.4 *Track Change* - The change in *wheel track* resulting from vertical suspension displacements of both wheels in the same direction.

6.3.5 *Rate of Track Change* - The change in *wheel track* per unit vertical displacement of both *wheel centers* in the same direction relative to the *sprung mass*.

6.4 WHEEL TOE -

6.4.1 *Static Toe-in (or Toe-out)* - Static toe-in (or toe-out) of a pair of wheels is the difference in the transverse distances between the *wheel planes* taken, respectively, at the extreme rear and front points of the *tire treads*. When the distance at the rear is greater the wheels are said to be "toed-in" by this amount; when smaller, the wheels are said to be "toed-out."

6.4.2 *Rate of Toe Change* - The change of *toe* per unit vertical displacement of both *wheel centers* relative to the *sprung mass*.

6.5 *COMPRESSION* - The relative displacement of *sprung* and *unsprung masses* in the suspension system in which the distance between the masses decreases from that at static condition.

6.5.1 *Ride Clearance* - The maximum displacement in *compression* of the *sprung mass* relative to the *wheel center* permitted by the suspension system, from the normal load position.

6.5.2 *Metal-to-Metal Position (Compression)* - The point of maximum *compression* travel limited by interference of substantially rigid members.

6.5.3 *Bump Stop* - An elastic member which increases the *wheel rate* toward the end of the *compression* travel.

The bump stop may also act to limit the *compression* travel.

6.6 *REBOUND* - The relative displacement of the *sprung* and *unsprung masses* in a suspension system in which the distance between the masses increases from that at static condition.

6.6.1 *Rebound Clearance* - The maximum displacement in *rebound* of the *sprung mass* relative to the *wheel center* permitted by the suspension system, from the normal load position.

6.6.2 *Metal-to-Metal Position (Rebound)* - The point of maximum *rebound* travel limited by interference of substantially rigid members.

6.6.3 *Rebound Stop* - An elastic member which increases the *wheel rate* toward the end of the *rebound* travel.

The *rebound stop* may also act to limit the rebound travel.

6.7 *CENTER OF PARALLEL WHEEL MOTION* - The center of curvature of the path along which each of a pair of *wheel centers* moves in a longitudinal vertical plane relative to the *sprung mass* when both wheels are equally displaced.

6.8 TORQUE ARM -

6.8.1 *Torque-Arm Center in Braking* - The instantaneous center in a vertical longitudinal plane through the *wheel center* about which the wheel moves relative to the *sprung mass* when the brake is locked.

6.8.2 *Torque-Arm Center in Drive* - The instantaneous center in a vertical longitudinal plane through the *wheel center* about which the wheel moves relative to the *sprung mass* when the drive mechanism is locked at the power source.

6.8.3 *Torque-Arm Radius* - The horizontal distance from the *torque-arm center* to the *wheel center*.

7. TIRES AND WHEELS

7.1 INDUSTRY STANDARDS

7.1.1 *Standard Loads and Inflation* - Those combinations of loads and inflation up to the maximum load and inflation recommended for best service by the tire industry for the various types of tires under the various service conditions as set up by the Tire and Rim Association and published in the yearly editions of the Tire and Rim Association Year Book.

7.1.2 *Rim Diameter* - The diameter at a reference point in relation to the rim tire *bead seat* and the rim flange. In rims for ground vehicles, this reference point is the intersection of the *bead seat* and the radial line forming the flange at the specified rim width.

In aircraft wheels, the diameter is measured at the point of tangency of the tapered *bead seat* and the radius connecting the flange to the tapered *bead seat*. (See Tire and Rim Association Year Book.)

7.1.3 *Rim Width* - The distance between the inside radial surfaces of the rim flanges. (See Tire and Rim Association Year Book.)

7.1.4 *Tire Section* - The width of the new tire mounted on specified rim, inflated to the maximum recommended pressure, including the normal *sidewalls* but not including protective rib, bars, and decorations. (See Tire and Rim Association Year Book.)

7.1.5 *Tire Width* - The width of a new tire, mounted on specified rim, inflated to the maximum recommended pressure, including protective rib, bars, and decorations. (See Tire and Rim Association Year Book.)

7.1.6 *Outside Diameter* - The unloaded maximum diameter

*Published in the SAE Handbook, available from Society of Automotive Engineers, Inc., Two Pennsylvania Plaza, New York, N. Y. 10001.

of the new tire inflated to the maximum recommended pressure mounted on a specified rim. (See Airplane Section, Tire and Rim Association Year Book.)

7.1.7 *Flat Tire Radius* - The distance from the *spin axis* to the road surface of a loaded tire at zero inflation.

7.2 GENERAL TERMS -

7.2.1 *Tread* - The tire tread is the peripheral position of the tire, the exterior of which maintains contact with the road surface.

7.2.1.1 *Tread Pattern* - The molded configuration on the face of the *tread*. It is generally composed of ribs, rows, grooves, bars, lugs, and the like.

7.2.1.2 *Sipes* - Sipes (slits, perforations) are cuts which do not remove material.

