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(R) Vehicle Dynamics Terminology

RATIONALE

SAE J670 was last updated over 30 years ago. Since the last revision, the field of vehicle dynamics has changed significantly. New systems such as four-wheel steering and active control have been applied to enhance the performance of vehicles. The terminology for vehicle dynamics needed to be updated to accommodate these new technologies and to make the definitions consistent with current usage in the field. Accordingly, many new terms have been added to the terminology to provide formal definitions for terms that are associated with these new technologies. A number of existing definitions, which were based on front-wheel steer vehicles with passive control, were also revised to accommodate new technologies.

In addition, new SAE and ISO standards have been published since the last revision of SAE J670 that directly relate to topics considered in SAE J670. The content of these new standards also indicated the need to revise SAE J670.

Specifically, in 1987, SAE published J1594, containing aerodynamics terminology previously appearing in SAE J670e. The aerodynamics section of SAE J670e is not included in the revised document, because those terms are now defined in SAE J1594.

In 1991, the International Organization for Standardization (ISO) published a vehicle dynamics vocabulary, ISO 8855. SAE J670e and ISO 8855 are incompatible in several aspects, the most notable being the axis systems defined in the two documents. SAE J670e utilizes an axis system based on aeronautical practice, with positive X forward, positive Y to the right, and positive Z down. ISO 8855 utilizes an axis system with positive X forward, positive Y to the left, and positive Z up. The revised SAE J670 embraces both of these axis orientations. The revised SAE J670 additionally addresses technical shortcomings found in both SAE J670e and ISO 8855 and is a harmonized superset of the two documents.

In 1998, SAE published J2047, containing definitions for tire performance terms that were previously defined in SAE J670e. The revised SAE J670 utilizes many definitions excerpted from SAE J2047, although some of these definitions are revised to enhance their applicability to vehicle dynamics.

Several of the sections of SAE J670e dealing with vibration terminology are not included in the new SAE J670, as the terms that were defined in these sections are commonly defined in engineering textbooks and the definitions are not specific to vehicle dynamics.

Finally, the terminology is extended to include definitions for many suspension and steering components, to enhance communication among vehicle dynamics professionals.

This seventh edition of SAE J670 replaces the preceding edition (SAE J670e) in its entirety.

SAE J670 has been reaffirmed to comply with the SAE Five-Year Review policy.

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FOREWORD

This terminology is intended to be sufficient to allow meaningful communication between vehicle dynamics professionals who need to describe the static and dynamic characteristics of automobiles, light trucks, and trailers. The terminology is to be used for presenting results and findings concerning the longitudinal, lateral, vertical and rotational dynamic performance of the applicable vehicles as predicted by analyses and simulations or as measured in tests and operational situations.

The purpose of this terminology is not to cover all terms in the manner of a dictionary or terms found in a basic engineering textbook. Rather, this document contains compatible definitions that have been carefully selected to aid in conveying ideas with rigor and accuracy in a readily understood and generally acceptable manner.

The terminology draws upon terms and definitions previously appearing in SAE J670e and ISO 8855 and further develops those that are applicable to the subjects covered by this document. For application to the study of vehicle dynamics, the tire terminology in this document contains pertinent definitions extracted from or based upon SAE J2047. Definitions for many chassis components are also provided.

Many of the definitions in the document contain terms appearing in *italic font*. Definitions for terms in *italic* may be found elsewhere in the document.

INTRODUCTION

ISO 8855:1991 is the international standard corresponding to SAE J670. The scopes of these two standards are different. The scope of SAE J670 is limited to passenger cars and light trucks with two axles, plus those vehicles in combination with single-axle trailers. The scope of ISO 8855 additionally includes heavy commercial vehicles, with multiple axles and multiple units. SAE J670 recognizes axis systems with both Z-Up and Z-Down orientations, while ISO 8855 only recognizes the Z-Up orientation. SAE J670 defines five axis systems: Earth, intermediate, vehicle, tire, and wheel, while ISO 8855 defines four axis systems: Earth, intermediate, vehicle, and wheel (equivalent to the SAE J670 tire system). SAE J670 accommodates four-wheel steering, while ISO 8855 does not. SAE J670 accommodates an inclined road surface that is non-uniform, while ISO 8855 is limited to application on a flat, horizontal road surface. SAE J670 includes definitions for many suspension and steering components, while component definitions are not included in ISO 8855. SAE J670 also defines many more terms (over 600) than are defined in ISO 8855 (approximately 130).

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1. SCOPE

The vehicle dynamics terminology presented herein pertains to passenger cars and light trucks with two axles and to those vehicles pulling single-axle trailers. The terminology presents symbols and definitions covering the following subjects: axis systems, vehicle bodies, suspension and steering systems, brakes, tires and wheels, operating states and modes, control and disturbance inputs, vehicle responses, and vehicle characterizing descriptors. The scope does not include terms relating to the human perception of vehicle response.

2. REFERENCES

2.1 Applicable Publications

The following publications form a part of this specification to the extent specified herein. Unless otherwise specified, the latest issue of SAE publications shall apply.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

SAE J1594 Vehicle Aerodynamics Terminology

SAE J2047 Tire Performance Technology

SAE J2564 Automotive Stability Enhancement Systems

2.1.2 ISO Publications

Available from ANSI, 25 West 43rd Street, New York, NY 10036, Tel: 212-642-4900, www.ansi.org.

ISO 8855:1991 Road vehicles—Vehicle dynamics and road-holding ability—Vocabulary

2.2 Related Publications

2.2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

SAE J1451 A Dictionary of Terms for the Dynamics and Handling of Single Track Vehicles (Motorcycles, Mopeds, and Bicycles)

SAE J1982 Nomenclature—Wheels for Passenger Cars, Light Trucks, and Multipurpose Vehicles

SAE M-105 SAE Glossary of Automotive Terms—Second Edition

SAE R-159 Dictionary of Automotive Engineering—Second Edition

2.2.2 ISO Publications

Available from ANSI, 25 West 43rd Street, New York, NY 10036, Tel: 212-642-4900, www.ansi.org.

ISO 611	Road vehicles—Braking of automotive vehicles and their trailers—Vocabulary
ISO 612	Road vehicles—Dimensions of motor vehicles and towed vehicles—Terms and definitions
ISO 1176	Road vehicles—Masses—Vocabulary and codes
ISO 3833	Road vehicles—Types—Terms and definitions
ISO 3877	Tyres, valves and tubes—List of equivalent terms—Part 1: Tyres
ISO 3911	Wheels and rims for pneumatic tyres—Vocabulary, designation and marking
ISO 4223	Definitions of some terms used in the tyre industry—Part 1: Pneumatic tyres
ISO 6725	Road vehicles—Dimensions of two-wheeled mopeds and motorcycles—Terms and definitions
ISO 6726	Mopeds and motorcycles with two wheels—Masses—Vocabulary
ISO 7237	Caravans—Masses and dimensions—Vocabulary
ISO 11838	Motorcycle and motorcycle-rider kinematics—Vocabulary

2.2.3 Other Publications

Bosch Automotive Handbook

Bosch Automotive Terminology

Tire and Rim Association Year Book

3. AXIS AND COORDINATE SYSTEMS

This terminology recognizes axis systems with two existing nominal orientations: the orientation originally defined by SAE J670, which was adopted from aeronautical convention, and the orientation defined in ISO 8855:1991. These axis orientations are equally acceptable, and the selection of the appropriate orientation should be based on the requirements of the analysis or test being performed. The ISO 8855 axis orientation is referred to as the Z-Up orientation, with the traditional SAE J670 axis orientation referred to as the Z-Down orientation. These two axis orientations are shown in Figure 1 below. When definitions are dependent upon the axis orientation, dual definitions are provided, with the definition based on the Z-Up axis orientation appearing first. Many of the terms in this section are also defined in SAE J2047.

