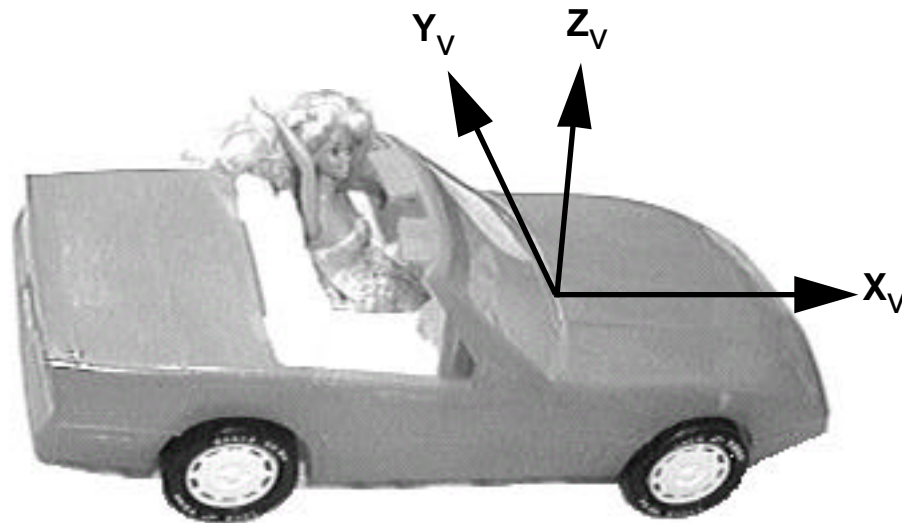


# Standard Terminology for Vehicle Dynamics Simulations



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## 1. Introduction

This technical memo defines specialized terms applicable to vehicle dynamics simulation programs. The motivation is to provide a common language for describing vehicle dynamics models. The definitions draw on two sources:

1. SAE Recommended Practice J670e, **Vehicle Dynamics Terminology** (first issued 1952, last updated 1976).
2. ISO 8855, **Road vehicles — Vehicle dynamics and road-holding ability — Vocabulary** (1991).

The writing of this memo was motivated by dissatisfaction with these two sources. SAE J670e was last updated before simulation programs existed for complex models. ISO 8855 is more simulation-oriented, but contains a few serious flaws. SAE is in the process of replacing J670e. These guidelines may be modified as the new SAE standard develops. In the meantime, this document is intended to establish useful conventions for vehicle dynamics simulation, maintaining compatibility with SAE and ISO when practical. Exceptions are noted when they occur.

Terms are not defined unless they are necessary for describing vehicle simulation programs. The level of detail is matched to models that are system based, rather than component based. To obtain generality, terms are defined without reference to specific models. Terms that are defined in this document are written in italics, followed by symbols when they exist. An index is included with page numbers where each term is defined. Definitions that are taken from SAE J670e and/or ISO 8855 are designated SAE and ISO, respectively, in parentheses. Conflicts with SAE or ISO are described in numbered notes in Section 7.

## 2. Vectors and angles

### 2.1 Vectors

*Acceleration vector* — time derivative of a *velocity vector* of a point.

*Angular acceleration vector* — time derivative of an *angular velocity vector* of a *reference frame*.

*Angular velocity vector* — vector describing the absolute 3D angular velocity of a *reference frame* with respect to the *inertial reference*. (Formally, it is a quantity that satisfies the equation:

$$\dot{\mathbf{r}} = \boldsymbol{\omega} \times \mathbf{r}$$

where  $\mathbf{r}$  is a vector fixed in a reference frame and  $\boldsymbol{\omega}$  is the angular velocity vector of the reference frame.)