7.2.1.3 *Slots* - Slots (kerfs) are molded or cut narrow grooves where material is removed or displaced.

7.2.1.4 *Voids* - Voids (or pits) are depressions formed by mixing nonadherent particles into the *tread* compound or by mechanical laceration.

7.2.2 *Sidewall* - The position of either side of the tire which connects the *bead* with the *tread*.

7.2.2.1 *Sidewall Rib* - A raised circumferential rib located on the *sidewall*.

7.2.3 *Bead* - The portion of the tire which fits onto the rim of the wheel.

7.2.3.1 *Bead Base* - The approximately cylindrical portion of the *bead* that forms its inside diameter.

7.2.3.2 *Bead Toe* - That portion of the *bead* which joins the *bead* base and the inside surface of the tire.

7.2.4 *Standing Wave* - The stationary deformation pattern assumed by a tire rolling under load when its *forward velocity* exceeds a certain critical value.

7.2.5 *Pressure Buildup* - The increase in the tire inflation pressure resulting from an increase in tire temperature.

7.3 TIRE MEASUREMENTS - (At Tire and Rim Association recommended inflations.)

7.3.1 *Tread Contour (or Tread Radius)* - The unloaded cross sectional shape of *tread* neglecting the tread-pattern depressions usually given as a radius or combination of radii.

7.3.2 *Tread Width* -

7.3.2.1 *Tread Arc Width* - The distance from edge to edge of the *tread* measured along the *tread contour*.

7.3.2.2 *Tread Chord Width* - The distance from edge to edge of the *tread* measured parallel to the *spin axis*.

7.3.2.3 *Tread Contact Width* - The distance between the extreme edges of road contact measured parallel to the *spin axis*.

7.3.2.4 *Tread Contact Length* - The perpendicular distance between the tangents to edges of the leading and following points of road contact and perpendicular to the *wheel plane*.

7.3.3 *Tread Depth* - The distance between the base of a tire *tread* groove and a line tangent to the surface of the two adjacent *tread* ribs or rows.

7.3.4 *Contact Area, Gross* - The total area enclosing the pattern of the tire *tread* in contact with a flat surface at a definite load and inflation pressure.

7.3.5 *Loaded Radius* - (R_Q) is the distance from the *center*

of tire contact to the *wheel center* measured in the *wheel plane*.

7.3.6 *Run-Out, Radial* -

7.3.6.1 *Unloaded Radial Wheel Run-Out* - The difference between the maximum and minimum wheel bead *seat* radii, measured in a plane perpendicular to the *spin axis*.

7.3.6.2 *Unloaded Radial Tire Run-Out* - The difference between maximum and minimum undeflected tire radii, measured in a plane perpendicular to the *spin axis* on a true running wheel.

7.3.6.3 *Loaded Radial Tire Run-Out* - The difference between maximum and minimum *loaded radii* at a given load, inflation and speed on a true running wheel.

7.3.7 *Run-Out, Lateral* -

7.3.7.1 *Lateral Wheel Run-Out* - The difference between maximum and minimum indicator readings, measured parallel to the *spin axis* on the inside vertical portion of the rim flange.

7.3.7.2 *Lateral Tire Run-Out* - The difference between maximum and minimum indicator readings, measured parallel to the *spin axis* at the widest point of each *sidewall* of a tire, on a true running wheel.

7.3.8 *Deflection (Static)* - The radial difference between the undeflected tire radius and the static *loaded radius*, under specified load and inflation.

7.3.8.1 *Per Cent Deflection* - Per cent deflection is the ratio of the *static tire deflection* to the undeflected radial distance from the outside diameter of the rim flange to the *outside diameter* of the tire, expressed in percentage units.

7.3.9 *Tire Rate (Static)* - See paragraph 4.3.2.

7.4 ROLLING CHARACTERISTICS - See Suspension, Geometry, Section 6 including paragraphs 6.2, Wheel Caster; 6.3, Wheel Camber; and 6.4, Wheel Toe.

7.4.1 *Revolutions per Mile* - The number of revolutions a tire makes in a mile under free rolling conditions, at a given load, inflation, and speed, usually stated at 35 mph. (See Tire and Rim Association Year Book.)

7.4.2 *N over V Ratio* - (Revolutions per minute per mile per hour) of a tire is the number of *revolutions per mile* divided by 60.

7.4.3 *Effective Rolling Radius* - (R_e) is the ratio of the linear velocity of the *wheel center* in the X'-direction to the *spin velocity*. (See paragraph 7.5.1)

7.4.4 *Spin Axis* - The axis of rotation of the wheel. (See Fig. 1.)

7.4.5 *Spin Velocity* - (Ω) is the angular velocity of the wheel about its *spin axis*.

7.4.6 *Slip or Creep* - The change in distance traveled per revolution due to driving or braking conditions, expressed in per cent of the distance traveled under the free-rolling condition.

