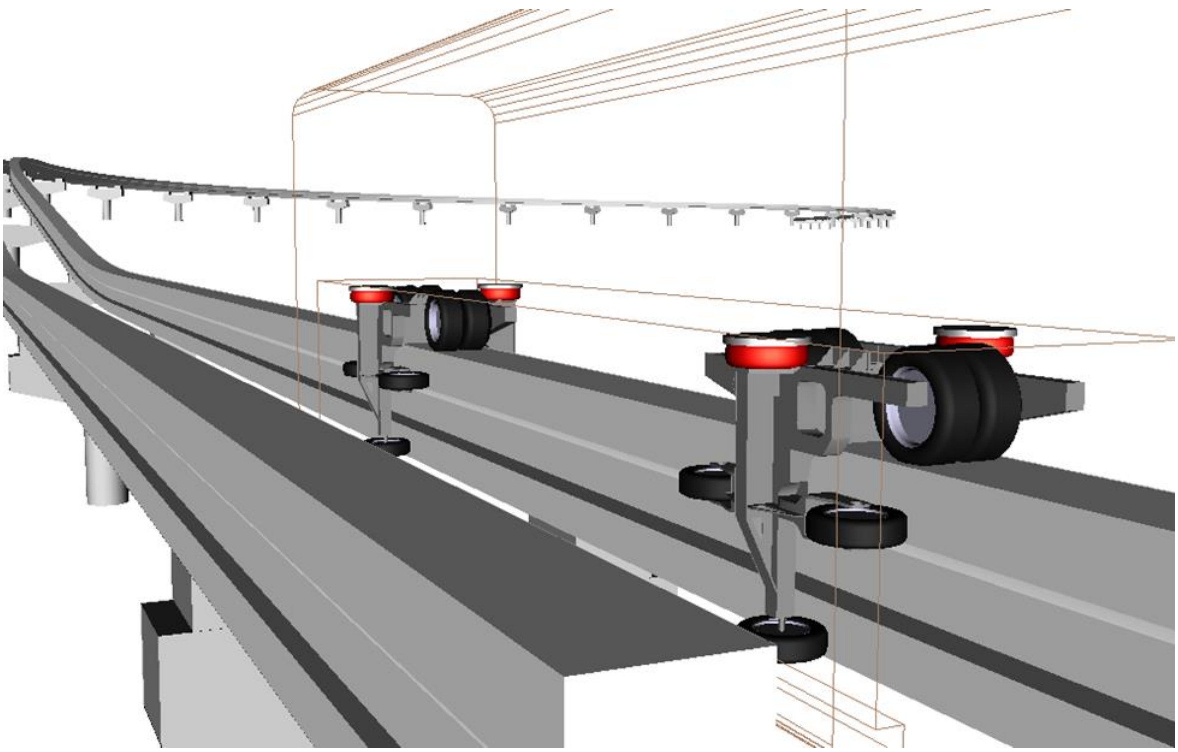
UNIVERSAL MECHANISM 7.0

Simulation of Monorail Train Dynamics

User's manual

2013



Contents

26. UM Module for simulation of monorail trains

26.1. General information

Program package Universal Mechanism includes a specialized module **UM Monorail Train** for analysis of 3D dynamics of both single vehicle and trains. The module includes additional tools integrated into the program kernel.

The module is available in the UM configuration if the sign + is set in the corresponding line of the **About** window, the **Help | About…** menu command, figure 26.1.

Figure 26.1. UM Monorail Train module is available

UM Monorail Train contains the following main components:

- tools for generation and visualization of guideway structure (bridge) geometry;
- tools for generation and visualization of guideway roughness (irregularities);
- mathematical models of tire forces (tire/road contact forces);
- set of typical dynamic experiments.

UM Monorail Train allows the user to solve the following problems:

- estimation of vehicle vibrations due to irregularities;
- estimation of vehicle dynamic performances on curving;
- parametric optimization of vehicle elements according to various criteria;
- longitudinal forces and vibrations for trains.

26.2. Base system of coordinates

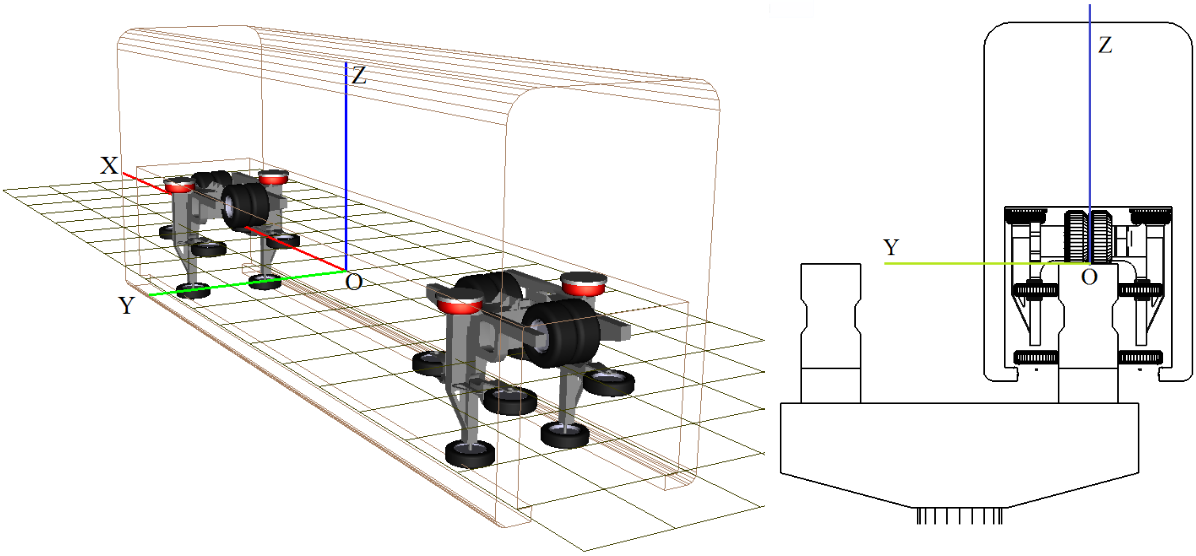


Figure 26.2. Base system of coordinates (SC0)

Inertial system of coordinates (SC0) in UM Monorail Train meets the following requirements (figure 26.2).

- Axis Z is vertical, axis X coincides with the vehicle longitudinal axis at its ideal position at the moment of motion start; direction of X axis corresponds to the motion direction of the vehicle.
- Origin of SC0 lies at the centerline of the ideal upper surface of track beam, i.e. the surface for driving wheels.

26.3. Development of vehicle model

The user develops the vehicle model in UMUmput.exe program. The model consists of bodies, joints and force element. We recommend to start the model development with studying the model delivered with UM **{UM Data}\Samples\Monorail\Monorail vehicle**.