The definitions in this section are intended to provide sufficient flexibility to accommodate the broad spectrum of modeling techniques that are currently used to represent the dynamics of vehicles as systems of multiple rigid bodies. Certain commonly used *axis systems* and *coordinate systems* are defined herein. However, there is no intent to limit an analyst or experimentalist to the use of only the *axis systems*, *coordinate systems*, or *reference frames* specifically defined.

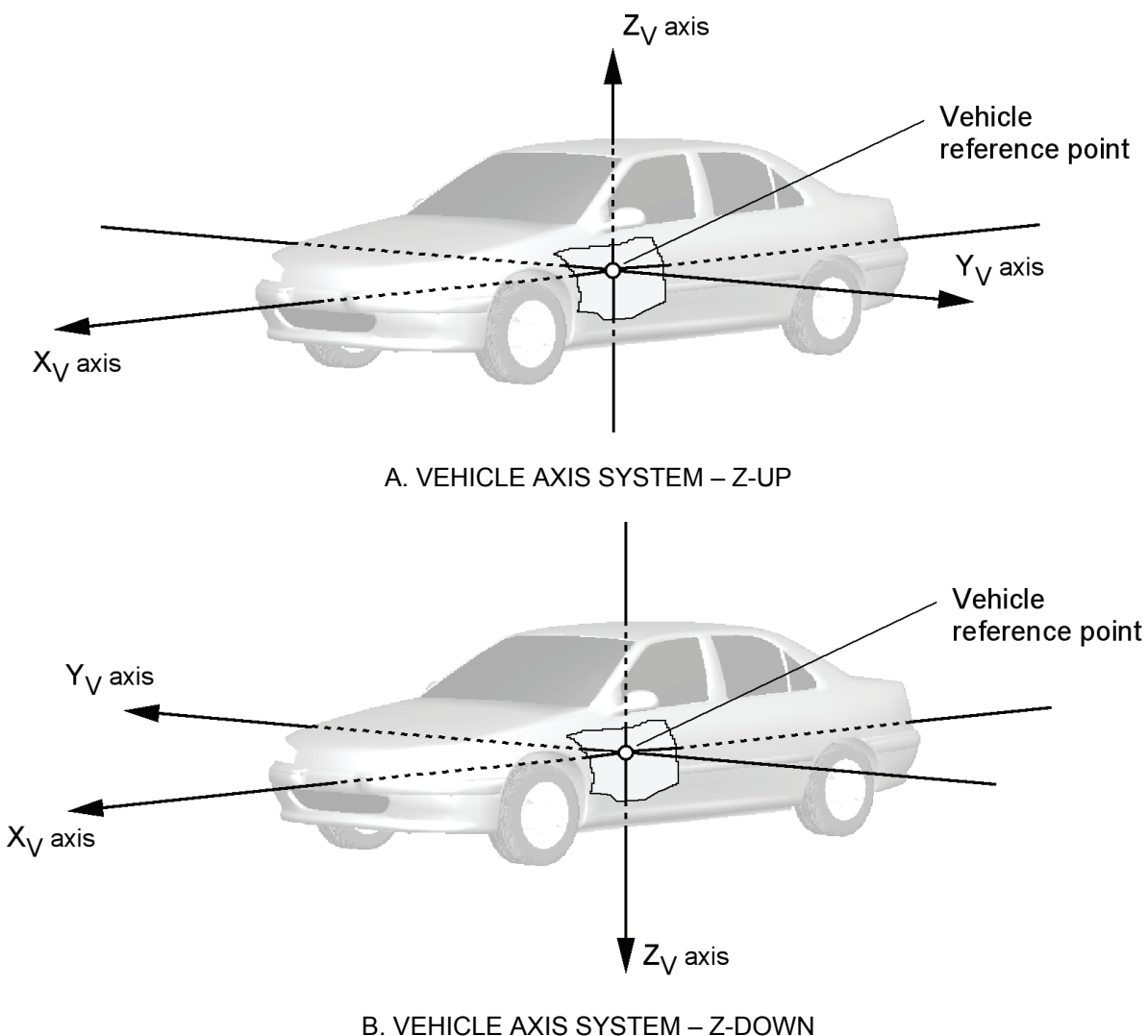


FIGURE 1 – ORIENTATIONS OF AXIS SYSTEMS

- 3.1 Reference Frame—A geometric environment in which all points remain fixed with respect to each other at all times.
- 3.2 Inertial Reference (Newtonian Reference)—A *reference frame* that is assumed to have zero linear and angular acceleration and zero angular velocity. In Newtonian physics, the Earth is assumed to be an inertial reference.
- 3.3 Axis System—A set of three orthogonal directions associated with X, Y, and Z axes. A right-handed axis system is assumed throughout this document, where:

$$\vec{Z} = \vec{X} \times \vec{Y} \quad (\text{Eq. 1})$$

- 3.4 Coordinate System—A numbering convention used to assign a unique ordered trio (x, y, z) of values to each point in a *reference frame*. A coordinate system consists of an *axis system* plus an origin point.
- 3.5 Ground Plane—A horizontal plane in the *inertial reference*, normal to the gravitational vector.
- 3.6 Road Surface—The surface, flat, curved, undulated, or other shape, supporting the *tire* and providing friction necessary to generate *tire shear forces* in the *road plane*.
- 3.7 Road Plane—1) A plane representing the *road surface* within each *tire contact patch*. For an uneven road, a different road plane may exist at each *tire contact patch*. 2) The plane formed when the individual road planes at each *tire contact patch* are essentially coplanar.

NOTE—For a planar *road surface*, the *road plane* will be coincident with the *road surface*. For *road surfaces* with surface contours having a wavelength similar to or less than the size of the *tire contact patch*, as in the case of many ride events, an equivalent *road plane* must be determined. Determination of the equivalent *road plane* is dependent on the requirements of the analysis being performed. The equivalent *road plane* may not be coincident with the actual *road surface* at the *tire contact center*.