7.5 TIRE FORCES AND MOMENTS - (See Note 2.)

7.5.1 *Tire Axis System (Fig. 1)* - The origin of the tire axis system is the *center of tire contact*. The X'-axis is the intersection of the *wheel plane* and the road plane with a positive direction forward. The Z'-axis is perpendicular to the road

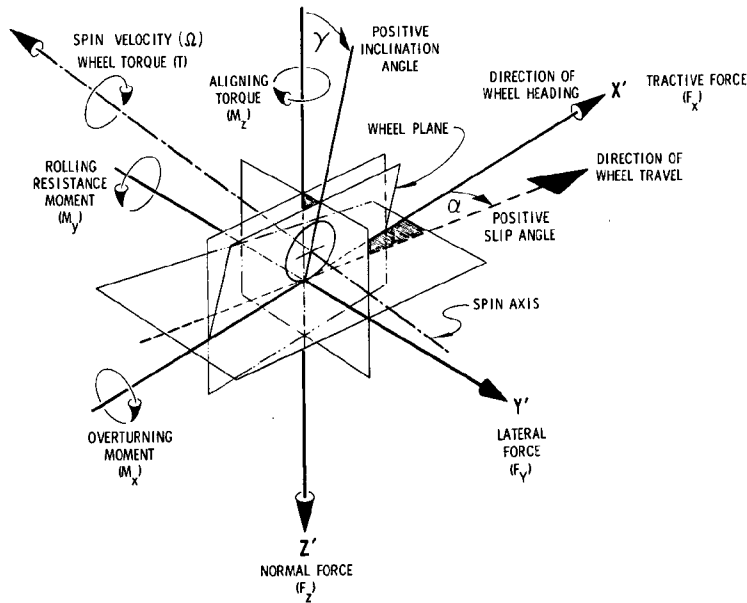


Fig. 1 - Tire axis system

plane with a positive direction downward. The Y'-axis is in the road plane, its direction being chosen to make the axis system orthogonal and right-hand.

7.5.2 Tire Angles -

7.5.2.1 Slip Angle - (α) is the angle formed between the direction of travel of the *center of tire contact* and the X'-axis.

7.5.2.2 Inclination Angle - (γ) is the angle formed between the X'Z' plane and the *wheel plane*. This angle is equivalent to *camber angle* (paragraph 6.3.1) except for the sign convention.

7.5.3 Tire Forces -

7.5.3.1 Tractive Force - (F_x) is the component in the X'-direction of the resultant force acting on the tire by the road.

7.5.3.2 Lateral Force - (F_y) is the component in the Y'-direction of the resultant force acting on the tire by the road.

7.5.3.3 Normal Force - (F_z) is the component in the Z'-direction of the resultant force acting on the tire by the road.

7.5.3.4 Vertical Load - The normal reaction of the tire on the road which is equal to the negative of *normal force*.

7.5.3.5 Cornering Force - The *lateral force* when the *inclination angle* is zero.

7.5.3.6 Camber Force (Camber Thrust) - The *lateral force* when the *slip angle* is zero.

7.5.3.7 Rolling Resistance Force - (F_r) is the force which must be applied to the wheel at the *wheel center* with a line of action parallel to the X'-axis so that its moment with respect to a line through the *center of tire contact* and parallel to the *spin axis* of the wheel will balance the moment of the tire contact forces about this line. This force can be computed from the forces and moments acting on the tire by the road.

$$F_r = \frac{M_y \cos \gamma + M_z \sin \gamma}{R_q}$$

(See Note 3.)

7.5.4 Tire Moments -

7.5.4.1 Overturning Moment - (M_x) is the moment about the X'-axis acting on the tire by the road.

7.5.4.2 Rolling Resistance Moment - (M_y) is the moment about the Y'-axis acting on the tire by the road.

7.5.4.3 Aligning Torque - (M_z) is the moment about the Z'-axis acting on the tire by the road.

7.5.4.4 Wheel Torque - (T) is the external torque applied from the vehicle about the *spin axis* of the wheel. The wheel torque applied can be computed from the forces and moments acting on the tire by the road.

$$T = F_x R_q + M_y \cos \gamma + M_z \sin \gamma$$

(See paragraph 7.5.3.7 and Note 3.)

7.5.5 Tire Coefficients -

7.5.5.1 Cornering Stiffness (Cornering Rate, Cornering Power) - (C_α) is the negative of the derivative of the *lateral force* with respect to *slip angle*. It may be evaluated at any set of operating conditions.

$$C_\alpha = - \frac{\partial F_y}{\partial \alpha}$$

(See Note 4.)

7.5.5.2 Cornering Coefficient - The ratio of *cornering stiffness* to the *vertical load*. It may be evaluated at any set of operating conditions.

7.5.5.3 Camber Stiffness (Camber Rate, Camber Thrust Rate) - (C_γ) is the derivative of the *lateral force* with respect to *inclination angle*. It may be evaluated at any set of operating conditions.

ing conditions.

$$C_{\gamma} = \frac{\partial F_y}{\partial \gamma}$$

(See Note 4.)

7.6 TIRE NOISE -

7.6.1 *Tread Noise* - The term applied to the sound produced on smooth road surfaces by the tire rolling freely (except for tire *rolling resistance* and wheel bearing friction) in a straight line.

7.6.2 *Road Noise* - The term applied to the sound produced on rough road surfaces by a tire rolling freely in a straight line.