26.3.1. Monorail identification

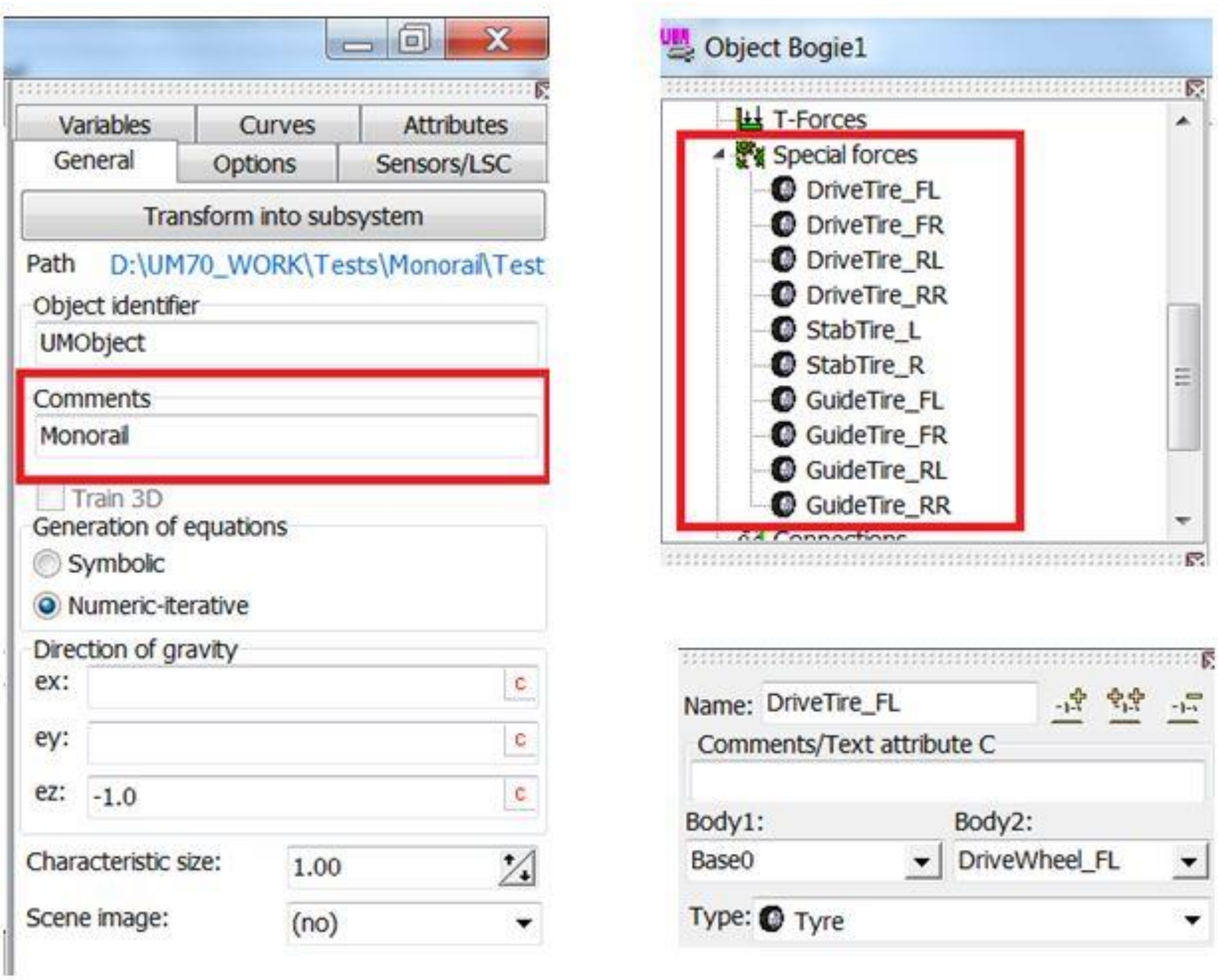


Figure 26.3. Text attribute 'Monorail'. Special forces 'Tires'

UM identifies the model as a monorail vehicle or a monorail train if the following two requirements are met in the model description:

- The standard text comment 'Monorail' must be set in the **Comments** box on the **General** tab of the data inspector, figure 26.3, left;
- Special forces of the **Tire** type are assigned to the wheels, figure 26.3, right.

26.3.2. Modeling wheels

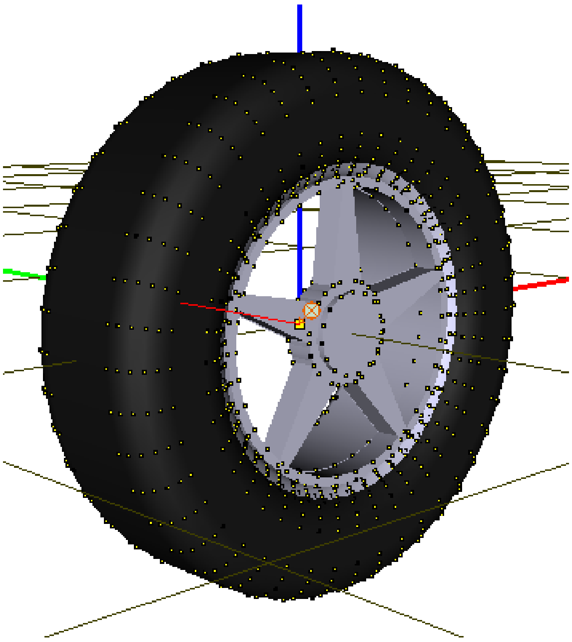


Figure 26.4. Model of a wheel as a body

A wheel in the UM model of a vehicle is a usual rigid body with assigned image and inertia parameters, figure 26.4. The following special features distinguish the wheel from other bodies in the model.

- Center of mass is located at the origin of the wheel-fixed system of coordinates (SC).
- Wheel rotation axis coincides with the Y-axis of the wheel-fixed SC.
- A special force element of **Tire** type should be created for each of the wheel, figure 26.3, right.
- The wheel should be connected to the vehicle by a rotational joint; **increment of joint coordinates must correspond to the motion of the vehicle ahead**.

In case of guiding and stabilizing wheels, the last requirements can be met if one of the joint vectors has opposite directions for the left and right wheels because the wheels rotate in different directions. Examples of rotational joints for the left and right guiding wheels are shown in figure 26.5, figure 26.6. Bogie-fixed joint vector for the left wheel is directed downwards whereas for the right wheel it is directed upwards.

