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Aerodynamics

Aerodynamic effects are represented in the vehicle model by a force vector acting on a point in the sprung mass and a moment vector applied to the sprung mass body. Each vector is built from three components (X, Y, and Z) that are parallel with the axes of the sprung mass coordinate system. The three force components are defined in terms of two dimensionless coefficients C_1 and C_2, the aerodynamic cross-section area A, and the dynamic air pressure Q:

$$F = C_1 \bullet C_2 \bullet A \bullet Q \tag{1}$$

where Q is:

$$Q = \frac{\rho V^2}{2} \tag{2}$$

ρ is air density, and V is air speed relative to the vehicle. Air density is normally 1.206 kg/m^3.

The coefficients C_1 and C_2 differ for the three force directions. The first, C_1, is a function of aerodynamic slip angle (β) while the other, C_2, is a function of both vehicle ride height (Z) and sprung mass pitch angle (θ). The coefficients are specified as tabular functions (i.e., Configurable Functions) of the dependent variables β, Z, and θ.

The point of application of the aerodynamic forces is the aerodynamic reference point. Aerodynamic effects are sometimes described in terms of a center of pressure, the point at which no moments are required to produce all aerodynamic effects. By convention in automotive engineering, however, aerodynamic effects are instead resolved to a set of forces at a reference location (reference point) and moments applied to the sprung mass body [1]. As noted in SAE J1594, an added advantage of this location is the direct translation of aerodynamic loading to the tire contact patch ground reactions.

Similarly, the general form of the aerodynamic moment equation is:

$$M = C_1 \bullet C_2 \bullet A \bullet L \bullet Q \tag{3}$$

where L is a reference length used to scale the moment equations. As with the force equations, the coefficients C_1 and C_2 differ for the three moment directions. The first coefficient, C_1, is a function of aerodynamic slip angle (β) while the second coefficient, C_2, is a function of both vehicle ride height (Z) and sprung mass pitch angle (θ).

In BikeSim, CarSim, and TruckSim, the six forces and moments can be described by six Configurable Functions that define the sensitivities of the coefficients in equations 1 and 3 relative to aerodynamic slip angle. Each of these functions are represented with a separate library screen, summarized in Table 1.

Table 1 also includes two libraries used to define wind conditions: the amplitude (speed) and direction (heading), where the heading is the yaw angle of the wind vector.

Table 1. Summary of aerodynamic libraries.

Library Screen	**Root Keyword**	**Description**
Aerodynamics: Fx (Drag) Coefficient	FX_AERO_SHAPING	C_1 coefficient for Fx
Aerodynamics: Fy (Side Force) Coefficient	FY_AERO_SHAPING	C_1 coefficient for Fy
Aerodynamics: Fz (Lift) Coefficient	FZ_AERO_SHAPING	C_1 coefficient for Fz
Aerodynamics: Mx (Roll Moment) Coefficient	MX_AERO_SHAPING	C_1 coefficient for Mx
Aerodynamics: My (Pitch Moment) Coefficient	MY_AERO_SHAPING	C_1 coefficient for My
Aerodynamics: Mz (Yaw Moment) Coefficient	MZ_AERO_SHAPING	C_1 coefficient for Mz
Wind Speed	WIND_SPEED	Absolute wind speed
Wind Heading	WIND_HEADING	Heading (yaw angle) of wind

The **Aerodynamics: Basic** screen is used for the vehicle lead unit and trailer(s) in which the aerodynamics vary only with aerodynamic slip angle. It includes links to the six libraries listed in Table 1 that involve the C_1 coefficient from equations 1 and 3. (The coefficient C_2 in equations 1 and 3 is set to unity when this screen is used.)

CarSim also includes a second, more extensive aerodynamics model that can be applied to lead units only. Using the **Aerodynamics: Pitch, Bounce, Yaw** screen, the six forces and moments are described by up to 12 Configurable Functions in which the sensitivities of the coefficients in equations 1 and 3 include aerodynamic slip angle, ride height, and sprung mass pitch angle (i.e., all content from Table 1 plus the additional content shown in Table 2).