7.6.3 Squeal -

7.6.3.1 *Cornering Squeal* - The noise produced between the tire and the road when a tire is rolling at a *slip angle*.

7.6.3.2 *Tractive Squeal* - The noise produced by fore-and-aft slippage between a rolling tire and road due to *tractive* or braking forces.

8. KINEMATICS: FORCE AND MOMENTS NOTATION

8.1 **EARTH-FIXED AXIS SYSTEM (X, Y, Z)** - This system is a right-hand orthogonal axis system fixed on the earth. The trajectory of the vehicle is described with respect to this earth-fixed axis system. The X and Y-axis are in a horizontal plane and the Z-axis is directed downward.

8.2 **VEHICLE AXIS SYSTEM (x, y, z)** - This system is a right-hand orthogonal axis system fixed in a vehicle such that with the vehicle moving steadily in a straight line on a level road, the x-axis is substantially horizontal, points forward, and is in the longitudinal plane of symmetry. The y-axis points to the driver's right and the z-axis points downward. (See Fig. 2.)

8.3 **ANGULAR ORIENTATION** - The orientation of the vehicle axis system (x, y, z) with respect to the earth-fixed axis

system (X, Y, Z) is given by a sequence of three angular rotations. The following sequence of rotations (see Note 5), starting from a condition in which the two sets of axis are initially aligned, is defined to be the standard:

- (1) A yaw rotation, Ψ , about the aligned z and Z-axis.
- (2) A pitch rotation, θ , about the vehicle y-axis.
- (3) A roll rotation, ϕ , about the vehicle x-axis.

8.4 **MOTION VARIABLES** - The Velocity of the vehicle relative to the earth-fixed axis system (X, Y, Z) is a vector quantity. The following motion variables are components of this vector resolved with respect to the moving vehicle axis system (x, y, z) relative to the earth-fixed axis system (X, Y, Z).

8.4.1 *Forward Velocity* (Longitudinal Velocity) (u) of a point in the vehicle is the component of the vector velocity in the x-direction.

8.4.2 *Lateral Velocity* (Sideslip Velocity) (v) of a point in the vehicle is the component of the vector velocity in the y-direction.

8.4.3 *Vertical Velocity* (Bounce Velocity) (w) of a point in the vehicle is the component of the vector velocity in the z-direction.

8.4.4 *Roll Velocity* (p) - The angular velocity about the x-axis.

8.4.5 *Pitch Velocity* (q) - The Angular velocity about the y-axis.

8.4.6 *Yaw Velocity* (r) - The angular velocity about the z-axis.

8.4.7 *Heading Angle* (Ψ) - The angle between the trace on the X-Y plane of the vehicle x-axis and the X-axis of the earth-fixed axis system. (See Fig. 3.)

8.4.8 *Sideslip Angle* (Attitude Angle) (β), is the angle between the traces on the X-Y plane of the vehicle x-axis and the vehicle velocity vector at some specified point in the vehicle. Sideslip angle is shown in Fig. 3 as a negative angle.

8.4.9 *Course Angle* (ν) is the angle between the trace of the vehicle velocity vector on the X-Y plane and X-axis of the earth-fixed axis system. A positive course angle is shown in