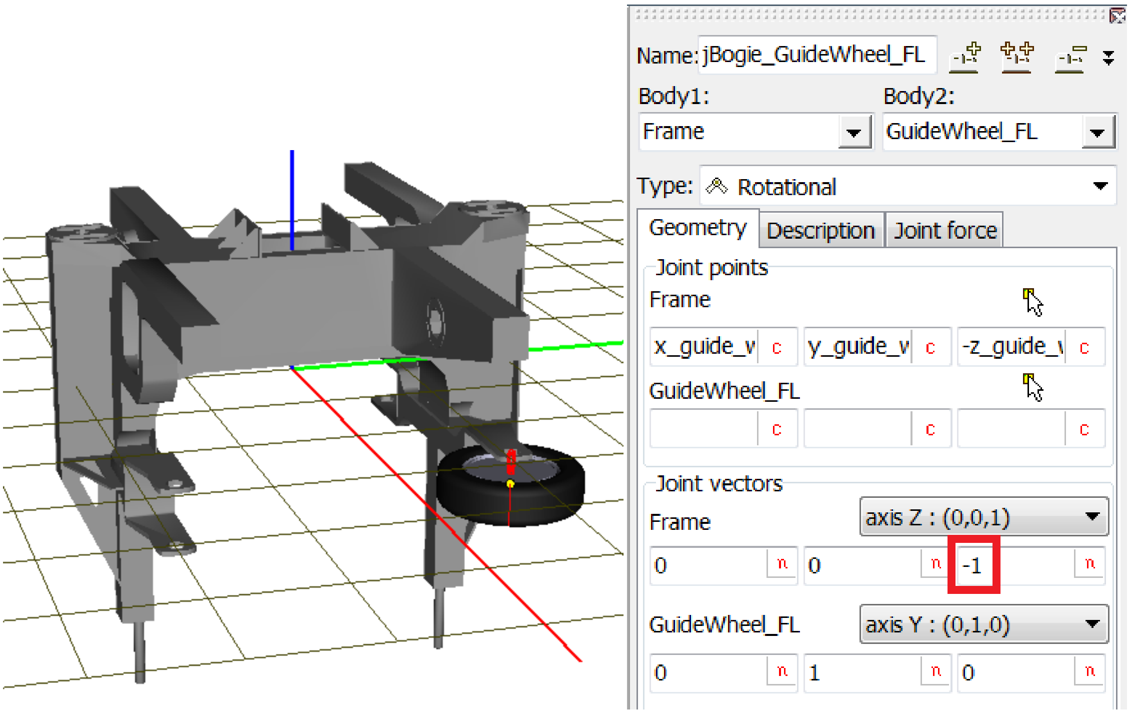


Figure 26.5. Joint for the left guiding wheel

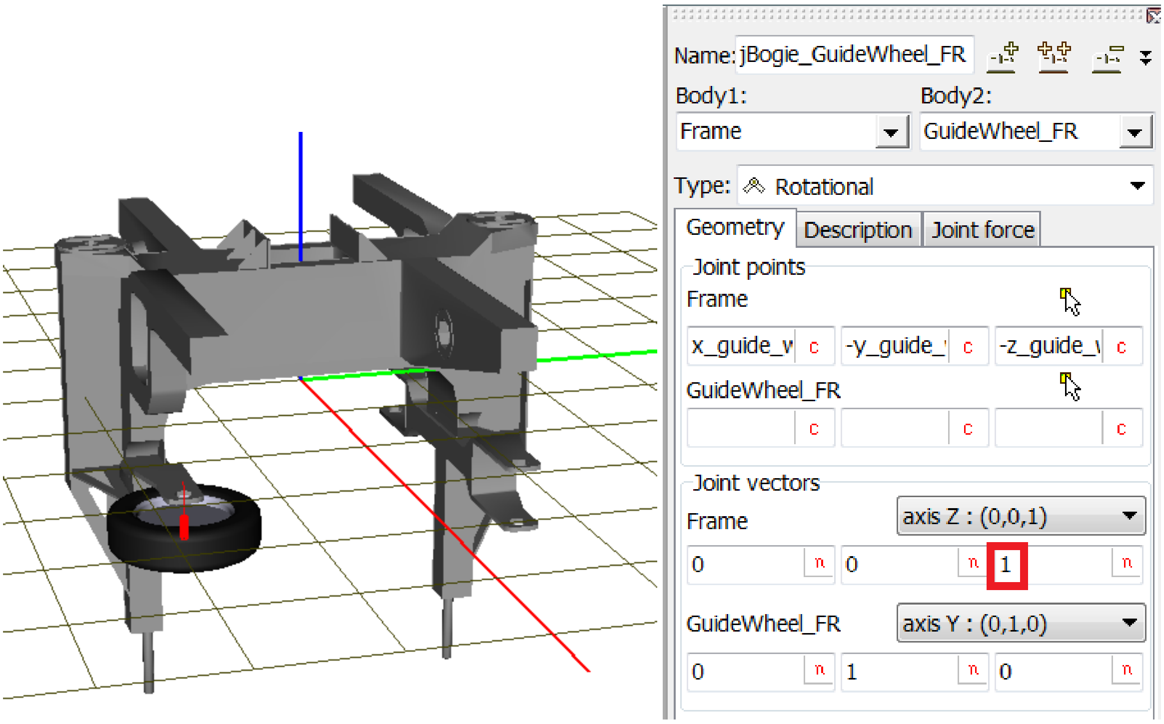


Figure 26.6. Joint for the right guiding wheel

We could recommend the following method for verification the correctness of joint description, figure 26.7.

- Set the contour type of graphics in the animation window by the button in the top of the window.
- Open the **Description** tab in the data inspector. Change the value of the coordinates 1,2,3… degrees and watch the direction of the wheel rotation.

- If the direction is false, change the direction of the bogie-fixed joint vector on the **Geometry** tab.

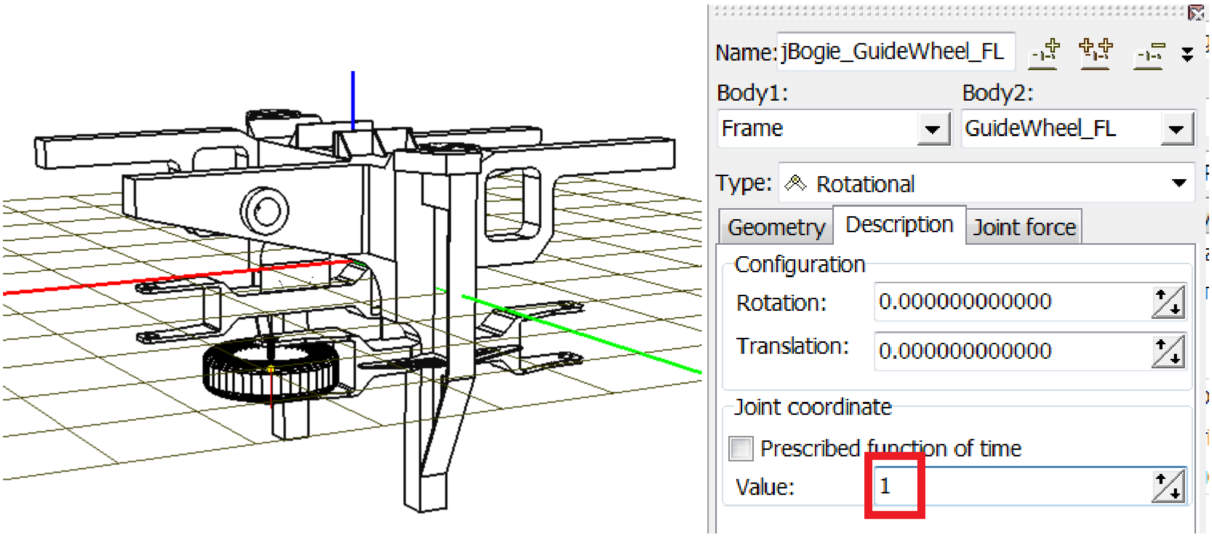


Figure 26.7. Increase of the joint coordinate

26.3.3. Suspension springs and shock absorbers

Linear suspension springs can be modeled by the *generalized linear force elements* (Chapter 2) if a stiffness matrix describes their stiffness properties.

Both linear and nonlinear bipolar springs and shock absorbers can be modeled by *bipolar force elements* (Chapter 2).

26.3.4. Air springs

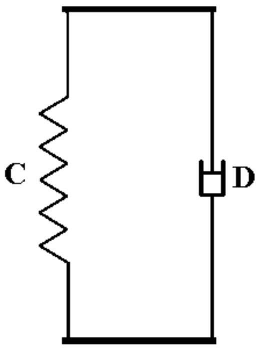


Figure 26.8. Simplest model of air spring

The simplest model of an air spring in shown in figure 26.8. A bipolar force element of the *Expression* type describes this model, the expression is

$$-C*(x-x0)-D*v$$

where *C*, *D* are the stiffness and damping constants, x_0 is the undeformed length of the element.

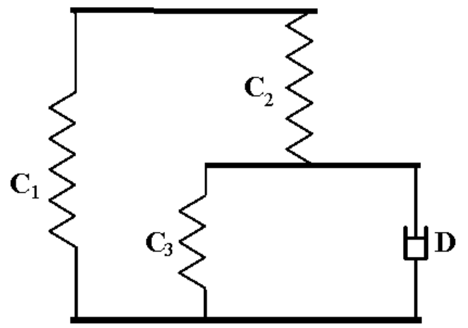


Figure 26.9. Nishimura model of air spring

The known Nishimura model of an air spring (figure 26.9) is created as a bipolar force element *'List of forces'* with two subelements: linear elastic and viscous-elastic (Chapter 2).

The stiffness and damping constants for the model are calculated according to the following formulas:

$$C_1 = nA_e^2 \frac{p_0}{V_r},\ C_2 = nA_e^2 \frac{p_0}{V_b},\ C_3 = (p_0 - p_a)\frac{dA_e}{dx},$$

$$D = R_f A_e^2 \rho_0 g.$$

Here A_e is the effective area of the spring, p_0, p_a are the initial absolute pressure and the atmospheric one, V_r, V_a are the reservoir and the air bug volumes, x is the coordinate, g is the gravity acceleration, $R_f = 0.126/d_s^3$ is the flow resistance coefficient, d_s is the diameter of the surge pipe. The number n is frequency dependent, $n = 1$ for low frequencies (<0.1Hz) and $n = 1.4$ for higher frequencies (>3Hz).

26.3.5. Bushings

UM supports both linear and nonlinear bushings. The mathematical model of bushings is described in Chapter 2, Sect. *Special forces/Bushings*. Input of the element parameters see in Chapter 3, Sect. *Data Input / Input of force elements / Special forces / Bushings*.