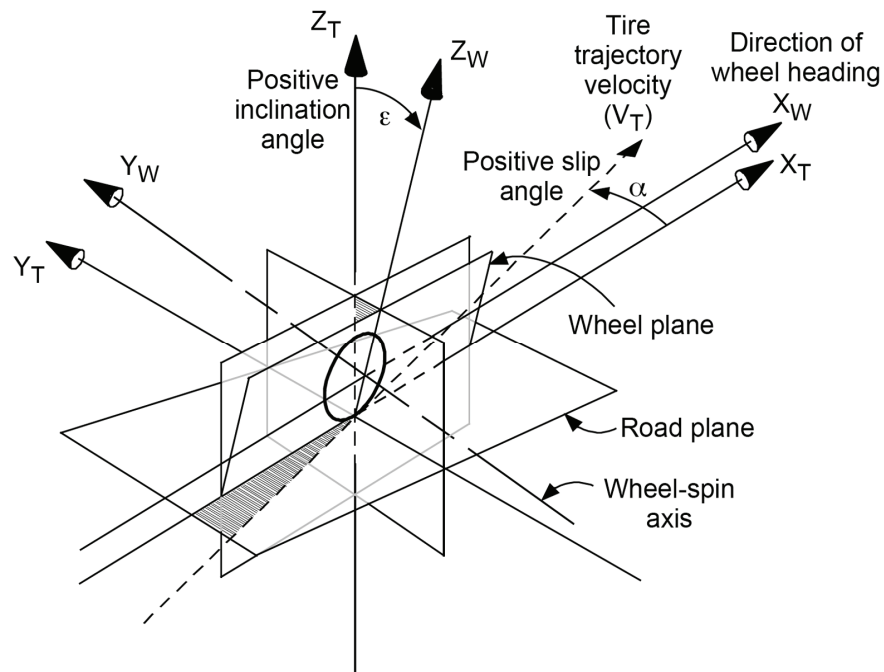
- 3.8 Vehicle Plane of Symmetry (Longitudinal Plane of Symmetry)—The median plane of a vehicle that is generally laterally symmetric. This plane typically contains the lateral midpoints of the *axles* and the *hitch point*.
- 3.9 Earth-Fixed Axis System (X_E , Y_E , Z_E)—An *axis system* fixed in the *inertial reference*. The X_E and Y_E axes are parallel to the *ground plane*. The Z_E axis is aligned with the gravitational vector. The positive Z_E axis points upward in the Z-Up orientation. The positive Z_E axis points downward in the Z-Down orientation. The orientation of the X_E and Y_E axes is arbitrary and should be based on the needs of the analysis or test.
- 3.10 Earth-Fixed Coordinate System (x_E , y_E , z_E)—A *coordinate system* based on the *Earth-fixed axis system* with an origin that is fixed in the *ground plane*. The location of the origin is generally an arbitrary point defined by the user.
- 3.11 Vehicle Axis System (X_V , Y_V , Z_V)—An *axis system* fixed in the *reference frame* of the vehicle *sprung mass*, so that the X_V axis is substantially horizontal and points forward (with the vehicle at rest), and is parallel to the *vehicle plane of symmetry*. The Y_V axis is perpendicular to the *vehicle plane of symmetry*. The Y_V axis points to the left and the Z_V axis points upward in the Z-Up orientation. The Y_V axis points to the right and the Z_V axis points downward in the Z-Down orientation. For articulated vehicles, a separate vehicle axis system may be defined for each unit. See Figure 1.
- 3.12 Vehicle Coordinate System (x_V , y_V , z_V)—A *coordinate system* based on the *vehicle axis system* with the origin located at the *vehicle reference point*.
- 3.13 Vehicle Reference Point—A point fixed in the vehicle *sprung mass*. See Figure 1.

NOTE—The *vehicle reference point* may be defined in a variety of locations, based on the needs of the analysis or test. Commonly used locations include the static *vehicle center of gravity*, the static *sprung-mass center of gravity*, the mid-*wheelbase* point at the height of the static *vehicle center of gravity*, and the center of the front *axle*.

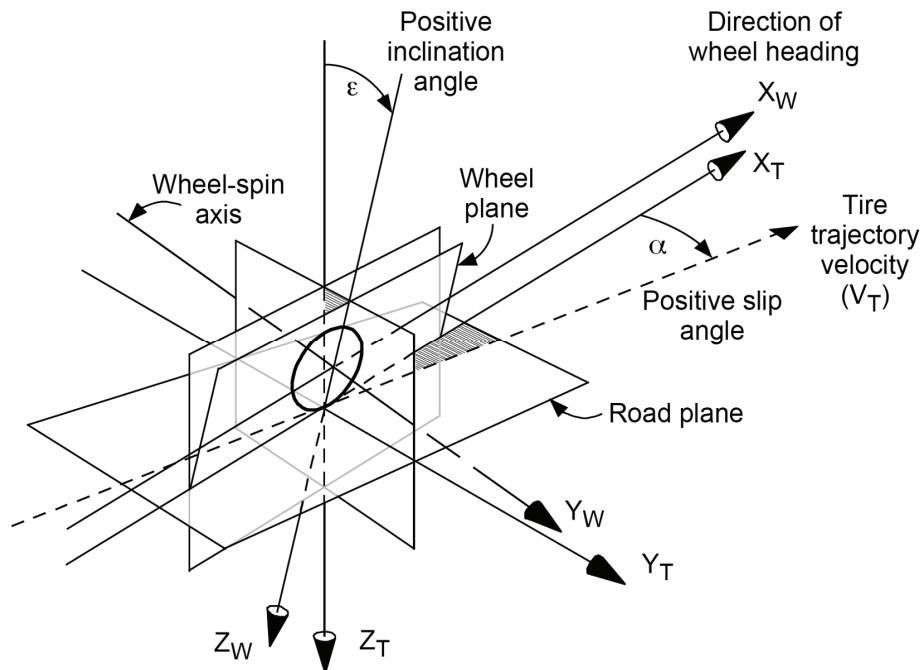
- 3.14 Intermediate Axis System (X, Y, Z)—A right-handed orthogonal *axis system* whose X and Y axes are parallel to the *ground plane*, with the X axis aligned with the vertical projection of the X_V axis onto the *ground plane*. The Z axis is parallel to the Z_E axis. The positive Z axis points upward in the Z-Up orientation. The positive Z axis points downward in the Z-Down orientation.

NOTE—The *intermediate axis system* is used to facilitate angular rotations using the *vehicle Euler angles* and the definition of angular orientation terms, the components of force and moment vectors, and the components of translational and angular motion vectors. See 4.2.2.1, 4.3, 4.2.1, 4.2.2.2, and 4.2.2.3, respectively. An *intermediate coordinate system* is not defined herein.

- 3.15 Tire Axis System (X_T, Y_T, Z_T)—An *axis system* whose X_T and Y_T axes are parallel to the local *road plane*, with the Z_T axis normal to the local *road plane*. The orientation of the X_T axis is defined by the intersection of the *wheel plane* and the *road plane*. The positive Z_T axis points upward in the Z-Up orientation. The positive Z_T axis points downward in the Z-Down orientation. A local tire axis system may be defined at each *wheel*. See Figure 2.



A. TIRE AND WHEEL AXIS SYSTEMS – Z-UP



B. TIRE AND WHEEL AXIS SYSTEMS – Z-DOWN

FIGURE 2 – TIRE AND WHEEL AXIS SYSTEMS

- 3.16 Tire Coordinate System (x_T, y_T, z_T)—A *coordinate system* based on the *tire axis system* with the origin fixed at the *contact center*.

NOTE—The Z-Down orientation of the *tire coordinate system* is equivalent to the orientation of the tire axis system defined in SAE J2047.