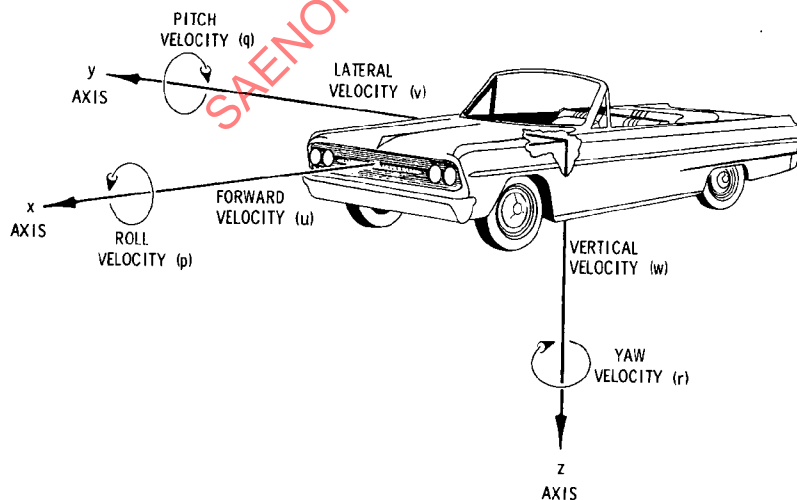


Fig. 2 - Directional control axis system

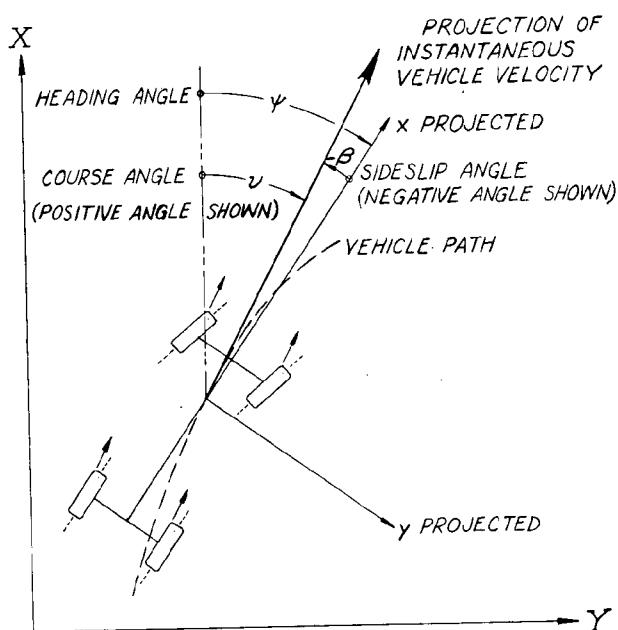


Fig. 3 - Heading, sideslip, and course angles

Fig. 3. Course angle is the sum of heading angle and sideslip angle ($\nu = \Psi + \beta$).

8.5 FORCES - The forces acting on the automobile can be summed into one force vector having the following components:

8.5.1 Longitudinal Force (F_x) - The force along the positive x-axis.

8.5.2 Lateral Force (F_y) - The force along the positive y-axis.

8.6 MOMENTS - The moments acting on the automobile can be summed into one moment vector having the following components:

8.6.1 Rolling Moment (M_x) - The moment tending to roll the vehicle about the x-axis, positive clockwise when looking in the positive direction of the x-axis.

8.6.2 Pitching Moment (M_y) - The moment tending to rotate the vehicle about the y-axis, positive clockwise when looking in the positive direction of the y-axis.

8.6.3 Yawing Moment (M_z) - The moment tending to rotate the vehicle about the z-axis, positive clockwise when looking in the positive direction of the z-axis.

9. DIRECTIONAL DYNAMICS

9.1 CONTROL MODES -

9.1.1 Position Control - That mode of vehicle control wherein inputs or restraints are placed upon the steering system in the form of displacements at some control point in the steering system (front wheels, Pitman arm, steering wheel), independent of the force required.

9.1.2 Fixed Control - That mode of vehicle control wherein the position of some point in the steering system (front wheels, Pitman arm, steering wheel) is held fixed. This is a

special case of position control.

9.1.3 Force Control - That mode of vehicle control wherein inputs or restraints are placed upon the steering system in the form of forces, independent of the displacement required.

9.1.4 Free Control - That mode of vehicle control wherein no restraints are placed upon the steering system. This is a special case of force control.

9.2 VEHICLE RESPONSE - The vehicle motion resulting from some internal or external input to the vehicle. Response tests can be used to determine the stability and control characteristics of a vehicle.

9.2.1 Control Response - The vehicle motion resulting from an input to the control (steering) element. (See Note 6.)

9.2.2 Disturbance Response - The vehicle motion resulting from unwanted force or displacement inputs applied to the vehicle. Examples of disturbances are wind forces or vertical road displacements.

9.2.3 Steady State - Steady state exists when periodic (or constant) vehicle responses to periodic (or constant) control and/or disturbance inputs do not change over an arbitrarily long time. The motion responses in steady state are referred to as steady state responses. This definition does not require the vehicle to be operating in a straight line or on a level road surface. It can also be in a turn of constant radius or on a cambered road surface.

9.2.4 Transient State - Transient state exists when the motion responses, the external forces relative to the vehicle, or the control positions are changing with time. (See Note 7.)

9.2.5 Trim - The steady state (that is, equilibrium) condition of the vehicle with constant input which is used as the reference point for analysis of dynamic vehicle stability and control characteristics.

9.2.6 Steady State Response Gain - The ratio of change in the steady state response of any motion variable with respect to change in input at a given trim.

9.2.7 Control Sensitivity (Control Gain) - The change in steady state lateral acceleration per unit change in reference steer angle at a given trim.

9.3 STABILITY - (See Note 8.)

9.3.1 Asymptotic Stability - Asymptotic stability exists at a prescribed trim if, any small temporary change in disturbance or control input, the vehicle will approach the motion defined by the trim.

9.3.2 Neutral Stability - Neutral stability exists at a prescribed trim if, for any small temporary change in disturbance or control input, the resulting motion of the vehicle remains close to, but does not return to, the motion defined by the trim.

9.3.3 Divergent Instability - Divergent instability exists at a prescribed trim if any small temporary disturbance or control input causes an ever increasing vehicle response without oscillation. (See Note 9.)