26.3.6. Longitudinal velocity control

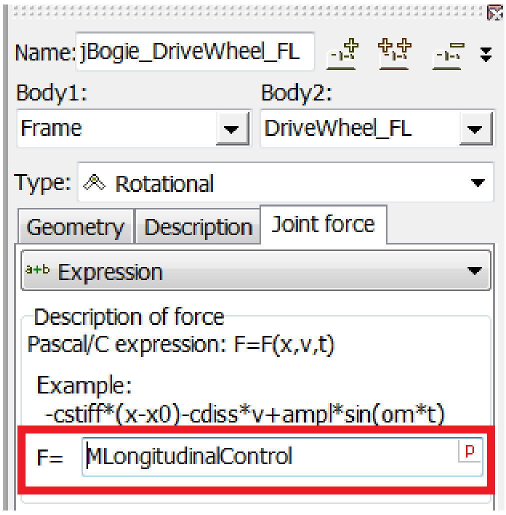


Figure 26.10. Joint torque for longitudinal velocity control

To make possible a control of the vehicle longitudinal velocity, the model of a vehicle needs a special traction joint torque. In the simplest case the torque is introduced in the driving wheel joint, which is a rotational joint connecting the driving wheel, figure 26.10. The model of the control torque is described as a joint torque of the *Expression* type by one and the same identifier for all of the driving wheels. The default identifier is (recommended)

MLongitudinalControl

The user may introduce another name of identifier.

26.4. Track macro profile and roughness

Guideway geometry is composed of two components: macro profile, and roughness.

26.4.1. Track macro profile

Track macro profile contains 3D information about the geometry of the centerline on the top of guiding beam. The centerline is composed of the horizontal (X-Y) and vertical profiles, which assumed to be independent. Both horizontal and vertical profiles are stored in *.mcg text files located by default in the **{UM Data}\Monorail\Macrogeometry** directory.

The **horizontal profile** includes any number of tangent sections, standard curves and plane curves specified by a set of points with optional smoothing by splines. The **standard curve** consists of two **transient sections** and a **steady section** with constant radius. The transient sections are the Euler's (Cornu's) spiral (clothoid), i.e. a plane curve whose curvature changes linearly with the curve length. Thus, the curvature increases from zero to the given value at the start transient section, is constant within the steady section, and finally decreases to zero at the end transient section.

The **horizontal profile** consists of any number of sections with constant slope and sections specified by a set of points with optional smoothing by splines. Coupling of sections with constant slopes is smoothed by circles with the given radii.

To generate a macro geometry file use the **Tools | Create macrogeometry…** menu command in UM Simulation program. The wizard of macro geometry appears (figure 26.11).

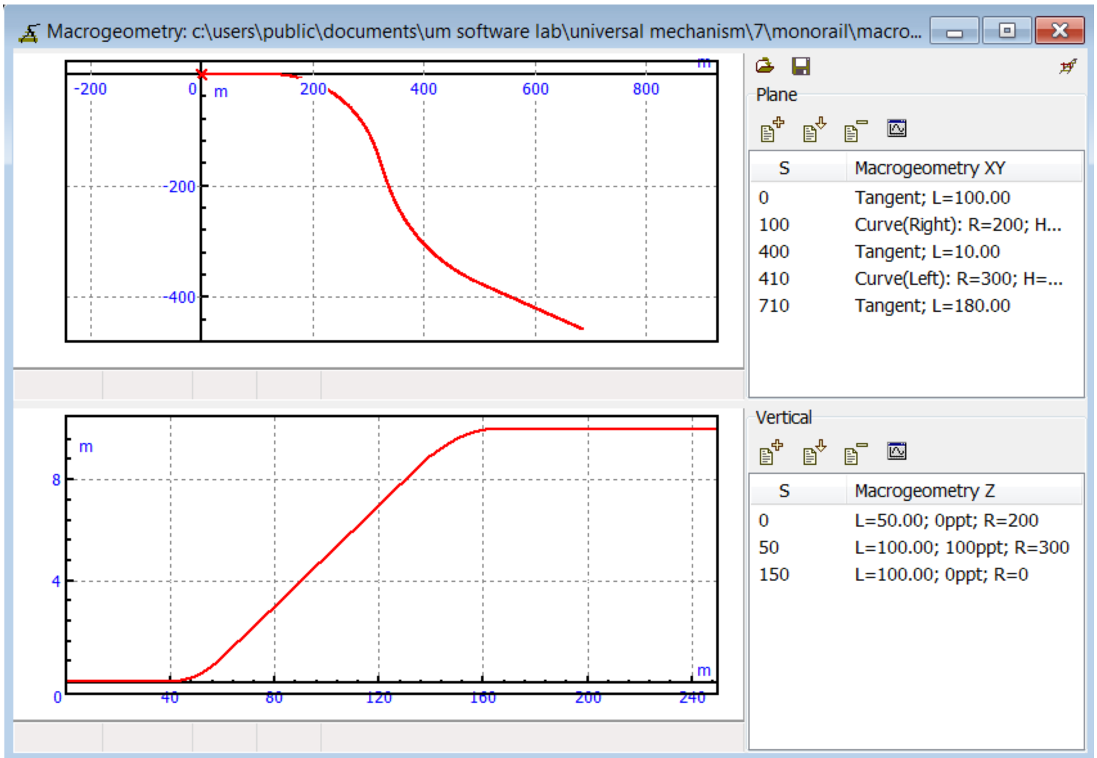


Figure 26.11. Wizard of macro geometry. Horizontal (upper plot) and vertical (lower plot) profiles

26.4.2. Track macrogeometry in horizontal plane

The upper part of the window in figure 26.11 is used for description of the track geometry in the horizontal plane.

- To *add* a section, click on the button and select the section type in the menu.

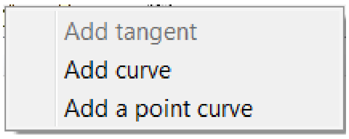


Figure 26.12. Section menu

- To *edit* the section parameters double click on the corresponding line of the section list or select the line and press Enter.
- To *insert* a section before the selected one, click on the button.
- The button *removes* the selected section from the list.

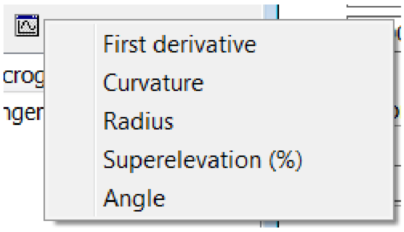


Figure 26.13. Additional plot information about profile

- The button allows the user to get some useful information about the horizontal profile like curvature and superelevation.

26.4.2.1. Tangent section

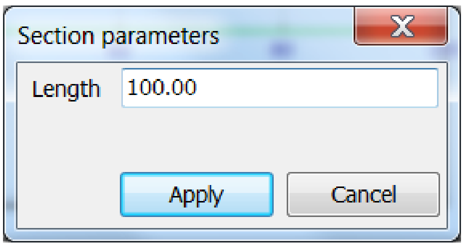


Figure 26.14. Parameters of a tangent section

Tangent section window contains the values of section length.

26.4.2.2. Curve section

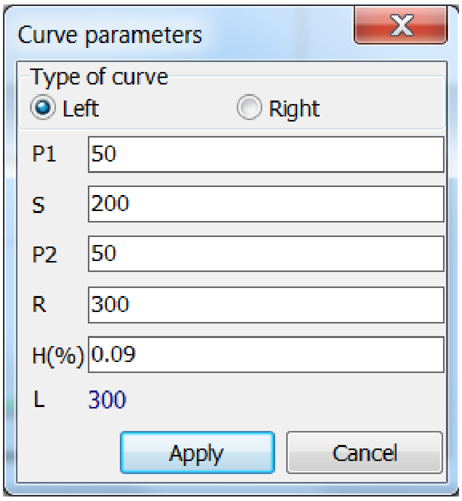


Figure 26.15. Window with curve parameters

Curve parameter window includes

- type of curve (left or right);
- geometric parameters of the curve: lengths of transient sections (P1, P2), length of steady curve section (S), radius (R), superelevation (H).