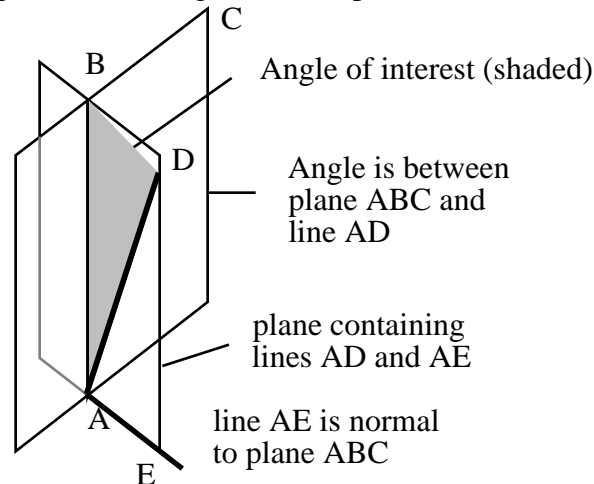
*Position vector* — *vector* describing the position of one point relative to a reference point. Unless specified otherwise, the reference point is the origin of the *Earth-fixed coordinate system*.

*Vector* — an object that has a direction in 3D space and a magnitude. The existence or meaning of a vector is not dependent on a choice of coordinate or axis system.

*Velocity vector* — time derivative of the *position vector* of a point.

## 2.2 Angles

An angle implies a rotation **from** a reference line **to** another line, in a plane containing both lines, **about** an axis that is perpendicular to both lines. The direction of the axis defines the sign convention of the angle, based on a right-handed rotation. (Line up your right-hand thumb with the axis direction, and your fingers curl in the direction of a positive rotation.) Sometimes an angle is defined between a line and a plane. In this case, the angle is taken from a projection of the line into the plane, as shown in Figure 1 for an angle between plane ABC and line AD.



**Figure 1. Angle between a plane and a line.**

## 2.3 Resultant force and moment vectors

All actions on a body that would cause it to accelerate in translation or rotation if not opposed by other actions can be combined into a single *resultant force vector* and a single *resultant moment vector* about a point at which the resultant force vector is assumed to apply. The resultant moment vector depends on the location of the point where the resultant force is assumed to apply. Resultant force and moment vectors are used to describe actions on the vehicle due to the ground, the air, and impacts with other objects.

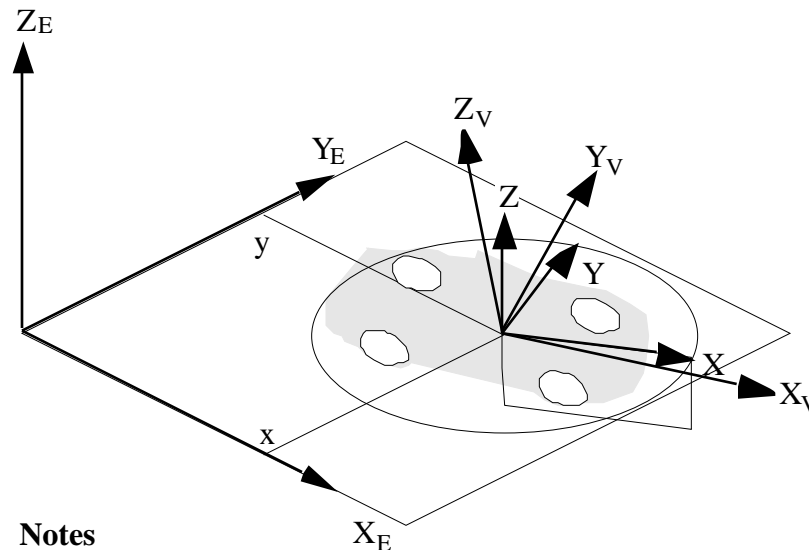
## 3. Axis and coordinate systems

### 3.1 Discussion

Multibody vehicle dynamics models are typically generated using right-handed *axis systems* and *coordinate systems*. The axis orientation for ISO 8855 has X forward, Z up, and Y pointing to the left-hand side of the vehicle. The current SAE J670e has Z-down, X forward, and Y pointing to the right. The Z-up convention is recommended for several reasons. Plots of Y vs. X show a top view of vehicle trajectories; plots of Z vs. X show a side view of vehicle trajectories; vertical tire forces are always positive; and wheel spin rates are positive for forward vehicle speeds. With the Z-down convention, all of these signs are reversed.