- 3.17 Wheel Axis System (X_W, Y_W, Z_W)—An *axis system* whose X_W and Z_W axes are parallel to the *wheel plane*, whose Y_W axis is parallel to the *wheel-spin axis*, and whose X_W axis is parallel to the local *road plane*. The positive Z_W axis points upward in the Z-Up orientation. The positive Z_W axis points downward in the Z-Down orientation. A local wheel axis system may be defined for each *wheel*. See Figure 2.

NOTE—This *axis system* definition is not consistent with the definition of wheel axis system found in ISO 8855:1991 or SAE J2047.

- 3.18 Wheel Coordinate System (x_W, y_W, z_W)—A *coordinate system* based on the *wheel axis system* with the origin fixed at the *wheel center*.

4. VEHICLE

4.1 Geometry and Masses

- 4.1.1 Wheelbase L —The distance between the *contact centers* of the *tires* on the same side of the vehicle, measured parallel to the X axis, with the vehicle at rest on a horizontal surface, at a prescribed *load condition*, set of *vehicle trim heights*, or set of *suspension trim heights*, with zero *steer angle*.

NOTE—A vehicle may have a different *wheelbase* on the left and right sides by design. It is common practice to average the left and right *wheelbases*; however, the difference may need to be taken into account in performing some analyses. The *wheelbase* typically changes as the *suspension trim heights* change.

- 4.1.2 Trailer Wheelbase—The distance between the vertical projections of the *articulation point* and the center of the trailer *axle* onto the *ground plane*, with the tow-vehicle/trailer combination at rest on a horizontal surface, at a prescribed *load condition*, set of *vehicle trim heights*, or set of *suspension trim heights*.

- 4.1.3 Track (Track Width, Wheel Track) T —The distance between the *contact centers* of a pair of *tires* on an *axle*, measured parallel to the Y axis, with the vehicle at rest on a horizontal surface, at a prescribed *load condition*, set of *vehicle trim heights*, or set of *suspension trim heights*. For vehicles with dual *tires*, it is the distance between the points centrally located between the *contact centers* of the inner and outer dual *tires*.

NOTE—For vehicles with *independent suspensions*, *track* typically changes as the *suspension trim heights* change.

- 4.1.4 Vehicle Trim Height—A vertical dimension that specifies the location of a fixed point on the vehicle body or chassis relative to ground.

NOTE—A set of congruous *vehicle trim heights* (minimum 3) are necessary to establish the orientation of the vehicle body or chassis relative to ground.

- 4.1.5 Suspension Trim Height—A vertical dimension that specifies the location of a point on a vehicle *suspension* relative to a point on the vehicle *sprung mass*.

- 4.1.6 Articulation Point—The instant center of rotation of the trailer relative to the towing vehicle.

NOTE—For trailers with a simple ball hitch, the *articulation point* is coincident with the center of the hitch ball.

- 4.1.7 Hitch Point(s)—The attachment point(s) of the trailer to the towing vehicle.

4.1.8 Unsprung Weight—All weight that is not carried by the *suspension*, but is supported directly by the *tires*. The unsprung weight includes the weight of the *tires* and *wheels* and all parts that move directly with the *tires* and *wheels*, plus a portion of the weight of the *suspension* linkages, *ride springs*, and driveshafts.

NOTE—It is common practice to include one-half the weight of the *suspension* linkage, *ride springs*, and driveshafts in the *unsprung weight*. For more detailed analyses, the weight distribution of the individual *suspension links* may need to be considered. *Unsprung weight* may also be separately defined for the front and rear *axles* and, further, for *independent suspensions*, for individual *suspension corners*. If *unsprung weight* is defined for subsets of the total unsprung weight, the location being referenced must be explicitly identified (e.g., Left Front Unsprung Weight).

4.1.9 Unsprung Mass—The *unsprung weight* divided by the gravitational constant.

NOTE—*Unsprung mass* may also be separately defined for the front and rear *axles* and, further, for *independent suspensions*, for individual *suspension corners*. If *unsprung mass* is defined for subsets of the total *unsprung mass*, the location being referenced must be explicitly identified (e.g., Left Front Unsprung Mass).

4.1.10 Effective Unsprung Mass—The equivalent mass which reproduces the kinetic energy or inertia forces produced by motion(s) of the unsprung parts while the *sprung mass* is stationary.

NOTE—*Effective unsprung mass* is not the same as the *unsprung mass*, in that it considers effects due to the rotational motion and rotational inertia of the *suspension links*, which usually decreases the apparent *unsprung mass*. This distinction may be important when performing certain dynamic analyses (e.g., ride). The value of *effective unsprung mass* may be different for different directions of excitation. Typically, *effective unsprung mass* is separately defined for the front and rear *axles* and, further, for *independent suspensions*, for individual *suspension corners*. The location being referenced must be explicitly identified (e.g., Left Front Effective Unsprung Mass).

4.1.11 Sprung Weight—All weight that is supported by the *suspension*, including portions of the weight of the *suspension* members. The sprung weight is the *vehicle operating weight* less the *unsprung weight*.

4.1.12 Sprung Mass—1) The *sprung weight* divided by the gravitational constant. 2) The portion of the vehicle supported by the *suspension*, frequently treated as a rigid body.

4.1.13 Base Vehicle Weight—The total weight of the vehicle, including all fluids necessary for normal operation, without fuel and without a *payload*.

4.1.14 Base Vehicle Mass—The *base vehicle weight* divided by the gravitational constant.

4.1.15 Curb Weight—The *base vehicle weight* plus a full tank of fuel.

4.1.16 Curb Mass—The *curb weight* of the vehicle divided by the gravitational constant.

4.1.17 Payload—The weight of the driver, passengers, and cargo at a given *load condition*.

4.1.18 Load Condition—A description of the loaded state of the vehicle being analyzed or tested. It includes descriptions of the fuel load and the *payload*, and the location(s) of the *payload*.

4.1.19 Vehicle Operating Weight *W*—The total weight of the vehicle at a given *load condition*, including the *base vehicle weight*, the weight of the fuel load, and the *payload*.

4.1.20 Vehicle Operating Mass—The *vehicle operating weight* divided by the gravitational constant.

4.1.21 Passenger Mass—The mass representative of a driver or passenger. The conventional mass of a passenger is fixed at 68 kg (150 lb).

4.1.22 Vehicle Center of Gravity (C.G.)—The center of gravity of the total vehicle at a given *load condition*.

NOTE—The symbols H or h are commonly used for the height of the *vehicle center of gravity* above ground, with the *suspensions* in equilibrium and the vehicle at rest on a flat, level surface. The symbols a and b are commonly used as the longitudinal distances from the front and rear *axle centerlines*, respectively, to the *vehicle center of gravity*.

4.1.23 Sprung-Mass Center of Gravity—The center of gravity of the vehicle *sprung mass* at a given *load condition*.

4.1.24 Mass Moments of Inertia (Total Vehicle)

4.1.24.1 Vehicle Roll Moment of Inertia—The moment of inertia of the total vehicle at a given *load condition*, taken about an axis parallel to the X_V axis, that passes through the *vehicle center of gravity*.