26.4.2.2.1. Point curve

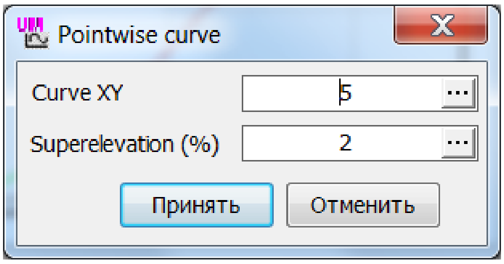


Figure 26.16. Point curve parameter window

Point curve can be used for the pointwise description of guideway horizontal geometry. Press  button for editing of the curve parameter in the curve editor.

- **Curve XY**

Curve editor is used for setting the guide beam centerline projection in XY plane. The section length is evaluated automatically as a length of XY curve.

The first point must have zero coordinates. The tangent to the curve at the first point must be equal to the positive direction of X axis.

Number of points and curve length are not limited. For example, it can be measured field data or analytically computed coordinates of nonstandard transient curve section.

The point list can be as follows:

X	Y	X	Y

0	0	26	0.4394
2	0.0002	28	0.5488
4	0.0016	30	0.675
6	0.0054	32	0.8192
8	0.0128	34	0.9826
10	0.025	36	1.1664
12	0.0432	38	1.3718
14	0.0686	40	1.6
16	0.1024	42	1.8522
18	0.1458	44	2.1296
20	0.2	46	2.4334
22	0.2662	48	2.7648
24	0.3456	50	3.125
26	0.4394		

The list is recommended to be prepared in MS Excel as a two-column table. Than it is copied to clipboard and pasted to the curve editor (all other points must be preliminary deleted from the curve editor list!). The curve is shown in figure 26.17. B-Spline smoothing is recommended for the curve approximation. Automatically evaluated curve length is shown in figure 26.18.

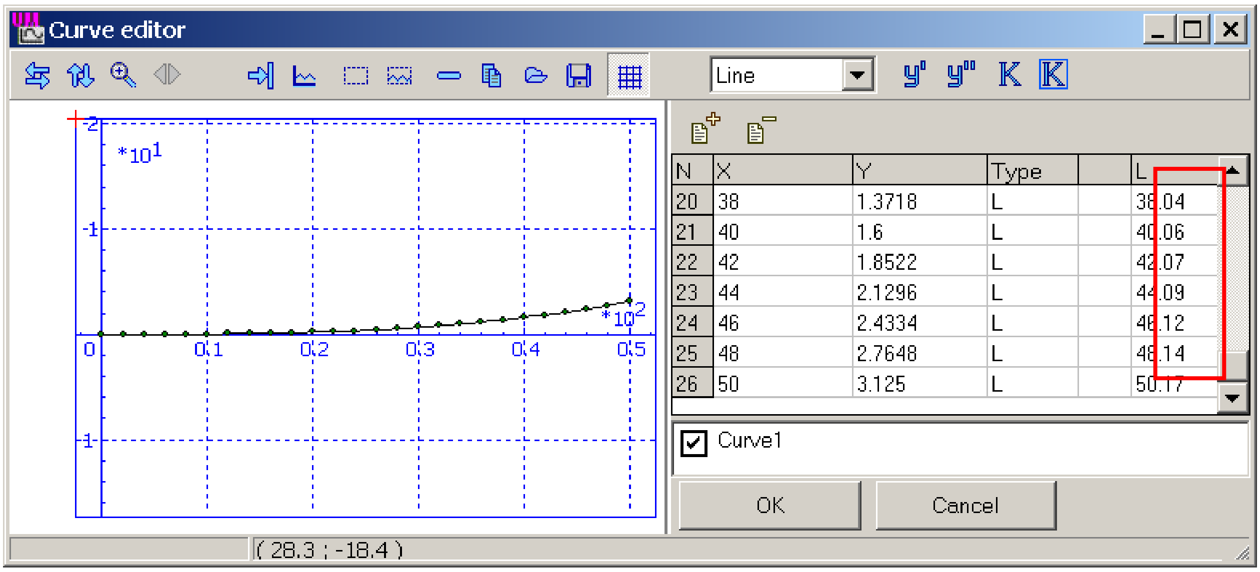


Figure 26.17. XY curve editor

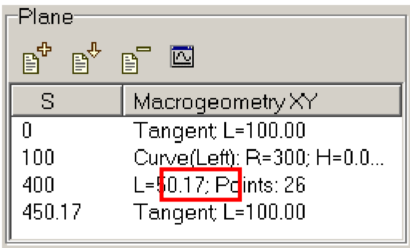


Figure 26.18. Point curve length

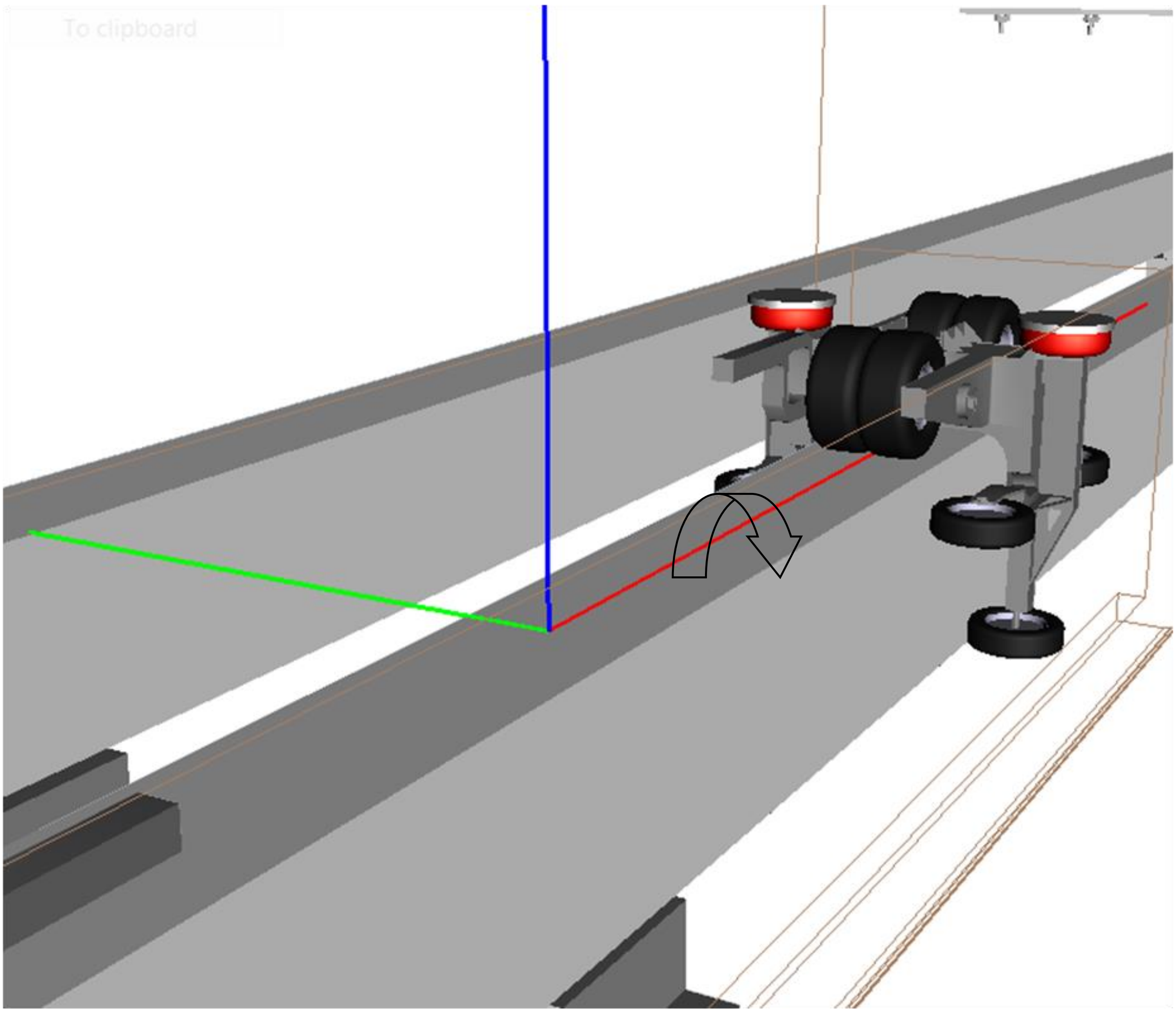


Figure 26.19. Direction of positive superelevation

- **Superelevation**

Superelevation is a function of the XY curve length. The user may use the length data evaluated in the last column in point table, figure 26.17.