Alternative right-handed systems can be used, so long as X is longitudinal, Y is lateral, and Z is vertical. All definitions that follow are independent of the polarities of X, Y, and Z. However, the sign conventions of many variables are dependent on the directions in which the axes are pointing. For example, yaw angle is always a rotation about the Z axis. With Z-up, positive yaw implies a left-hand turn; with Z-down, positive yaw implies a right-hand turn.

All of the coordinate systems and axes are built from four reference directions: (1) vertical, as defined by the direction of the gravity vector, (2) the X axis of the *vehicle reference frame*, (3) the Y (spin) axis of a wheel of interest, and (4) the direction normal to the road at the *center of tire contact*. The Appendix summarizes the mathematical definitions of five *axis systems* described below. Figure 2 shows the three axis systems associated with the entire vehicle. The *intermediate axis system* is used the most for vehicle-level definitions. It has a Z axis that is parallel to the gravity vector, and an X axis that is in the same vertical plane as the vehicle longitudinal axis. Figure 3 shows the tire and wheel axis systems.



**Notes**

1. Z is parallel to  $Z_E$
2. X is in the vertical plane containing  $X_V$
3. The angle between  $X_E$  and X is

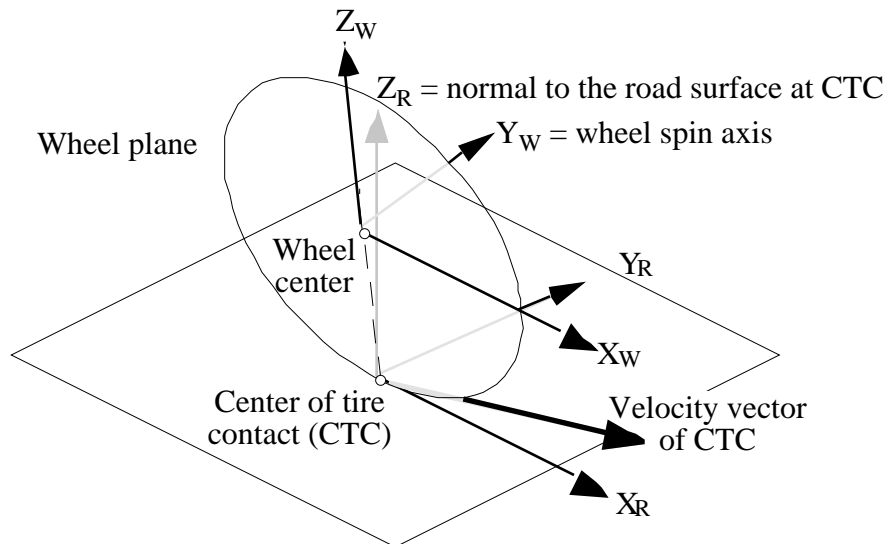
**Figure 2. Earth, vehicle, and intermediate axis systems.**

**3.2 Definitions**

*Axis system* — a set of three mutually orthogonal X, Y, and Z axes. In a right-handed system,  $Z = X \times Y$ .

*Coordinate system* — a numbering convention used to assign a unique ordered trio of numbers to each point in a *reference frame*. A typical rectangular coordinate system consists of an *axis system* plus an origin point.

*Earth-fixed axis system* ( $X_E, Y_E, Z_E$ ) — right-handed orthogonal *axis system* fixed in the *inertial reference*. The  $Z_E$  axis is parallel to the gravity vector. The recommended orientation is with  $Z_E$  pointing up. (See Figure 2.) (ISO, SAE)<sup>17</sup>



**Figure 3. Tire and wheel axis systems.**

*Earth-fixed coordinate system* — coordinate system based on the *earth-fixed axis system* and an origin that lies in a reference ground plane.

*Inertial (Newtonian) reference* — a reference frame that is assumed to have zero *acceleration* and zero *angular velocity*.

*Intermediate axis system* ( $X$ ,  $Y$ ,  $Z$ ) — right-handed orthogonal *axis system* whose  $Z$  axis is parallel to  $Z_E$ , and whose  $Y$  axis is perpendicular to both  $Z_E$  and  $X_V$ . This axis system can be obtained by rotating the Earth-fixed axis system about the  $Z_E$  axis by the vehicle *yaw angle*. (See Figure 2.) (ISO)

*Reference frame* — a geometric environment in which points remain fixed with respect to each other at all times.