4.1.24.2 Vehicle Pitch Moment of Inertia—The moment of inertia of the total vehicle at a given *load condition*, taken about an axis parallel to the Y_V axis, that passes through the *vehicle center of gravity*.

4.1.24.3 Vehicle Yaw Moment of Inertia—The moment of inertia of the total vehicle at a given *load condition*, taken about an axis parallel to the Z_V axis, that passes through the *vehicle center of gravity*.

4.1.24.4 Vehicle Roll-Yaw Product of Inertia—The product of inertia of the total vehicle at a given *load condition*, taken about the axes used to determine the *vehicle roll moment of inertia* and the *vehicle yaw moment of inertia*.

4.1.25 Mass Moments of Inertia (Sprung Mass)

4.1.25.1 Sprung-Mass Roll Moment of Inertia—The moment of inertia of the vehicle *sprung mass*, taken about an axis parallel to the X_V axis that passes through the *sprung-mass center of gravity*.

4.1.25.2 Sprung-Mass Pitch Moment of Inertia—The moment of inertia of the vehicle *sprung mass*, taken about an axis parallel to the Y_V axis that passes through the *sprung-mass center of gravity*.

4.1.25.3 Sprung-Mass Yaw Moment of Inertia—The moment of inertia of the vehicle *sprung mass*, taken about an axis parallel to the Z_V axis that passes through the *sprung-mass center of gravity*.

4.1.25.4 Sprung-Mass Roll-Yaw Product of Inertia—The product of inertia of the vehicle *sprung mass*, taken about the axes used to determine the *sprung-mass roll moment of inertia* and the *sprung-mass yaw moment of inertia*.

4.1.26 Dynamic Index – Pitch (k_{YV}^2/ab Ratio – Pitch)—The square of the radius of gyration of the *sprung mass* about an axis parallel to the Y_V axis that passes through the *sprung-mass center of gravity*, divided by the product of the two longitudinal distances (a and b) from the *sprung-mass center of gravity* to the front and rear *axle centerlines*.

4.1.27 Dynamic Index – Yaw (k_{ZV}^2/ab Ratio – Yaw)—The square of the radius of gyration of the *vehicle operating mass* about an axis parallel to the Z_V axis that passes through the *vehicle center of gravity*, divided by the product of the two longitudinal distances (a and b) from the *vehicle center of gravity* to the front and rear *axle centerlines*.

4.2 Kinematics

4.2.1 Translational Motion Variables

In the following paragraphs, velocity and acceleration are relative to the *Earth-fixed axis system* (X_E , Y_E , Z_E). They are resolved into components in the *intermediate axis system* (X , Y , Z).

NOTE—It is also possible to resolve velocity and acceleration vectors into components in other *axis systems*. For example, velocity and acceleration vectors may be resolved in the *vehicle axis system* (X_V , Y_V , Z_V) to produce v_{XV} , v_{YV} , v_{ZV} and a_{XV} , a_{YV} , a_{ZV} . Traditionally, v_{XV} , v_{YV} , v_{ZV} have been represented by the symbols u , v , w .

4.2.1.1 Velocities

4.2.1.1.1 Vehicle Velocity $\vec{v}$ —A vector quantity expressing the velocity of the *vehicle reference point*.

4.2.1.1.2 Vehicle Speed—The magnitude of the *vehicle velocity*. In many cases, this is approximated by the *longitudinal velocity*.

4.2.1.1.3 Longitudinal Velocity v_x —The scalar value of the component of *vehicle velocity* in the direction of the X axis.

$$v_x = \vec{v} \cdot \hat{X} \quad (\text{Eq. 2})$$

4.2.1.1.4 Lateral Velocity v_y —The scalar value of the component of *vehicle velocity* in the direction of the Y axis.

$$v_y = \vec{v} \cdot \hat{Y} \quad (\text{Eq. 3})$$

4.2.1.1.5 Vertical Velocity v_z —The scalar value of the component of *vehicle velocity* in the direction of the Z axis.

$$v_z = \vec{v} \cdot \hat{Z} \quad (\text{Eq. 4})$$

4.2.1.1.6 Horizontal Velocity Vector $\vec{v}_H$ —The vector projection of *vehicle velocity* onto the X–Y plane.

$$\vec{v}_H = \vec{v} - (\vec{v} \cdot \hat{Z})\hat{Z} = v_x\hat{X} + v_y\hat{Y} \quad (\text{Eq. 5})$$

4.2.1.1.7 Horizontal Velocity v_H —The magnitude of the *horizontal velocity vector*.

NOTE—*Horizontal velocity* is also the resultant of *longitudinal velocity* and *lateral velocity*.

4.2.1.2 Accelerations

4.2.1.2.1 Vehicle Acceleration $\vec{a}$ —A vector quantity expressing the acceleration of the *vehicle reference point*.

4.2.1.2.2 Longitudinal Acceleration a_x —The scalar value of the component of *vehicle acceleration* in the direction of the X axis.

$$a_x = \vec{a} \cdot \hat{X} \quad (\text{Eq. 6})$$

4.2.1.2.3 Lateral Acceleration a_y —The scalar value of the component of *vehicle acceleration* in the direction of the Y axis.

$$a_y = \vec{a} \cdot \hat{Y} \quad (\text{Eq. 7})$$

NOTE—In *steady state*, *lateral acceleration* is equal to the product of *centripetal acceleration* times the cosine of the vehicle's *sideslip angle*. Since in most test conditions the *sideslip angle* is small, for practical purposes *lateral acceleration* may be considered equal to *centripetal acceleration*.

4.2.1.2.4 Vertical Acceleration a_z —The scalar value of the component of *vehicle acceleration* in the direction of the Z axis.

$$a_z = \vec{a} \cdot \hat{Z} \quad (\text{Eq. 8})$$

- 4.2.1.2.5 Tangential Acceleration a_T —The scalar value of the component of *vehicle acceleration* in the direction of the *horizontal velocity vector*.

$$a_T = \vec{a} \cdot \hat{v}_H \quad (\text{Eq. 9})$$

- 4.2.1.2.6 Centripetal Acceleration a_C —The scalar value of the component of *vehicle acceleration* in the direction of the horizontal normal to the *horizontal velocity vector*.

$$a_C = \vec{a} \cdot (\hat{Z} \times \hat{v}_H) \quad (\text{Eq. 10})$$

- 4.2.1.2.7 Horizontal Acceleration Vector $\vec{a}_H$ —The vector projection of *vehicle acceleration* onto the X–Y plane.

$$\vec{a}_H = \vec{a} - (\vec{a} \cdot \hat{Z})\hat{Z} = a_X \hat{X} + a_Y \hat{Y} \quad (\text{Eq. 11})$$

- 4.2.1.2.8 Horizontal Acceleration a_H —The magnitude of the *horizontal acceleration vector*.

NOTE—*Horizontal acceleration* is also the resultant of *longitudinal acceleration* and *lateral acceleration* or the resultant of *tangential acceleration* and *centripetal acceleration*.

4.2.2 Angular Motion Variables

4.2.2.1 Angles

The sign of angles resulting from angular rotations is determined in accordance with the right-hand rule.