The positive direction of superelevation is show in figure 26.19.

Remark. The user should take care of the continuity of superelevation function.

26.4.3. Track macrogeometry in vertical plane

The lower part of the window in figure 26.20 is used for description of the track geometry in the vertical plane.

- To *add* a section, click on the button and select the section type in the menu.

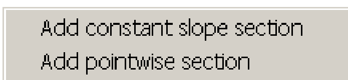


Figure 26.20. Section menu

- To *edit* the section parameters double click on the corresponding line of the section list or select the line and press Enter.

26.4.3.1. Constant slope section

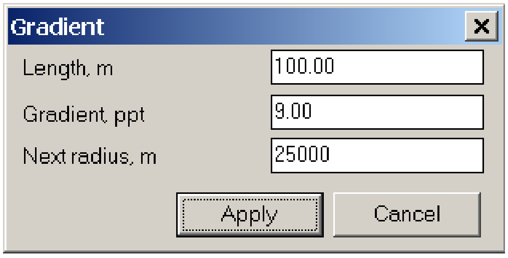


Figure 26.21. Constant slope section parameters

The following parameters can be set in Gradient window (figure 26.21):

- length of section (m);
- gradient in ppt (parts per thousand or meters per kilometer);
- radius of circle on smoothing the gradient change.

26.4.3.2. Point section

Point curve can be used for the description of vertical guide beam centerline coordinate as a function of the XY curve length. Curve editor is used for description of functions, see figure 26.22. Curve editor opens when section editing starts.

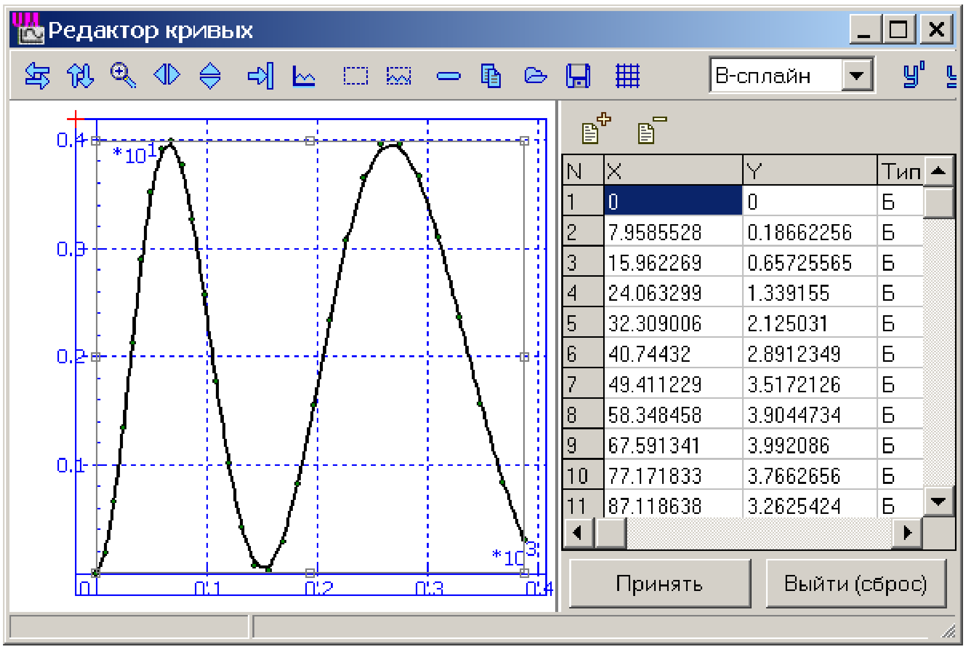


Figure 26.22. Parameters of point section

X parameter corresponds to curve length value; Y parameter – to Z coordinate of track axis. B-Splines are recommended for approximation.

Remarks.	Use zero smoothing radius value for constant slope section if point section is next to it, otherwise the vertical profile will have a break of tangent.

26.4.4. Track roughness (irregularities)

Development of track roughness (irregularities) files *.irr is considered in details in 12_UM_Automotive.pdf file, Sect. *Micro profile (irregularities).*

Here we consider some features related to monorail trains.

- **Driving wheels**

Unlike the road vehicles, equal irregularities are assumed to the left and right driving wheel, i.e. only one *.irr file is required for the vertical track roughness description.

- **Guiding and stabilizing wheels**

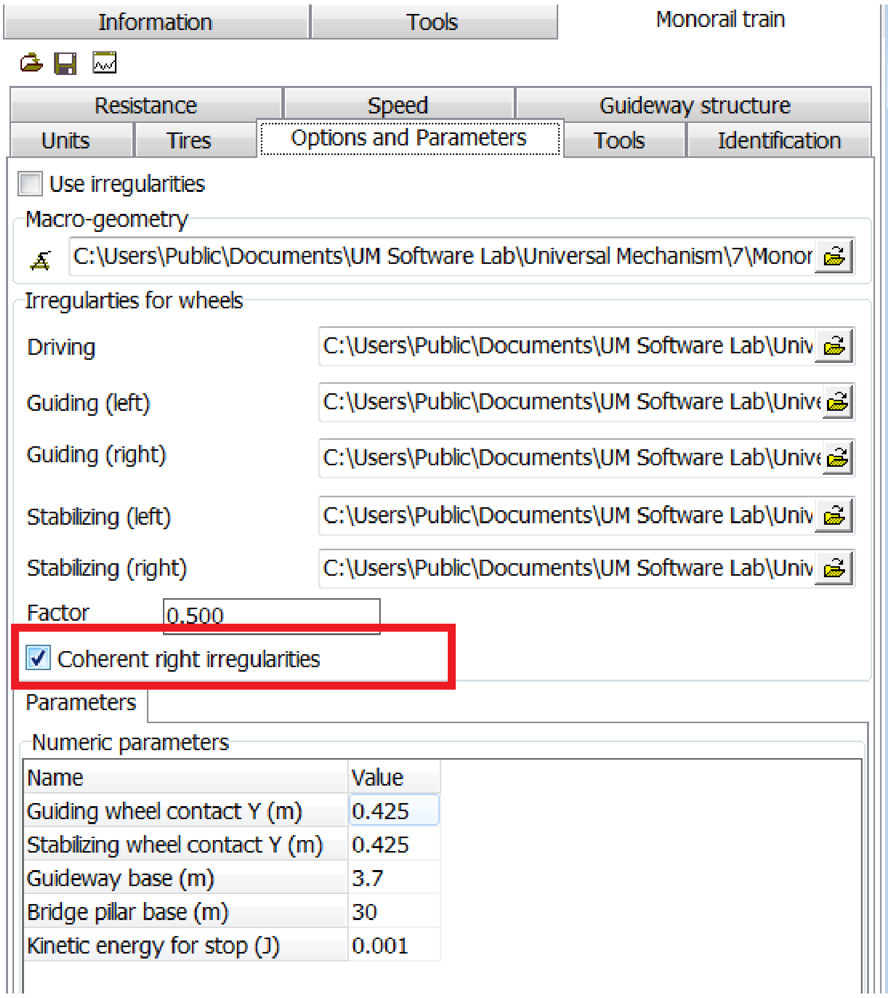


Figure 26.23. Parameter “Coherent right irregularities”

Description of irregularities for the left and right wheels depends on the key **Coherent right irregularities**, figure 26.25. This key affects the sign of the irregularity height for the right wheels only. If the key is checked, positive directions for the left and right irregularities are the same. If not, the direction for the right irregularities changes to opposite one, figure 26.24.