*Road axis system* ( $X_R$ ,  $Y_R$ ,  $Z_R$ ) — right-handed orthogonal *axis system* whose  $Z_R$  axis is normal to the road, at the *center of tire contact*, and whose  $X_R$  axis is perpendicular to the wheel *spin axis* ( $Y_W$ ). For an uneven road, a different road axis system exists for each tire. (See Figure 3.) (SAE, ISO<sup>1</sup>)

*Road plane* — a reference plane tangent to the road surface at the tire *contact center*. For an uneven road, a different road plane exists for each tire.

*Vehicle axis system* ( $X_V$ ,  $Y_V$ ,  $Z_V$ ) — right-handed orthogonal *axis system* fixed in the *vehicle reference frame*. The  $X_V$  axis is primarily horizontal in the *vehicle plane of symmetry* and points forward. The  $Z_V$  axis is vertical and the  $Y_V$  axis is lateral. The directions should coincide with the *earth-fixed axis system* when the vehicle is upright and aligned with the  $X_V$  axis parallel to the  $X_E$  axis. (See Figure 2.) (SAE, ISO)<sup>2</sup>

*Vehicle plane of symmetry* — the lateral ( $X_V Z_V$ ) center plane of the vehicle.

*Vehicle reference frame* — *reference frame* associated with the vehicle body. It is typically defined to coincide with the undeformed body of the vehicle body structure.

*Wheel axis system* ( $X_W$ ,  $Y_W$ ,  $Z_W$ ) — right-handed orthogonal *axis system* whose  $Y_W$  axis is parallel with the *spin axis* of the wheel and whose  $X_W$  axis is perpendicular to  $Z_R$ . (See Figure 3.)

## 4. Entire vehicle

### 4.1 Size

*Wheelbase*  $L_{WB}$ — the distance between the *centers of tire contact* on one side of the vehicle. Wheelbase is generally variable with suspension deflection. (ISO)

### 4.2 Components of vectors

Forces, moments, and motion vectors for the entire vehicle are commonly decomposed into three rotational and three translational terms. The following adjectives should be used.

*Lateral* — Y component of force or translational motion vector. (ISO)

*Longitudinal* — X component of force or translational motion vector. (ISO)

*Pitch* — Y component of moment or rotational motion vector. (ISO)

*Roll* — X component of moment or rotational motion vector. (ISO)

*Vertical* — Z component of force or translational motion vector. (ISO)

*Yaw* — Z component of moment or rotational motion vector. (ISO)

### 4.3 Points

*C.G. (Center of gravity)* — a point in the *vehicle reference frame* that coincides with the center of mass of the entire vehicle when the suspensions are in equilibrium and the vehicle is resting on a flat level surface.

*Aerodynamic reference point* — a point in the *vehicle reference frame* that lies in the intersection of the *vehicle plane of symmetry* and the ground plane, mid-way between the front and rear axles, when the suspensions are in equilibrium and the vehicle is resting on a flat level surface.

*Vertical position Z* —  $Z_E$  coordinate of the *C.G.*

*X position X* —  $X_E$  coordinate of the *C.G.*

*Y position Y* —  $Y_E$  coordinate of the *C.G.*

### 4.4 Translational motion

*Lateral acceleration*  $A_y$  — Y component of *acceleration vector* of the *C.G.* (SAE, ISO)<sup>4</sup>

*Lateral velocity*  $V_y$  — Y component of *velocity vector* of the *C.G.* (SAE, ISO)<sup>4</sup>

*Longitudinal acceleration*  $A_x$  — X component of *acceleration vector* of the *C.G.* (ISO)<sup>4,5</sup>

*Longitudinal velocity*  $V_x$  — X component of *velocity vector* of the *C.G.* (ISO)<sup>4,5</sup>