Note Values for ρ can be specified in two places: either with the vehicle aerodynamic properties (i.e., the **Aerodynamics: Basic** screen or the more detailed **Aerodynamics: Pitch, Bounce, Yaw** screen), or with the wind description on the **Wind Speed** screen.

If ρ is specified on both the vehicle aerodynamics screen and the **Wind Speed** screen, the value associated with the **Wind Speed** screen will override the value set on the Aerodynamics screen because the associated dataset files for controls and disturbances are read by the VehicleSim (VS) Solver programs after reading data for the vehicle.

Table 2. Summary of libraries for CarSim extended aerodynamic effects.

Library Screen	Root Keyword	Description
Aerodynamics: Fx (Drag) Coef. Bounce/Pitch	`FX_AERO_SHAPING_2`	C_2 coefficient for Fx
Aerodynamics: Fy (Side Force) Coef. Bounce/Pitch	`FY_AERO_SHAPING_2`	C_2 coefficient for Fy
Aerodynamics: Fz (Lift) Coef. Bounce/Pitch	`FZ_AERO_SHAPING_2`	C_2 coefficient for Fz
Aerodynamics: Mx (Roll Moment) Coef. Bounce/Pitch	`MX_AERO_SHAPING_2`	C_2 coefficient for Mx
Aerodynamics: My (Pitch Moment) Coef. Bounce/Pitch	`MY_AERO_SHAPING_2`	C_2 coefficient for My
Aerodynamics: Mz (Yaw Moment) Coef. Bounce/Pitch	`MZ_AERO_SHAPING_2`	C_2 coefficient for Mz

Aerodynamics: Basic Screen

Use the screen shown in Figure 1 to assemble the aerodynamic effects acting on a vehicle lead unit (CarSim, TruckSim, BikeSim) and trailers (CarSim and TruckSim).