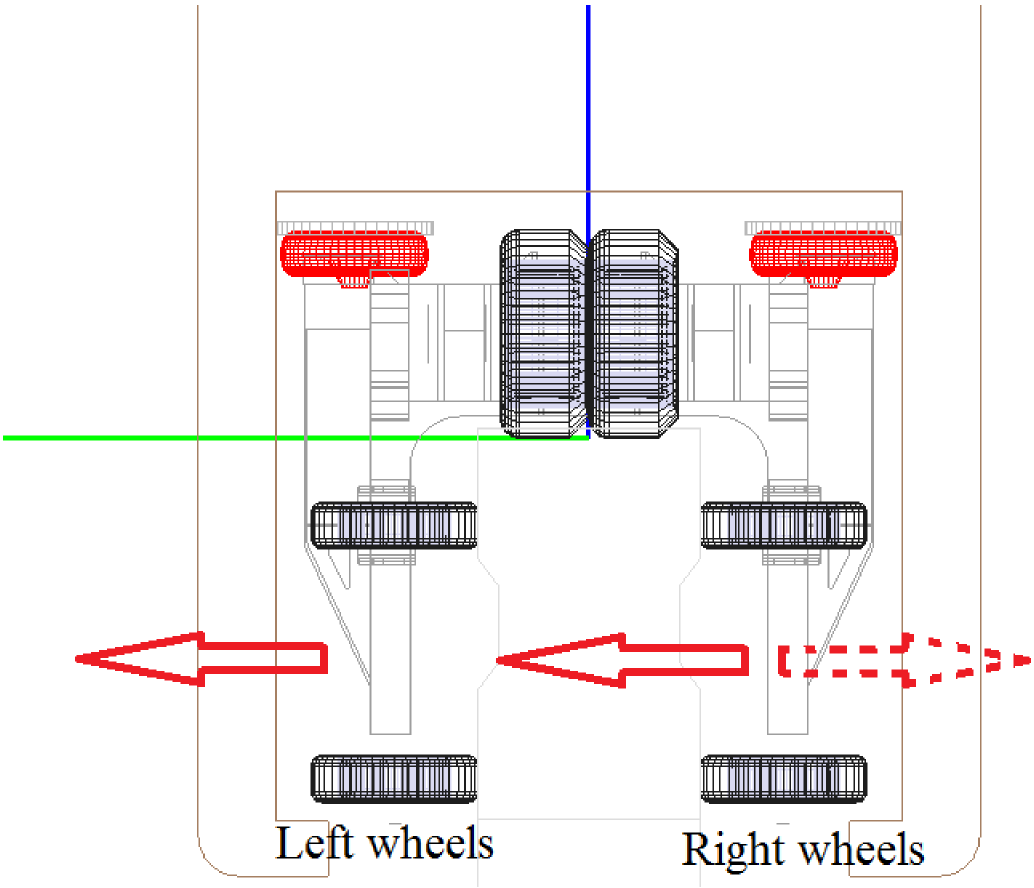


Figure 26.24. Positive direction of left and right irregularities for different values of the key "Coherent right irregularities"

One of the possible ways to define the horizontal beam irregularities is to consider them as a sum of two functions: horizontal irregularities of the beam centerline $y_c(s)$ and deviation in the beam width from the constant value $y_w(s)$. In this case the irregularities for the left and right wheels are

$$y_l(s) = y_c(s) + y_w(s)/2$$

$$y_r(s) = y_c(s) - y_w(s)/2$$

if the key **Coherent right irregularities** is checked and

$$y_l(s) = y_c(s) + y_w(s)/2$$

$$y_r(s) = -y_c(s) + y_w(s)/2$$

otherwise.

If the irregularities for the left and right wheels are independent stochastic functions, the key value can be ignored.

26.4.4.1. Assigning irregularities

Use the **Monorail train | Options and Parameter** tab of the **Object simulation inspector** to select the irregularity files for the wheels by clicking the buttons (figure 26.23). Paths to selected files are stored in the configuration file *.mrt.

Current irregularities are visualized by clicking the button.

Irregularity profiles are corrected at the first two-meter distance to provide a smooth run of a vehicle on the irregularities, figure 26.25. Thus, the vehicle at start is always on an absolutely even horizontal plane.

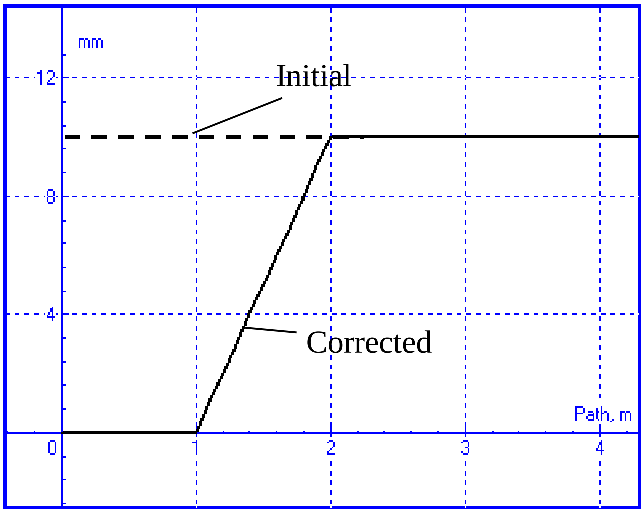


Figure 26.25. Correction of irregularities

26.5. Tire models

Models of tire/road interaction forces are considered in details in 12_UM_Automotive.pdf file, Sect. *Tyre models*. Parameters describing the models are stored in *.tr files. The default directory for these files is {UM Data}\monorail\tire. The user may use the built-in **Wizard of tire models** for changing model parameters.

26.6. Simulation of monorail dynamics

26.6.1. Preparing for simulation

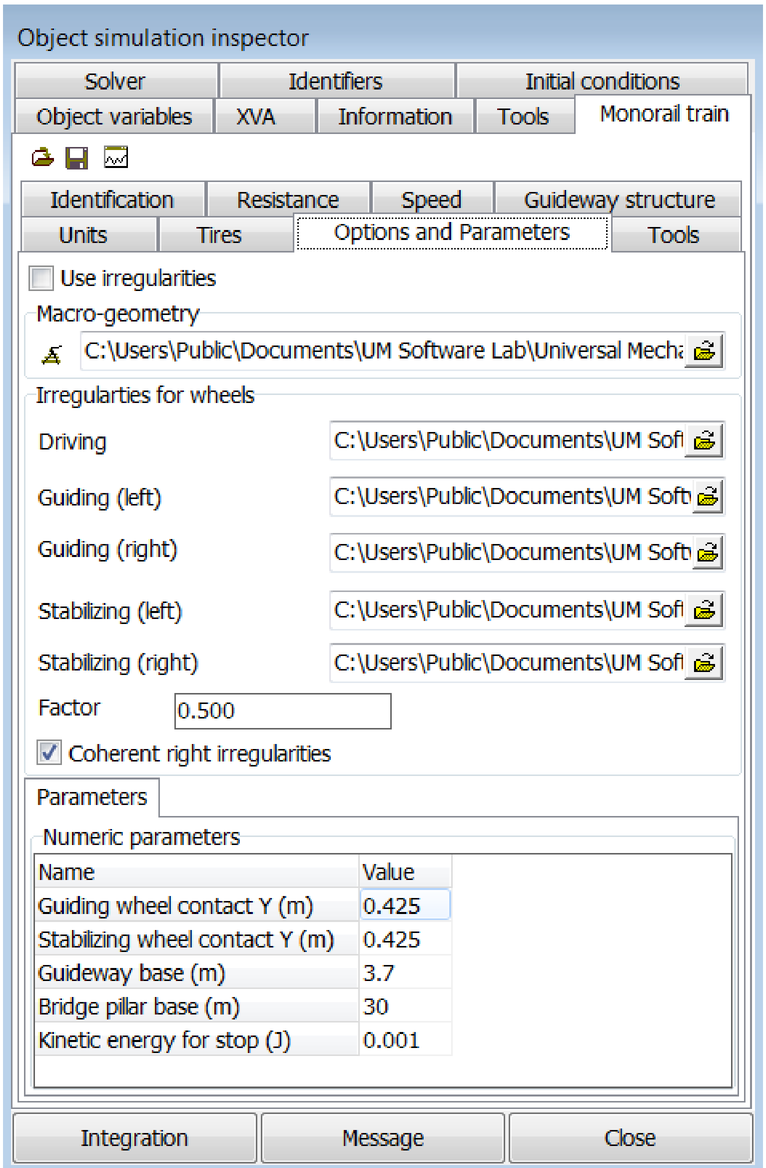


Figure 26.26. Object simulation inspector

The most part of the monorail specific data is entered and modified with the help of the **Monorail train** tab in the **Object simulation inspector**, figure 26.26. Use the **Analysis | Simulation…** menu command of the UM Simulation program to open the inspector. The entered data can be saved in vehicle configuration files *.mrt. Use the buttons on the tab to read/write data.