Vertical acceleration  $A_z$  — Z component of *acceleration vector* of the C.G. (ISO)<sup>4,6</sup>

Vertical velocity  $V_z$  — Z component of *velocity vector* of the C.G. (ISO)<sup>4,6</sup>

#### 4.5 Angles

*Aerodynamic sideslip angle*  $\delta_{aero}$  — angle from X axis to velocity vector of air relative to the *vehicle reference frame*. (SAE)

*Euler angles* (  $\psi$ ,  $\theta$ ,  $\phi$  ) — sequence of consecutive rotations about  $Z_E$ , Y, and  $X_V$  axes to convert from the *earth-fixed axis system* to the *vehicle axis system*. Note that  $\psi$  is not identical to *roll* ( $\phi_V$ ) when *pitch* is non-zero. (SAE, ISO)

*Pitch*  $\theta$  — angle from X axis to  $X_V$  axis, about Y axis. (SAE, ISO)

*Roll*  $\phi_V$  — angle from  $X_E Y_E$  plane to  $Y_V$  axis, about X axis (SAE, ISO)<sup>3</sup>

*Sideslip angle*  $\delta$  — angle from the X axis to the projection of the C.G. velocity vector onto the XY plane, about the Z axis.

Sideslip can be calculated from the lateral velocity  $V_y$  and longitudinal velocity  $V_x$ .

$$\delta = \tan^{-1} \frac{V_y}{V_x} \text{ (SAE, ISO)}$$

*Yaw*  $\psi$  — angle from  $X_E$  axis to X axis, about Z axis (SAE, ISO)

#### 4.6 Angular velocity and acceleration

*Pitch acceleration*  $\dot{\theta}_y$  — Y component of *angular acceleration vector* of *vehicle reference frame*.<sup>7</sup>

*Pitch velocity*  $\dot{\theta}_y$  — Y component of *angular velocity vector* of *vehicle reference frame*.<sup>8</sup>

*Roll acceleration*  $\dot{\phi}_x$  — X component of *angular acceleration vector* of *vehicle reference frame*.<sup>7</sup>

*Roll velocity*  $\dot{\phi}_x$  — X component of *angular velocity vector* of *vehicle reference frame*.<sup>8</sup>

*Yaw acceleration*  $\dot{\psi}_z$  — Z component of vehicle *angular acceleration vector*. (ISO)

*Yaw velocity*  $\dot{\psi}_z$  — Z component of vehicle *angular velocity vector*. (SAE, ISO)

#### 4.7 Aerodynamic Forces and moments

Forces and moments acting from the air on the vehicle are summed into a single resultant aerodynamic force vector, and a single resultant aerodynamic moment vector taken about the *aerodynamic reference point*.

*Aerodynamic lateral force*  $F_{yaero}$  — Y component of aerodynamic resultant force. (SAE)

*Aerodynamic longitudinal force*  $F_{xaero}$  — X component of aerodynamic resultant force. (SAE)

*Aerodynamic pitch moment*  $M_{yaero}$  — Y component of aerodynamic resultant moment. (SAE<sup>19</sup>)



*Aerodynamic roll moment*  $M_{x_{aero}}$  — X component of aerodynamic resultant moment. (SAE<sup>19</sup>)

*Aerodynamic vertical force*  $F_{z_{aero}}$  — Z component of aerodynamic resultant force. (SAE)

*Aerodynamic yaw moment*  $M_{z_{aero}}$  — Z component of aerodynamic resultant moment. (SAE<sup>19</sup>)

## 5. Suspensions and steering

For solid axles, the term *suspension* normally refers to the suspension for both sides of the axle. For independent suspensions, the term *suspension* refers to one side. The term *axle suspension* always refers to both sides.