- 4.2.2.1.1 Vehicle Angular Orientation—The orientation of the *vehicle axis system* (X_V , Y_V , Z_V) with respect to the *Earth-fixed axis system* (X_E , Y_E , Z_E), for example, as obtained by a sequence of three angular rotations through the *vehicle Euler angles*.

- 4.2.2.1.2 Vehicle Euler Angles (ψ , θ , ϕ)—A sequence of consecutive angular rotations about the Earth-fixed Z_E axis, the intermediate Y axis, and the vehicle X_V axis to obtain the *vehicle angular orientation*. See Table 1.

TABLE 1 – VEHICLE EULER ANGLES AND STANDARD ORDER OF ROTATION

Rotation Order	Angle Produced by Rotation	Rotation Nature
First Rotation	Yaw (ψ)	X_E axis to the X axis about the Z_E axis
Second Rotation	Pitch (θ)	X axis to the X_V axis about the Y axis
Third Rotation	Roll (ϕ)	Y axis to the Y_V axis about the X_V axis

NOTE—There are other possible sets of orientation angles that can be applied to axis rotations. In choosing a sequence of rotations, the second rotation should ideally span a small angle. The sequence of rotations specified above is preferable for use with the vehicle *sprung mass*, where the magnitude of the *pitch angle* is usually small. Other sets of orientation angles could be chosen for use with individual vehicle components (e.g., rotating *wheels*).

- 4.2.2.1.3 Yaw Angle (Heading Angle) ψ —The angle from the X_E axis to the X axis, about the Z_E axis. See Figure 3.

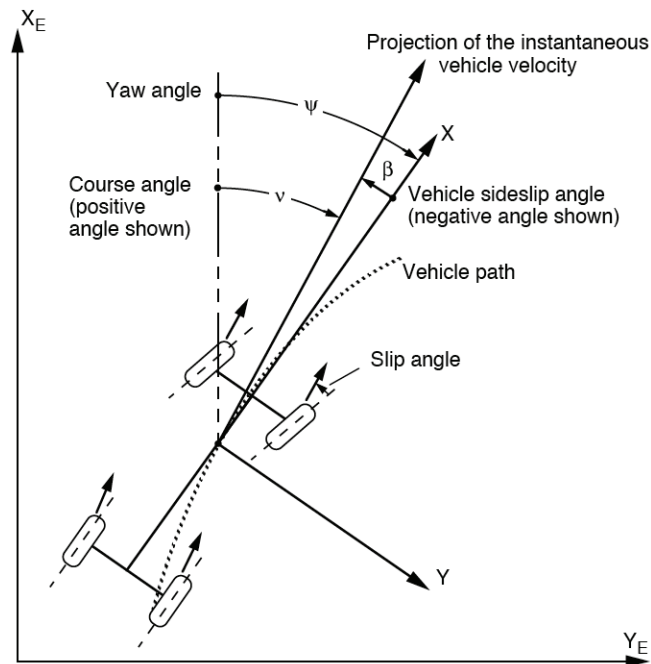


FIGURE 3 – YAW, SIDESLIP, AND COURSE ANGLES
(Z-Down Axis Orientation)

4.2.2.1.4 Pitch Angle θ —The angle from the X axis to the X_V axis, about the Y axis.

NOTE—The *pitch angle* is not measured relative to the *road plane*, thus a vehicle at rest on an inclined planar *road surface* will have a non-zero *pitch angle*.

4.2.2.1.5 Roll Angle ϕ —The angle from the Y axis to the Y_V axis, about the X_V axis.

4.2.2.1.6 Vehicle Roll Angle ϕ_V —The angle from the *ground plane* to the Y_V axis, about the X axis.

NOTE—The *vehicle roll angle* is different from *roll angle* (4.2.2.1.5) if the *pitch angle* is not zero. The *vehicle roll angle* may be computed using the equation:

$$\sin \phi_V = \sin \phi \cos \theta \quad (\text{Eq. 12})$$

The *vehicle roll angle* is not measured relative to the *road plane*; thus, a vehicle at rest on an inclined planar *road surface* will have a non-zero *vehicle roll angle*.

4.2.2.1.7 Sideslip Angle—At a given point, the angle from the X axis to the vertical projection of the velocity vector of the point onto the *ground plane*, about the Z axis.

4.2.2.1.8 Vehicle Sideslip Angle (Attitude Angle) β —The angle from the X axis to the vertical projection of *vehicle velocity* onto the *ground plane*, about the Z axis. See Figures 3 and 4.

NOTE—*Vehicle sideslip angle* may also be calculated from the *longitudinal velocity* v_X and the *lateral velocity* v_Y :

$$\beta = \text{Arc tan } \frac{v_Y}{v_X} \quad (\text{Eq. 13})$$

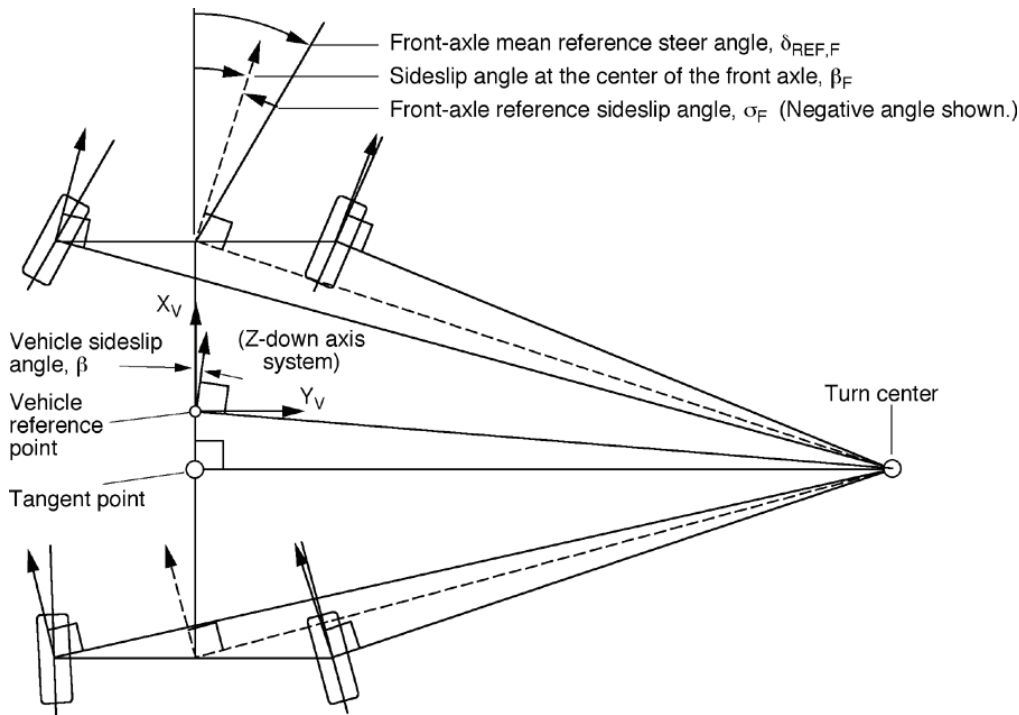


FIGURE 4 – VEHICLE SIDESLIP, REFERENCE STEER, AND AXLE REFERENCE SIDESLIP ANGLES
(Z-Down axis orientation)