9.3.4 Divergent Instability Boundary - Divergent instability boundary is defined for a fixed speed as that lateral acceleration at which the derivative of the reference steer angle with respect to lateral acceleration is zero (Fig. 4). The vehicle is divergently unstable when this derivative is negative. The di-

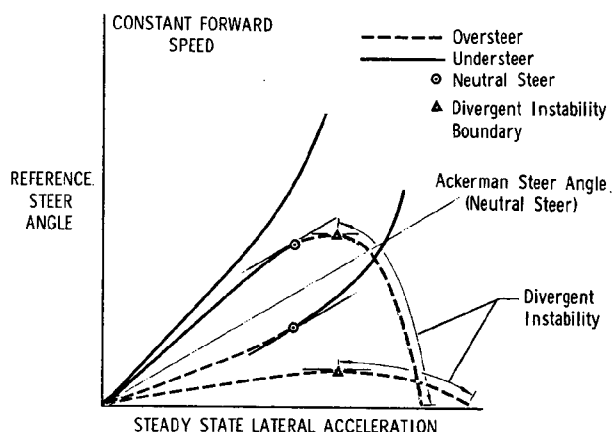


Fig. 4 - Steer properties

vergent instability boundary will generally be a function of speed.

9.3.5 *Oscillatory Instability* - Oscillatory instability exists if a small temporary disturbance or *control input* causes an oscillatory *vehicle response* of ever increasing amplitude about the initial *trim*. (See Note 10.)

9.4 SUSPENSION STEER AND ROLL PROPERTIES (Fig. 4) - (See Note 11.)

9.4.1 *Ackerman Steer Angle* - (δ_a) is the angle whose tangent is the wheel base divided by the radius of turn.

9.4.2 *Reference Steer Angle* - (δ) is the angle of the steered wheels (measured from the straight ahead position) which would result from an input to some point of an infinitely stiff steering system with no *roll* of the vehicle. (See Note 12.)

9.4.3 *Neutral Steer* - A vehicle is neutral steer at a given *trim* if the change in *reference steer angle* per unit change in steady state lateral acceleration at constant speed is equal to the change in *Ackerman steer angle* per unit change in steady state lateral acceleration. (See Note 13.)

9.4.4 *Understeer* - A vehicle is understeer at a given *trim* if the change in *reference steer angle* per unit change in steady state lateral acceleration at constant speed is greater than the change in *Ackerman steer angle* per unit change in steady state lateral acceleration. (See Note 13.)

9.4.5 *Oversteer* - A vehicle is oversteer at a given *trim* if the change in *reference steer angle* per unit change in steady state lateral acceleration at constant speed is less than the change in *Ackerman steer angle* per unit change in steady state lateral acceleration. (See Note 13.)

9.4.6 *Characteristic Speed* - That forward speed for an *understeer* vehicle at which the control sensitivity at zero lateral acceleration *trim* is one-half the *control sensitivity* of a *neutral steer* vehicle.

9.4.7 *Critical Speed* - That forward speed for an *oversteer* vehicle at which the *control sensitivity* at zero lateral acceleration *trim* is infinite.

9.4.8 *Neutral Steer Line* - The set of points in the x-z plane at which external lateral forces applied to the *sprung mass* produce no *steady state yaw velocity*.

9.4.9 *Static Margin* - The horizontal distance from the center of gravity to the *neutral steer line* divided by the wheel-base. It is positive if the center of gravity is forward of the *neutral steer line*.

9.4.10 *Roll Steer* - The steering motion of the front or rear wheels with respect to the *sprung mass* that is due to the relative rolling motion of the *sprung* to the *unsprung mass*. It is called *roll understeer*, if its influence is such as to induce vehicle *understeer*; and it is called *roll oversteer*, if its influence is such as to induce vehicle *oversteer*.

9.4.11 *Roll Steer Coefficient* - The change in steer angle per unit change in *roll angle* about a horizontal axis in the *sprung mass* plane of symmetry.

9.4.12 *Deflection Steer* (Compliance Steer) - The steering motion of the front or rear wheels with respect to the *sprung mass* resulting from compliance in, and forces on, the suspension and steering linkages. It is called *deflection understeer* if its influence is such as to induce vehicle *understeer* and it is called *deflection oversteer* if its influence is such as to induce vehicle *oversteer*. Suspension and steering linkage deflections may be caused by forces and moments in any of the planes defined by the axis system.

9.4.13 *Deflection Steer Coefficient* - The change in steer angle per unit change in force or moment applied to the tire at the road contact.

9.4.14 *Roll Camber Coefficient* - The *camber* motion of the wheels that is due to the relative rolling motion of the *sprung* to the *unsprung mass*.

9.4.15 *Roll Camber Coefficient* - The change in wheel *inclination angle* per unit change in *roll angle* about a horizontal axis in the *sprung mass* plane of symmetry.

9.4.16 *Deflection Camber* (Compliance Camber) - The *camber* motion of the wheels resulting from compliance in the suspension linkage. Suspension deflections may be caused by forces and moments in any of the planes defined by the axis system.

9.4.17 *Deflection Camber Coefficient* - The change in wheel *inclination angle* per unit change in force or moment applied to the tire at the road contact.

9.4.18 *Roll Center* - That point in the transverse vertical plane through any pair of *wheel centers* and equidistant from them, at which lateral forces may be applied to the *sprung mass* without producing an angular (roll) displacement of the *sprung mass*.

9.4.19 *Neutral Roll Axis* - The line joining the front and rear *roll centers*.

9.4.20 *Roll Rate* - The change in the restoring couple exerted by the suspension at either pair of wheels on the *sprung mass* of the vehicle per unit change in *roll angle* of the *sprung mass* about a horizontal axis. Roll rate of the complete vehicle is the sum of the separate roll rates of all vehicle suspensions.