### 5.1 Size and weight

*Track*  $L_{TK}$  — distance between the *centers of tire contact* for one axle. In case of dual wheels, the midpoints of the *centers of tire contact* for each side are used. Track is normally variable with suspension *jounce*. (ISO)

*Unsprung weight* — portion of weight supported by a tire that is considered to move with the wheel. This usually includes a portion of the weight of the suspension elements. (SAE)

### 5.2 Kinematics

*Camber* — outward angular lean of wheel relative to *vehicle reference frame*: angle from  $Z_V$  axis to the  $X_W Z_W$  plane. Regardless of the choice of coordinate systems, outward lean is positive. The symmetric sign convention is convenient for describing certain kinematical and compliance relationships for both sides of the vehicle. (SAE, ISO)<sup>9</sup>

*Compliance camber* — portion of *camber* due to tire forces (except vertical) and moments. (SAE, ISO)

*Compliance steer*  $c$  — portion of *steer* due to tire forces (except vertical) and moments. (SAE, ISO)

*Damper mechanical advantage*  $R_d$  — Ratio of damper compression per unit of wheel jounce. This ratio is usually less than unity.

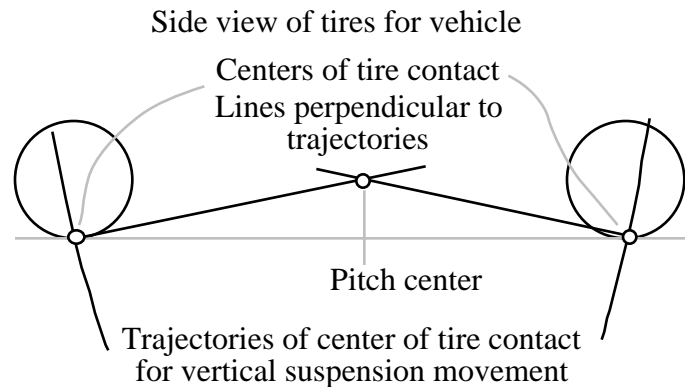
*Driver steer*  $d$  — portion of *steer* due to steering wheel angle, with no forces or moments applied by the road to the tires, and with no suspension movement.

*Jounce* — Vertical movement of wheel or axle relative to the *vehicle reference frame*. Jounce is positive for compressive movement (wheel moving up relative to the body). There is not a standard definition of zero jounce. (SAE<sup>18</sup>)

*Kinematical camber* — *camber* measured with no tire forces or moments other than vertical. (Also defined as *camber* minus *compliance camber*.)<sup>9,10</sup>

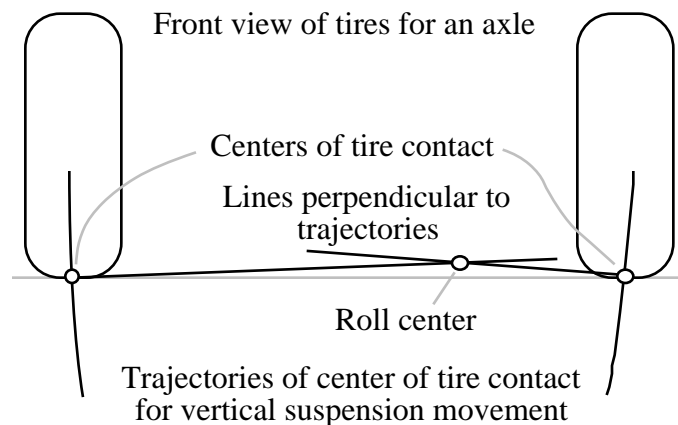
*Kinematical steer*  $k$  — *steer* measured with zero steering wheel angle and no tire forces or moments other than vertical. (Also defined as *steer angle* minus *compliance steer* and minus *driver steer*.)<sup>9,10</sup>

*Pitch center* — imaginary point in the  $X_V Z_V$  plane through the lateral center of the *vehicle reference frame* at which a longitudinal force applied to the vehicle body is reacted without causing suspension jounce (front or rear). An alternate definition is that the pitch center is the intersection of the two lines shown in Figure 4. Note: this definition of pitch center does not take into account the “wind up” effects of drive train torque applied to the wheels from the vehicle body.



**Figure 4. Pitch center.**

*Roll center* — imaginary point in the  $Y_V Z_V$  plane containing the two *wheel centers* of an axle, at which a lateral force applied to the vehicle body is reacted without causing *suspension roll angle*. (ISO, SAE) An alternate definition is that the roll center is the intersection of the two lines shown in Figure 5. (Note: the figure shows a non-equilibrium position of the vehicle.)