- 4.2.2.1.9 Tangent Point—The point on the X axis whose *sideslip angle* is zero. See Figure 4.
- 4.2.2.1.10 Axle Reference Sideslip Angle σ_F, σ_R —The *sideslip angle* at the center of a steered *axle* minus the *mean reference steer angle* for the *axle*. See Figure 4.
- 4.2.2.1.11 Trailer Yaw Articulation Angle $\Gamma (\Delta\psi)$ —The angle from the trailer X_V axis to the normal projection of the tow vehicle X_V axis onto the trailer X_V – Y_V plane, about the trailer Z_V axis. The polarity is determined in the trailer *axis system*.
- 4.2.2.1.12 Trailer Pitch Articulation Angle $\Delta\theta$ —The angle from the trailer X_V axis to the normal projection of the tow vehicle X_V axis onto the trailer X_V – Z_V plane, about the trailer Y_V axis. The polarity is determined in the trailer *axis system*.
- 4.2.2.1.13 Trailer Roll Articulation Angle $\Delta\phi$ —The angle from the trailer Y_V axis to the normal projection of the tow vehicle Y_V axis onto the trailer Y_V – Z_V plane, about the trailer X_V axis. The polarity is determined in the trailer *axis system*.
- 4.2.2.2 Angular Velocities

In the following paragraphs, angular velocities are relative to the *Earth-fixed axis system* (X_E, Y_E, Z_E). They are resolved into components in the *intermediate axis system* (X, Y, Z).

NOTE—It is also possible to resolve angular velocity vectors into components in other *axis systems*. For example, angular velocity vectors may be resolved in the *vehicle axis system* (X_V, Y_V, Z_V) to produce $\omega_{X_V}, \omega_{Y_V}, \omega_{Z_V}$. Traditionally, $\omega_{X_V}, \omega_{Y_V}, \omega_{Z_V}$ have been represented by the symbols p, q, r .

- 4.2.2.2.1 Vehicle Angular Velocity $\vec{\omega}$ —A vector quantity expressing the angular velocity of the *vehicle axis system*.

4.2.2.2.2 Roll Velocity ω_X —The scalar value of the X component of *vehicle angular velocity*.

$$\omega_X = \vec{\omega} \bullet \hat{X} \quad (\text{Eq. 14})$$

4.2.2.2.3 Pitch Velocity ω_Y —The scalar value of the Y component of *vehicle angular velocity*.

$$\omega_Y = \vec{\omega} \bullet \hat{Y} \quad (\text{Eq. 15})$$

4.2.2.2.4 Yaw Velocity (Yaw Rate) ω_Z —The scalar value of the Z component of *vehicle angular velocity*.

$$\omega_Z = \vec{\omega} \bullet \hat{Z} \quad (\text{Eq. 16})$$

4.2.2.3 Angular Accelerations

In the following paragraphs, angular accelerations are relative to the *Earth-fixed axis system* (X_E, Y_E, Z_E). They are resolved into components in the *intermediate axis system* (X, Y, Z). Suggested symbols are not provided for angular accelerations, since the mathematical symbol normally used for angular acceleration (α) is used for tire *slip angle* in vehicle dynamics.

NOTE—It is also possible to resolve angular acceleration vectors into components in other *axis systems*. For example, angular acceleration vectors may be resolved in the *vehicle axis system* (X_V, Y_V, Z_V).

4.2.2.3.1 Vehicle Angular Acceleration—A vector quantity expressing the angular acceleration of the *vehicle axis system*.

4.2.2.3.2 Roll Acceleration—The scalar value of the X component of *vehicle angular acceleration*.

4.2.2.3.3 Pitch Acceleration—The scalar value of the Y component of *vehicle angular acceleration*.

4.2.2.3.4 Yaw Acceleration—The scalar value of the Z component of *vehicle angular acceleration*.

4.2.3 Vehicle Trajectory Measures

4.2.3.1 Vehicle Trajectory—The path of a selected point on the vehicle in the *Earth-fixed coordinate system*. This point is usually the *vehicle reference point*.

4.2.3.2 Vehicle Path—The vertical projection of the *vehicle trajectory* onto the *ground plane*.

4.2.3.3 Path Radius R —The instantaneous radius of curvature of the *vehicle path*.

NOTE—*Path radius* is the perpendicular distance between the *vehicle path* and the *turn center*. The *path radius* of the *vehicle reference point* may be calculated as:

$$R = \frac{v_H^2}{a_C} \quad (\text{Eq. 17})$$

4.2.3.4 Turn Center—The instantaneous center of curvature of the *vehicle path*.

4.2.3.5 Path Curvature κ —The inverse of *path radius*. Path curvature may be calculated as:

$$\kappa = \frac{1}{R} \quad (\text{Eq. 18})$$

4.2.3.6 Normalized Path Curvature—The *wheelbase* divided by the *path radius* of the *tangent point*.

NOTE—*Normalized path curvature* is the small angle approximation, in radians, of the *included Ackermann steer angle*.

4.2.3.7 Course Angle ν —The angle from the X_E axis to the vertical projection of *vehicle velocity* onto the X_E – Y_E plane. See Figure 3. Course angle can be computed from the *yaw angle*, ψ , and the *vehicle sideslip angle*, β :

$$\nu = \psi + \beta \quad (\text{Eq. 19})$$

4.3 Forces and Moments

External forces and moments acting on the vehicle at any instant may be summed into one resultant force vector and one resultant moment vector. The line of action of the resultant force vector may be moved to any point of interest, providing that the resultant moment vector is altered accordingly. In the following paragraphs, forces and moments are resolved into components in the *intermediate axis system* (X , Y , Z).

NOTE—It is also possible to resolve force and moment vectors into components in other *axis systems*. For example, force and moment vectors may be resolved in the *vehicle axis system* (X_V , Y_V , Z_V) to produce F_{X_V} , F_{Y_V} , F_{Z_V} and M_{X_V} , M_{Y_V} , M_{Z_V} . Traditionally, F_{X_V} , F_{Y_V} , F_{Z_V} have been represented by the symbols X , Y , Z and M_{X_V} , M_{Y_V} , M_{Z_V} have been represented by the symbols L , M , N .

4.3.1 Forces

4.3.1.1 Vehicle Force $\vec{F}$ —A vector quantity expressing the sum of the external forces acting on the vehicle at any instant, with its line of action passing through the *vehicle reference point*.

4.3.1.2 Longitudinal Force F_X —The scalar value of the component of *vehicle force* in the direction of the X axis.

$$F_X = \vec{F} \cdot \hat{X} \quad (\text{Eq. 20})$$

4.3.1.3 Lateral Force F_Y —The scalar value of the component of *vehicle force* in the direction of the Y axis.

$$F_Y = \vec{F} \cdot \hat{Y} \quad (\text{Eq. 21})$$

4.3.1.4 Vertical Force F_Z —The scalar value of the component of *vehicle force* in the direction of the Z axis.

$$F_Z = \vec{F} \cdot \hat{Z} \quad (\text{Eq. 22})$$

4.3.2 Moments

4.3.2.1 Vehicle Moment $\vec{M}$ —A vector quantity expressing the sum of the external moments acting on the vehicle at any instant, consistent with the line of action of the *vehicle force*.