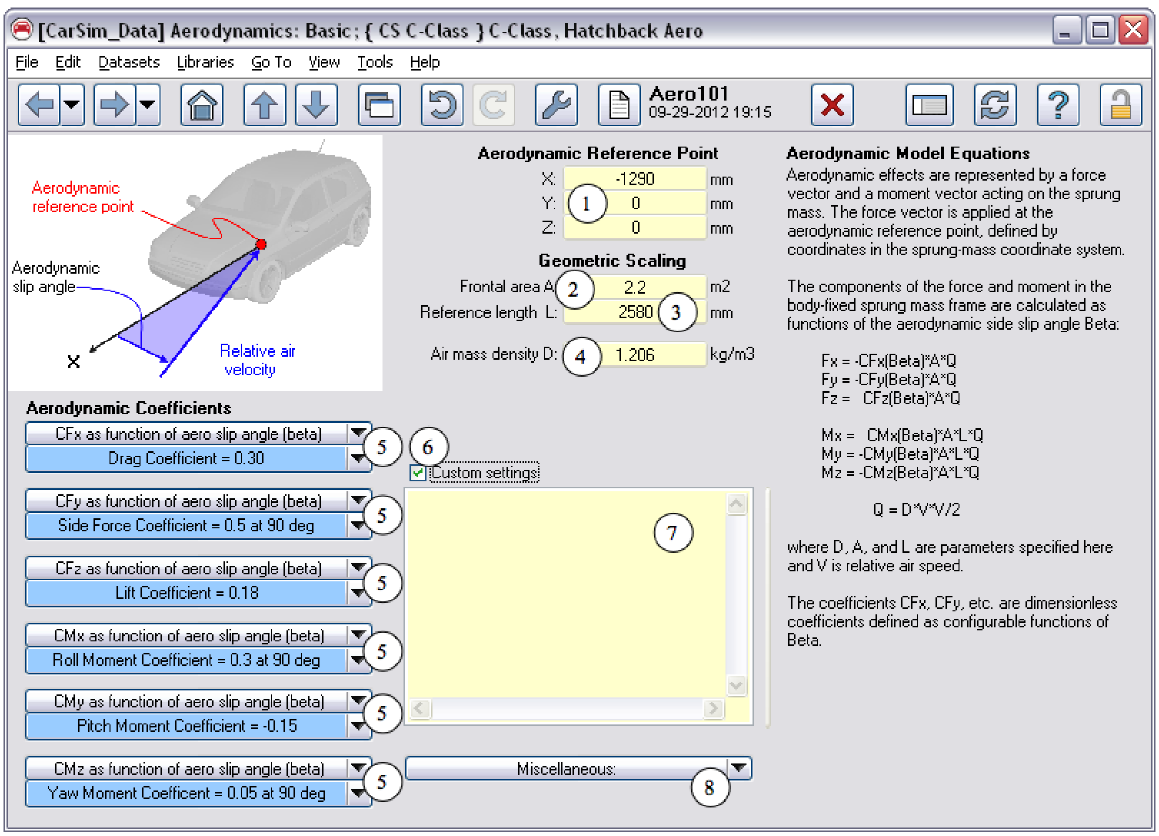

*Figure 1. The **Aerodynamics: Basic** Screen.*

① Coordinates of the aerodynamic reference point in the coordinate system of the sprung mass (keywords = `X_REF_AERO[(IUNIT)]`, `Y_REF_AERO[(IUNIT)]`, H_REF_AERO[(IUNIT)]). According to SAE J1594 [1], the reference point is located in the ground plane at the center of the wheels (i.e., half the track width and half the wheelbase). With this convention, the X coordinate for a motor vehicle is the negative of half the wheelbase. For a trailer, the X coordinate is the negative of the distance from the hitch to the axle center. Furthermore, the lateral (Y) coordinate is zero and the height (Z) is close to zero (it is zero if your definition of the sprung mass coordinate system has the origin in the ground plane in the design load condition). Although the reference point is nominally located in the ground plane, it is attached to the sprung mass body and moves with it. Therefore, the forces are always applied at the same point in the sprung mass regardless of its orientation in space.

Note If you follow the convention that the X coordinate of the aerodynamic reference point is the negative of half the wheelbase, be sure to change the coordinate if the wheelbase is changed. For TruckSim vehicles with tandem axles, "wheelbase" is typically based on the midpoint of the tandem pair of axles.

2 Frontal area of vehicle unit used to calculate aerodynamic forces and moments (keyword = AREA_AERO[(IUNIT)]).

3 Aerodynamic reference length (keyword = L_REF_AERO[(IUNIT)]). This length is used to scale the three aerodynamic moments applied to the sprung mass. It is usually the wheelbase length.

4 Air mass density ρ (see equation 2, keyword = D_AIR). As noted earlier, air density can also be specified on the **Wind Speed** screen. If a run is made with a wind dataset that specifies ρ, that value will override the value specified on this screen.

5 Definitions of the coefficient C_1 in equations 1 and 3. Each of these coefficients has an associated drop-down control that can be used to specify its value as either a constant, or with a link to another dataset in which the coefficient is defined using a Configurable Function based on aerodynamic slip angle (Figure 2).

Figure 2. Drop-down control to specify coefficient as constant or Configurable Function.

When the coefficient is set to a constant, a yellow field is shown for the value (Figure 2). If the Configurable Function option is chosen, a blue link is used to connect to another dataset (Figure 1) with access to the libraries shown in Table 1.

6 Checkbox to show more controls for custom settings. When checked, a Miscellaneous yellow field 7 and Miscellaneous link 8 are displayed.

7 Miscellaneous yellow field. This has no predefined purpose but is available to add VS Commands or model parameter using their math model keywords. Its visibility is controlled by the Custom settings checkbox 6.

8 Miscellaneous link. This has no predefined purpose but can be used to link to a dataset that specifies parameters for extensions to the model or information for the animator. Its visibility is controlled by the Custom settings checkbox 6.