**Figure 5. Roll center.**

*Spring mechanical advantage  $R_s$* — Ratio of spring compression per unit of wheel jounce. This ratio is usually less than unity.

*Steer* — angle from X axis to the  $X_W$  axis, about the Z axis. (SAE, ISO)

*Suspension roll angle*— angle from line joining the *wheel centers* of an axle to the  $X_V Y_V$  plane in the *vehicle reference frame*. (SAE, ISO)

*Toe* — inward steer of wheel relative to the *vehicle reference frame*: angle from X axis to the  $X_W$  axis. Regardless of the choice of coordinate systems, inward steer is positive. The symmetric

sign convention is convenient for describing certain kinematical and compliance relationships for both sides of the vehicle. (SAE, ISO)<sup>11</sup>

### 5.3 Forces and moments

*Auxiliary roll moment*  $M_{aux}$  — the *suspension roll moment* minus the moments due to the *suspension forces* from the two sides. A positive moment causes positive vehicle roll.

*Damping force*  $F_d$  — Compressive force applied to the vehicle body by a damper.

*Spring force*  $F_s$  — Compressive force applied to the vehicle body by a suspension spring.

*Suspension roll moment*  $M_{roll}$  — total static roll moment applied to *sprung mass* due to *suspension roll angle*. A positive moment causes positive vehicle roll.

## 6. Tires and wheels

### 6.1 Kinematics

*Center of tire contact* — point at intersection of a line passing through the wheel center and the road, where the line is parallel with the  $Z_W$  axis. (The *center of tirecontact* is not necessarily at the center of the tire contact patch. See Figure 3.) (SAE, ISO)

*Inclination* — lean (angle) of wheel relative to *roadplane*: angle from  $Z_R$  axis to the  $Z_W$  axis, about the  $X_R$  axis. (SAE, ISO)<sup>12</sup>

*Longitudinal slip* — the ratio:  $\frac{\omega - \omega_0}{\omega_0}$

where  $\omega$  is the *angular velocity* of the wheel about its *spin axis* and  $\omega_0$  is the free rolling angular velocity of the wheel that would be measured at zero *slip angle* and zero *inclination*. ( $\omega_0$  is the longitudinal velocity of the wheel center, divided by the effective circumference of the tire at that speed and load condition.) (SAE, ISO)<sup>13</sup>

*Slip angle* — angle from the  $X_R$  axis to the *velocity vector* of the *center of tire contact*, about the  $Z_R$  axis. (See Figure 3.) (SAE, ISO)

*Spin axis*  $Y_W$  — axis of rotation of wheel about spindle. (See Figure 3.) (SAE)

*Wheel center* — intersection of *spin axis* and *wheel plane*. (See Figure 3.) (SAE, ISO)

*Wheel plane* — central plane of wheel, normal to the *spin axis*. (See Figure 3.) (SAE, ISO)

### 6.2 Forces and moments

Forces and moments acting from the ground on the tire are summed into a single resultant force vector and a single resultant moment vector taken about the *center of tire contact*.

*Aligning moment*  $M_z$  —  $Z_R$  component of ground resultant moment. (SAE, ISO)

*Overtopping moment*  $M_x$  —  $X_R$  component of ground resultant moment. (SAE, ISO)

*Rolling moment*  $M_y$  —  $Y_R$  component of ground resultant moment. (SAE<sup>14</sup>, ISO)

*Driving moment* —  $Y_W$  component of moment applied by the vehicle to the wheel about the spin axis. (SAE<sup>14</sup>)

*Lateral tire force*  $F_y$  —  $Y_R$  component of ground resultant force. (SAE, ISO<sup>15</sup>)

*Longitudinal tire force*  $F_x$  —  $X_R$  component of ground resultant force. (SAE, ISO<sup>15</sup>)

*Vertical tire force*  $F_z$  —  $Z_R$  component of ground resultant force. (SAE<sup>16</sup>, ISO<sup>15</sup>)