4.3.2.2 Roll Moment M_X —The scalar value of the component of the *vehicle moment* in the direction of the X axis.

$$M_X = \vec{M} \cdot \hat{X} \quad (\text{Eq. 23})$$

4.3.2.3 Pitch Moment M_Y —The scalar value of the component of the *vehicle moment* in the direction of the Y axis.

$$M_Y = \vec{M} \cdot \hat{Y} \quad (\text{Eq. 24})$$

4.3.2.4 Yaw Moment M_Z —The scalar value of the component of the *vehicle moment* in the direction of the Z axis.

$$M_Z = \vec{M} \bullet \hat{Z} \quad (\text{Eq. 25})$$

5. SUSPENSION AND STEERING

5.1 General Nomenclature

5.1.1 Suspension—A system that provides ride freedom and kinematic control of the motions of the *wheels* at a given longitudinal position on the vehicle.

5.1.1.1 Independent Suspension—A *suspension* utilizing a separate kinematic control mechanism for the *wheel* on each side of the vehicle.

5.1.1.2 Solid-Axle Suspension—A *suspension* utilizing an essentially rigid *axle*.

5.1.1.3 Suspension Corner—For an *independent suspension*: 1) The portion of the *suspension* that controls the kinematic motion of a single *wheel* (left front, right front, left rear, or right rear). 2) The assemblage of the *suspension*, *wheel*, *tire*, *brake*, and all other components that move with a single *wheel*.

5.2 Suspension Components

The terms contained in this section and the following section are defined to facilitate communication between vehicle dynamics professionals and engineers involved in the mechanical design of *suspension* and steering systems. Alternative names in common use have been provided for many of these terms. Additional names may be associated with some of these terms due to differences in national or corporate practice.

5.2.1 Axle—1) An essentially rigid member used to connect *wheels* on opposite sides of the vehicle at a given longitudinal position. The axle/*wheel* assembly has *suspension ride* and *suspension roll* degrees of freedom relative to the *sprung mass*. 2) The imaginary line connecting the *wheel centers* on opposite sides of the vehicle at a given longitudinal position. 3) Less rigorously, the assemblage of the *suspension*, *wheels*, *tires*, *brakes*, and all other components that move with the *wheels* at a given longitudinal position of the vehicle.

5.2.2 Ball Joint (Rod End)—An assemblage of essentially rigid parts, allowing rotational but not translational motion, generally used to connect a *link* or *control arm* to the *knuckle*, or used at each end of a *tie rod*.

5.2.3 Bushing—A compliant part that provides primarily rotational motion between a *link* or *control arm* and the body/frame or the *knuckle*. In its most typical form, it is comprised of two (usually steel) concentric cylinders between which is bonded an elastomeric core. Under load, it allows all three linear and all three angular deflections.

5.2.4 Control Arm (Wishbone)—A *suspension* part generally used to connect a *knuckle* or *axle* to the *sprung mass*. Kinematically, it consists of a revolute joint at its base and a spherical joint or a revolute joint at its apex. It constrains the motion of the apex to a circular path in a plane perpendicular to the hinge axis at its base. In its most typical form, it is roughly triangular with *bushings* having collinear axes at its base and a *ball joint* at its apex. It may take many forms, with a *bushing* or *ball joint* used at any of the three corners.

5.2.5 Damper—A *suspension* part used to provide damping, most commonly in *bounce* and *roll*. A typical damper provides primarily viscous damping, with some attendant Coulomb friction.

5.2.5.1 Shock Absorber—A *damper* that adds negligible kinematic constraint to the *suspension*.

5.2.5.2 Strut—A *damper* that also contributes to rotational constraint of the *knuckle* in camber and caster.

- 5.2.6 Jounce Stop (Jounce Bumper, Bump Stop)—The part that directly limits *jounce* travel of a *suspension*. Jounce stops are usually elastomeric bumpers, but are not limited to this configuration.
- 5.2.7 Rebound Stop—The part that directly limits *rebound* travel of a *suspension*. Rebound stops may be elastomeric bumpers like *jounce stops*, but are often internal stops built into *dampers*.
- 5.2.8 Knuckle (Hub Carrier, Upright)—A *suspension* part that includes the spindle, to which the *control arm(s)*, *link(s)*, *strut*, *ride spring*, and *tie rod* may be attached.
- 5.2.9 Link—An essentially rigid two-force member used to provide kinematic constraint. It typically has a *ball joint* or *bushing* at either end.
- 5.2.9.1 Lateral Link—A *link* used to provide primarily lateral constraint.
- 5.2.9.2 Leading Link—A *link* used to provide primarily longitudinal constraint whose rearward pivot is attached to the *sprung mass*.
- 5.2.9.3 Trailing Link—A *link* used to provide primarily longitudinal constraint whose forward pivot is attached to the *sprung mass*.
- 5.2.10 Ride Spring—A spring designed to provide ride compliance for the *suspension*.

NOTE—Commonly used *ride springs* consist of coil springs, leaf springs, torsion bars, and air springs.

- 5.2.11 Stabilizer Bar (Anti-Roll Bar, Anti-Sway Bar)—A torsional spring which is loaded in *suspension roll* to provide additional *suspension roll stiffness*.

NOTE—In its most typical form, a *stabilizer bar* is “U” shaped with the center section orientated laterally and attached to the *sprung mass* with *bushings*. Each end of the “U” attaches to the *control arm*, *knuckle*, or *strut* of an *independent suspension* or the end of an *axle* of a *solid-axle suspension*. Many permutations exist, using *links*, *ball joints* or *bushings* at different locations or with the center section attached to the *unsprung mass*, in the case of a *solid-axle suspension*.

- 5.2.12 Track Bar (Panhard Rod)—A *link* used to provide the primary lateral constraint between the *axle* and the *sprung mass*.
- 5.2.13 Watt Linkage—A four-bar linkage used to provide the primary lateral constraint between the *axle* and the *sprung mass*. It is typically comprised of a vertical member pivoted on the *axle* and two *lateral links*, each attached to it and to the *sprung mass*.

5.3 Steering Components

- 5.3.1 Steering Wheel (Hand Wheel)—The wheel used directly by the driver to steer the vehicle. See Figures 5 and 6.
- 5.3.2 Steering Column—A torsional member carrying rotational motion and torsional loads from the *steering wheel* to the *intermediate shaft*. See Figures 5 and 6.
- 5.3.3 Intermediate Shaft—A member carrying rotational motion and torsional loads from the *steering column* to the *input shaft*. This component generally contains one or more universal joints or flexible couplings and may also contain a slip joint. See Figures 5 and 6.
- 5.3.4 Steering Gear—A gear train and/or mechanism, with housing, carrying steering motion and loads from the *intermediate shaft* to the *tie rods* or *Pitman arm*. A steering gear may have provisions for power assist.
- 5.3.4.1 Rack and Pinion Steering Gear—A *steering gear* employing a rack and pinion gear set. This design transfers rotational motion of the *input shaft* to translational motion of the steering rack. It is used with laterally orientated *tie rods* connected directly to the rack. See Figure 5.