Aerodynamics: Pitch, Bounce, Yaw

This screen is not supported in BikeSim or TruckSim, nor for use with trailers in CarSim.

Use the screen shown in Figure 3 to assemble the aerodynamic effects acting on a motor vehicle lead unit. This screen is used when detailed aerodynamic properties are known and their variation with vehicle ride height and pitch angle is important.

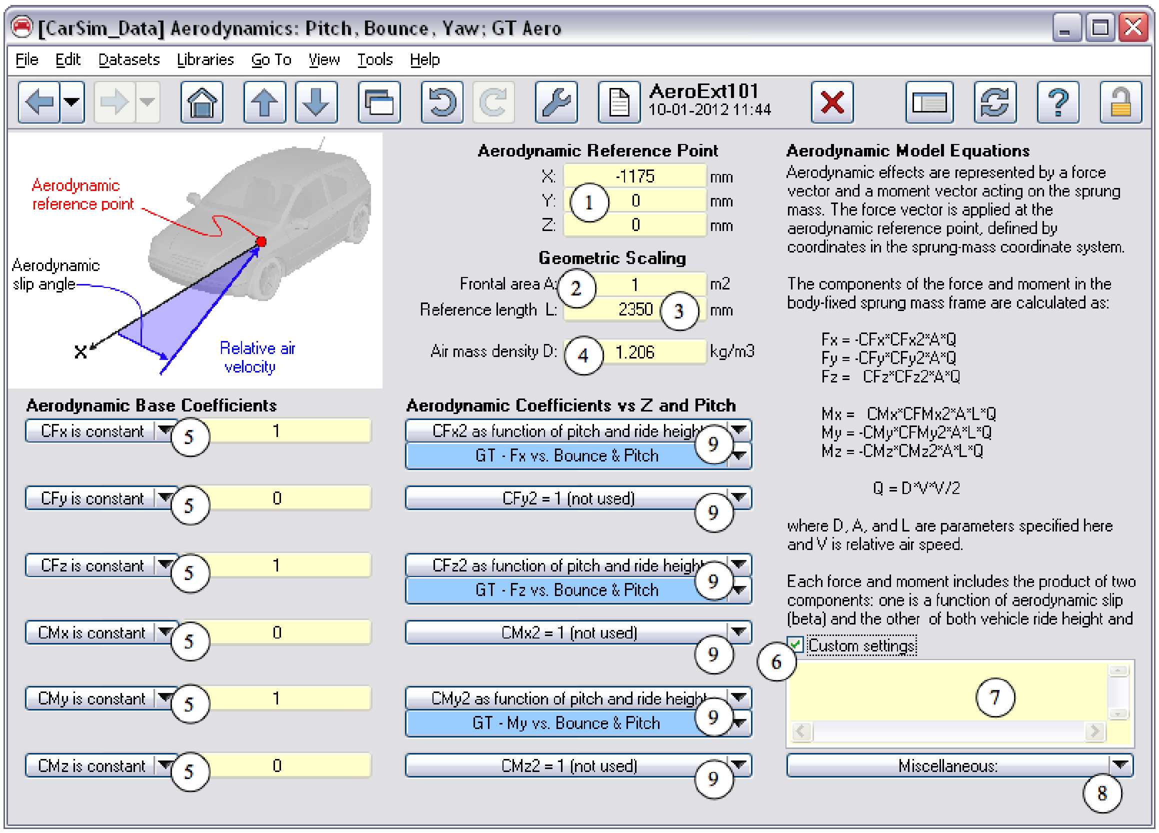

*Figure 3. The **Aerodynamics: Pitch, Bounce, Yaw** screen.*

The controls from the **Aerodynamics: Basic** screen (Figure 1) are also on this screen and were described in the previous section. This screen has additional controls for the coefficient C_2 used for each force and moment 9.

9 Definitions of the coefficient C_2 in equations 1 and 3. Each of these coefficients has an associated drop-down control that can be used to specify that the coefficient is not used (it is set to unity), or that it is defined with a Configurable Function based on vehicle pitch angle and ride height.