9.4.21 *Roll Rate Distribution* - The division of the total *roll rate* between front and rear suspensions expressed as the percentage of the total.

9.5 TIRE LOAD TRANSFER -

9.5.1 *Lateral Tire Load Transfer* - The *vertical load* transferred from one of the front tires (or rear tires) to the other

that is due to acceleration, rotational, or inertial effects in the lateral direction.

9.5.2 Lateral Tire Load Transfer Distribution - The division of the total lateral tire load transfer between the front and rear tires expressed as the percentage of the total.

9.5.3 Longitudinal Tire Load Transfer - The vertical load transferred from a front tire to the corresponding rear tire that is due to acceleration, rotational, or inertial effects in the longitudinal direction.

9.5.4 Overturning Couple - The overturning moment on the vehicle with respect to a central, longitudinal axis in the road plane due to lateral acceleration and roll acceleration.

9.5.5 Overturning Couple Distribution - The division of the total overturning couple between the front and rear suspensions expressed as the percentage of the total.

10. AERODYNAMIC NOMENCLATURE

10.1 AERODYNAMIC MOTION VARIABLES -

10.1.1 Ambient Wind Velocity (v_a) is the horizontal component of the air mass velocity relative to the earth-fixed axis system in the vicinity of the vehicle.

10.1.2 Ambient Wind Angle (ν_a) is the angle between the X axis of the earth-fixed axis system and the ambient wind velocity vector. A positive ambient wind angle is shown in Fig. 5.

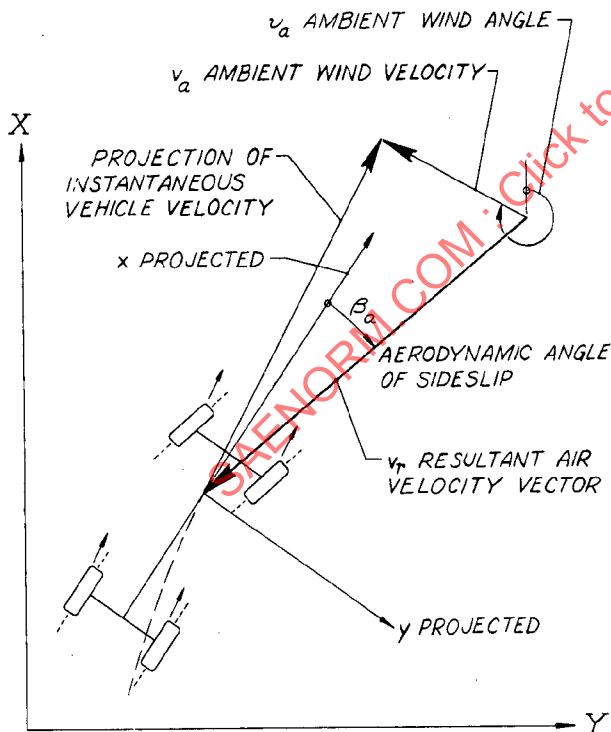


Fig. 5 - Wind vectors

10.1.3 Resultant Air Velocity Vector (v_r) is the vector difference of the ambient wind velocity vector and the projection of the velocity vector of the vehicle on the X-Y plane.

10.1.4 Aerodynamic Sideslip Angle (β_a) is the angle between the traces on the vehicle X-Y plane of the vehicle X-axis and the resultant air velocity vector at some specified point in the vehicle.

10.1.5 Aerodynamic Angle of Attack - (α_a) is the angle between the vehicle x-axis and the trace of the resultant air velocity vector on a vertical plane containing the vehicle x-axis.

10.2 AERODYNAMIC FORCE AND MOMENT COEFFICIENTS -

10.2.1 Reference Dimensions

10.2.1.1 Vehicle Area (A) is the projected frontal area including tires and underbody parts.

10.2.1.2 Vehicle Wheelbase (ℓ) is the characteristic length upon which aerodynamic moment coefficients are based.

10.2.2 Standard Air Properties

10.2.2.1 The density of standard dry air shall be taken as 2378×10^{-6} slugs/ft at 59 F and 29.92 in. Hg.

10.2.2.2 The viscosity of Standard dry air shall be taken as 373×10^{-9} slugs/ft-sec.

10.2.3 Force Coefficients

10.2.3.1 The Longitudinal Force Coefficient (C_x) is based on the aerodynamic force acting on the vehicle in the x direction (as established by paragraph 8.2) and is defined as:

$$C_x = \frac{F_x}{qA}$$

where q is dynamic pressure at any given relative air velocity as given by the formula

$$q = \frac{\rho v^2}{2}$$

10.2.3.2 The Lateral Force Coefficient (C_y) is based on the aerodynamic force acting on the vehicle in the y direction (as established by paragraph 8.2) and is defined as:

$$C_y = \frac{F_y}{qA}$$

10.2.3.3 The Normal Force Coefficient (C_z) is based on the aerodynamic force acting in the z direction (as established by paragraph 8.2) and is defined as:

$$C_z = \frac{F_z}{qA}$$

10.2.4 Moment Coefficients

10.2.4.1 The Rolling Moment Coefficient (C_{M_x}) is based

on the rolling moment deriving from the distribution of aerodynamic forces acting on the vehicle and is defined as:

$$C_{M_x} = \frac{M_x}{qA\ell}$$

10.2.4.2 The Pitching Moment Coefficient (C_{M_y}) is based on the pitching moment deriving from the distribution of aerodynamic forces acting on the vehicle and is defined as:

$$C_{M_y} = \frac{M_y}{qA\ell}$$

10.2.4.3 The Yawing Moment Coefficient (C_{M_z}) is based on the yawing moment deriving from the distribution of aerodynamic forces acting on the vehicle and is defined as:

$$C_{M_z} = \frac{M_z}{qA\ell}$$

NOTES

1. The *center of tire contact* may not be the geometric center of the tire contact area due to distortion of the tire produced by applied forces.

2. It is important to recognize that to make axis transformations and resolve these forces with respect to the direction of vehicle motion, it is essential to measure all six force and moment components defined in paragraphs 7.5.3.1-7.5.3.3 and 7.5.4.1-7.5.4.3.

3. This rolling resistance force definition has been generalized so that it applies to wheels which are driven or braked. The *wheel torque* can be expressed in terms of the *tractive force*, *rolling resistance force*, and *loaded radius* by the equation

$$T = (F_x + F_r) R\ell$$

For a free-rolling wheel, the *rolling resistance force* is therefore the negative of the *tractive force*.

4. For small *slip* and *inclination angles*, the *lateral force* developed by the tire can be approximated by:

$$F_y = C_{\alpha}\alpha + C_{\gamma}\gamma$$

5. Angular rotations are positive clockwise when looking in the positive direction of the axis about which rotation occurs.

6. Although the steering wheel is the primary directional control element, it should be recognized that *tractive forces* at the wheels resulting from driver inputs to brakes or throttle can modify directional response.

7. Transient responses are described by the terminology normally employed for other dynamic systems. Some terminology is described in the "Control Engineers' Handbook,"* but a more complete terminology is contained in ANS C85.1-1963.**

8. Passenger vehicles exhibit varying characteristics depending upon environment and *trim*. Environment refers to the atmospheric and road conditions which affect vehicle parameters. For example, temperature may change shock absorber damping characteristics and a slippery road surface may change tire cornering properties. *Trim* has been previously defined as the vehicle operating condition within a given environment, and may be specified in part by steer angle, *forward velocity*, and lateral acceleration. Since all these factors change the vehicle behavior, the vehicle *stability* must be examined separately for each environment and *trim*.

Given a set of vehicle parameters based on particular environment, the vehicle may be examined for each theoretically attainable *trim*. The conditions which most affect *stability* are the *steady state* values of *forward velocity* and lateral accelerations. In practice, it is possible for a vehicle to be stable under one set of operating conditions and unstable in another.

9. Divergent instability may be illustrated by operation above the *critical speed of an oversteer vehicle*. Any input to the steering wheel will place the vehicle in a turn of ever decreasing radius unless the driver makes compensating motions of the wheel to maintain general equilibrium. This condition represents *divergent instability*. A linear mathematical analog of a vehicle is *divergently unstable* when its characteristic equation has any positive real roots.

10. Oscillatory instability may be illustrated by the *free control response* following a pulse input of displacement or force to the steering wheel. Some vehicles will turn first in one direction, and then the other, and so on, until the *amplitude* of the motion increases to the extent that the vehicle "spins out." In this event, the vehicle does not attempt to change its general direction of motion, but does not achieve a *steady state* condition and has an *oscillatory* motion. A linear mathematical analog of a vehicle is *oscillatorily unstable* when its characteristic equation has any complex roots with positive real parts.

11. It is possible for a vehicle to be *understeer* for small inputs and *oversteer* for large inputs, (or the opposite) as shown in Fig. 4, since it is a nonlinear system and does not have the same characteristics at all *trims*. Consequently, it is necessary to specify the range of inputs and velocities when making a determination of the vehicle's *steer characteristics*.

There is a set of equivalent definitions in terms of *yaw velocity* or curvature (reciprocal of radius of curvature), which can be used interchangeably with these definitions. These definitions only apply to two-axle vehicles, since the *Ackerman steer angle* only applies to two-axle vehicles.

12. The actual front wheel steer angle is a function of the steering input to some point in the steering system, the change in steer angle caused by the tire forces and moments acting on the suspension and steering system compliance, and the change in steer angle due to the roll angle and suspension geometry. Since the tire forces and moments and vehicle roll angle are dependent upon the vehicle motions, the effects of the compliance and geometry modify the *vehicle response* and *stability*, and must be included in *stability* and *response* analyses. It is convenient, however, to have a reference which is referred

*John G. Truxal (Ed.), "Control Engineers' Handbook." New York: McGraw-Hill.

**"Terminology for Automatic Control." ANS C85.1-1963. Published by American Society of Mechanical Engineers.