## 7. Notes

1. The ISO “wheel” axis system is similar to the “road” system defined in this document, except ISO does not account for inclined road surfaces.
2. Neither SAE nor ISO are explicit about the reference frame for the vehicle coordinate system, although both clearly involve the body.
3. SAE and ISO call this angle “vehicle roll,” and both call the Euler angle roll. (This document emphasizes vehicle roll, which is measurable, whereas the Euler angle is not.)
4. Neither SAE nor ISO define the point whose velocity and acceleration vector are being described.
5. SAE defines “longitudinal” velocity and acceleration as the  $X_V$  component, and “forward” velocity as the  $X$  component. The  $X$  component of acceleration is not covered.
6. SAE defines “normal” velocity and acceleration using the  $Z_V$  axis. The  $Z$  components of acceleration and velocity are not covered.
7. SAE does not define angular accelerations; ISO defines them as second derivatives of Euler angles.
8. SAE defines angular velocities about the  $X_V$ ,  $Y_V$ ,  $Z_V$  axes; ISO defines them as derivatives of Euler angles (only the roll derivative is measurable).
9. SAE and ISO define camber relative to  $Z_E$ , rather than  $Z_V$ .
10. ISO defines “camber angle change due to wheel travel kinematics” and “steer angle change due to wheel travel kinematics.”
11. ISO and SAE define both a toe angle and a toe displacement. SAE does not define a sign convention for toe angle.
12. The ISO definition of inclination is relative to absolute vertical ( $Z_E$ ) rather than the vector normal to the road ( $Z_R$ ).
13. SAE defines longitudinal slip with units of percentage (a factor of 100 higher than the ISO definition). ISO uses the symbol  $S_{XW}$  instead of  $K$  ( $K$  is used by Pacejka).
14. SAE uses the names “aligning torque,” “rolling resistance moment,” and “wheel torque” for “aligning moment,” “rolling moment,” and “driving moment,” respectively.
15. ISO uses the names “lateral force at wheel,” “longitudinal force at wheel,” and “vertical force at wheel.”

16. SAE uses the name “normal force” for negative force (relative to the SAE Z direction) and “vertical load” for the negative of “normal force.”
17. omitted.
18. SAE calls compressive suspension deflection “compression.”
19. SAE does not define the point about which aerodynamic moments are taken.

## Appendix

Table 1 defines the intermediate, wheel, and road axis systems in terms of the earth axis system ( $X_E, Y_E, Z_E$ ), the vehicle axis system ( $X_V, Y_V, Z_V$ ), the wheel spin axis ( $Y_W$ ), and the road normal ( $Z_R$ ). Two equivalent definitions are provided for the X and Y axes of the intermediate system.

**Table 1. Axis system definitions.**

Name	X (forward)	Y (left)	Z (up)	Names of Axes
Earth	$X_E$	$Y_E$	$Z_E$	$X_E, Y_E, Z_E$
Vehicle	$X_V$	$Y_V$	$Z_V$	$X_V, Y_V, Z_V$
Intermediate	$\frac{(Z_E \times X_V) \times Z_E}{ (Z_E \times X_V) \times Z_E }$	$\frac{Z_E \times X_V}{ Z_E \times X_V }$	$Z_E$	$X, Y, Z$ ( $Z=Z_E$ )
	$X_E \cos(\ ) + Y_E \sin(\ )$	$Y_E \cos(\ ) - X_E \sin(\ )$		
Wheel	$\frac{Y_W \times Z_R}{ Y_W \times Z_R }$	$Y_W$	$\frac{(Y_W \times Z_R) \times Y_W}{ (Y_W \times Z_R) \times Y_W }$	$X_W, Y_W, Z_W$
Road	$\frac{Y_W \times Z_R}{ Y_W \times Z_R }$	$\frac{Z_R \times (Y_W \times Z_R)}{ Z_R \times (Y_W \times Z_R) }$	$Z_R$	$X_R, Y_R, Z_R$ ( $X_R=X_W$ )

Note: the axes names  $X_W, Y_W$ , and  $Z_W$  have a different meaning in ISO 8855.

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