Wind Heading, Aerodynamic Slip, and Air Speed

Wind heading is defined in the global coordinate system as the yaw angle of the wind vector. There are no compass directions defined in CarSim, TruckSim, or BikeSim. Yaw angle of the wind is the angle from the global X axis to the direction the wind is blowing toward. Global yaw of the wind is defined to be zero when the wind is blowing in the positive X direction, 90 degrees when the wind is blowing in the positive Y direction, 180 degrees when the wind is blowing in the negative X direction, and -90 degrees when the wind is blowing in the negative Y direction.

If the vehicle is pointed in the positive X direction (Figure 4), the vehicle yaw angle (`YAW`) is zero, and the wind heading (`YAW_WIND`) is also zero, then the wind is a perfect tailwind. With these conditions, if the vehicle is stopped (`Vx = 0`), the vehicle aerodynamic slip angle (`BETAAIR`) is 180 degrees. The aerodynamic slip angle is the angle from the vehicle heading (the vehicle local X direction) to the relative wind. The relative wind is the sum of the (1) global wind vector, and the (2) wind vector contributed by the vehicle's motion.

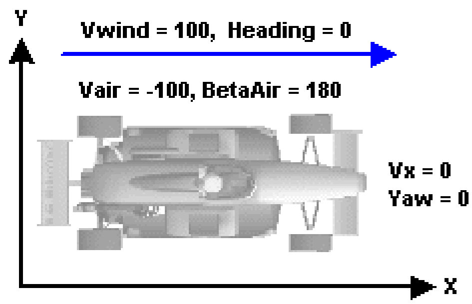

Figure 4: Vehicle Stopped with Tailwind

Under these conditions, the relative wind speed is the negative of the global wind speed because it is a tailwind. The relative wind speed is the magnitude of the vector sum of the (1) global wind speed vector, and the (2) air speed contributed by the vehicle motion, the relative wind.

As another example, a vehicle is driving at 100 km/h in the positive Y direction (Figure 5). A 100 km/h (`VWIND`) wind is *from* 45 degrees to the right of the path of the car. In this case, the global wind heading (`YAW_WIND`) is 225 degrees or -135 degrees (the direction it is blowing *toward* in the global reference frame), the vehicle heading (`YAW`) is 90 degrees, the aerodynamic slip angle (`BETAAIR`) is -22.5 degrees, and the relative wind speed (`VAIR`) is approximately 185 km/h.

The airspeed due to vehicle motion can also be thought of as the airspeed that would be present in the absence of wind.

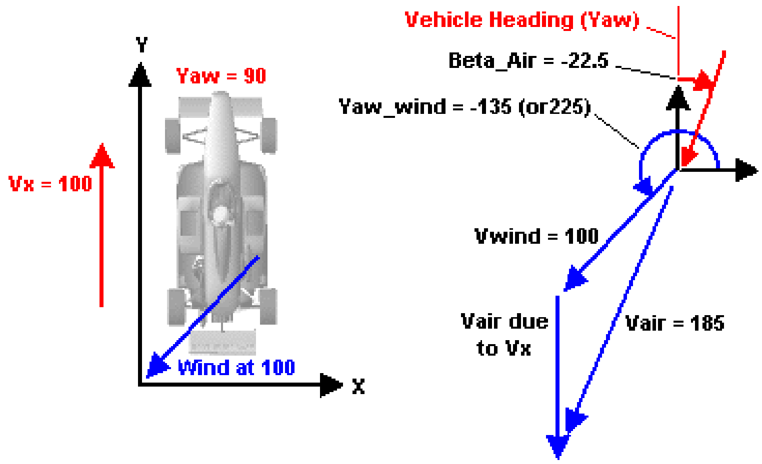

Figure 5: Airspeed Vector

References

1. "Vehicle Aerodynamics Terminology," SAE J1594_201007, Warrendale, PA: SAE International, 2010.
2. "Vehicle Dynamics Terminology," SAE J670_200801, Warrendale, PA: SAE International, 2008.