The monorail configuration data is saved automatically in the *last.car* file if the **Monorail train configuration** key is on in the options of the UM Simulation program, figure 26.27. Use the **Tools | Options…** menu command to call this window.

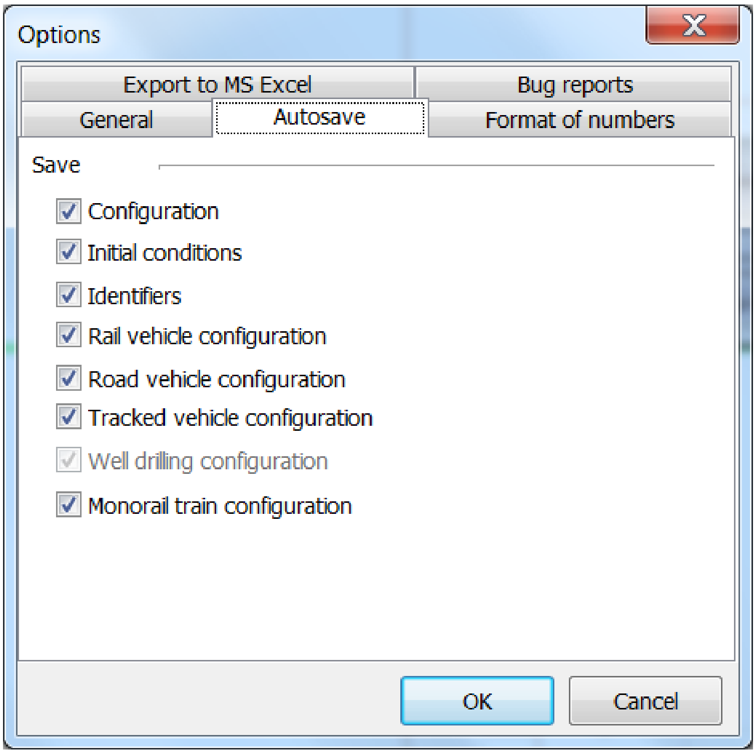


Figure 26.27. Options of UM Simulation program

General information about UM Simulation program and its tools are concentrated in Chapter 4.

The user should follow some definite steps to make a new created monorail model ready for simulation.

1. Create a monorail train model in UM Input program.
2. Run the UM Simulation program.
3. Assign tire models to the wheels on the **Monorail train | Tires** tab. If necessary, create new tire models.
4. Assign a preliminary created file of macro-geometry by the , figure 26.26. Use the  button to view/modify the macro-geometry.
5. If necessary, check the option **Use Irregularities** and assign irregularity files, figure 26.26. The **Factor** increases (<1) or decreases (>1) assigned irregularities.
6. Set the guideway structure geometrical parameters, figure 26.26:

   - **Guiding wheel contact Y** (m) – a half of guiding beam width on the level of guiding wheels.
   - **Stabilizing wheel contact Y** (m) – a half of guiding beam width on the level of stabilizing wheels.
   - **Guideway base (m)** – distance between two parallel guiding wheels, has a visual effect only.
   - **Bridge pillar base (m)** – distance between bridge pillars in longitudinal direction, has a visual effect only.

7. Set the **Kinetic energy for stop** parameter (figure 26.26), which is used in equilibrium simulation (speed mode v=0).

26.6.1.1. Identification of longitudinal velocity control

Use the **Monorail train | Identification** tab of the **Object simulation inspector** to identify the *longitudinal velocity control* parameters. Select the '*Control* V' data type in the drop-down menu

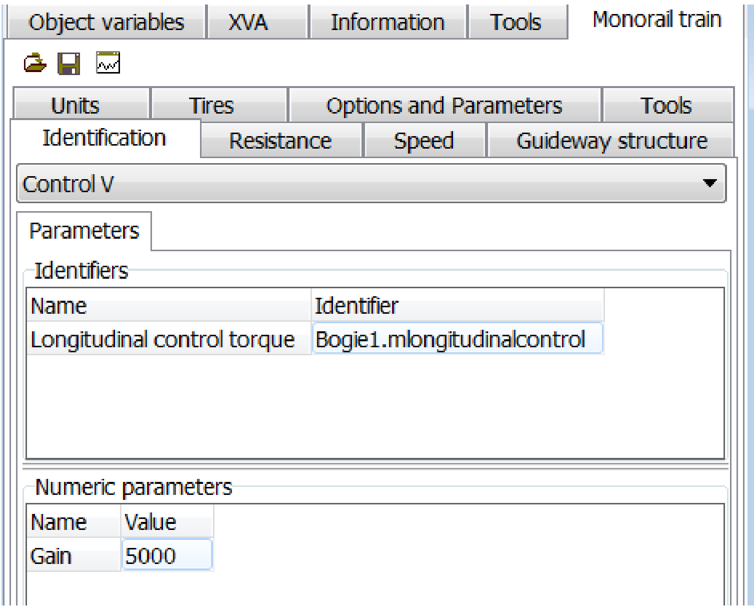


Figure 26.28. Identification of longitudinal velocity control parameters

Identification of the longitudinal velocity control parameters of the model requires selecting of one identifier, Sect. 26.3.6, figure 26.28:

- Longitudinal control torque

as well as one numeric values

- Control gain

Double click be the left mouse button on the corresponding table row to assign a model identifier. Use the direct input to set the gain value.

The control of the longitudinal velocity is realized to the proportional control law

$$M = -K(v - v_d),$$

where M is the torque (the value of the torque identifier), K is the gain, v is the current velocity of the vehicle, and v_d is the desired velocity, which can be both constant and some function of time.

26.6.1.2. Creating longitudinal velocity functions

Use the **Road vehicle | Tools** tab of the **Object simulation inspector** to specify the desired *longitudinal velocity* functions.

Using this interface the user specifies a dependence on time or distance of the desired longitudinal speed, figure 26.29.

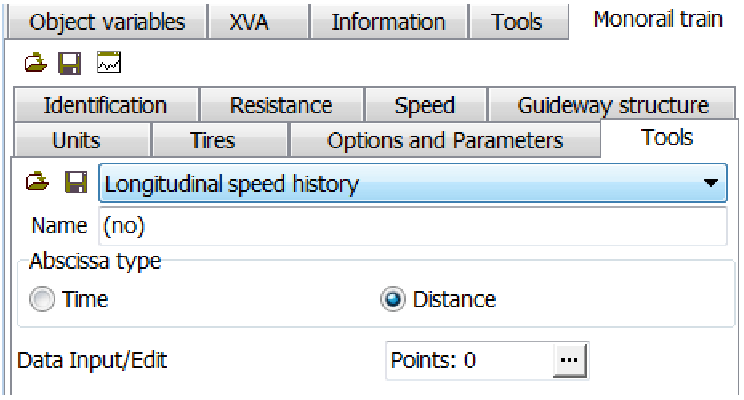


Figure 26.29. Interface for functions of time and distance

The function is a set of points with a possible spline smoothing. To set the function, the user calls the curve editor by clicking the ... button.

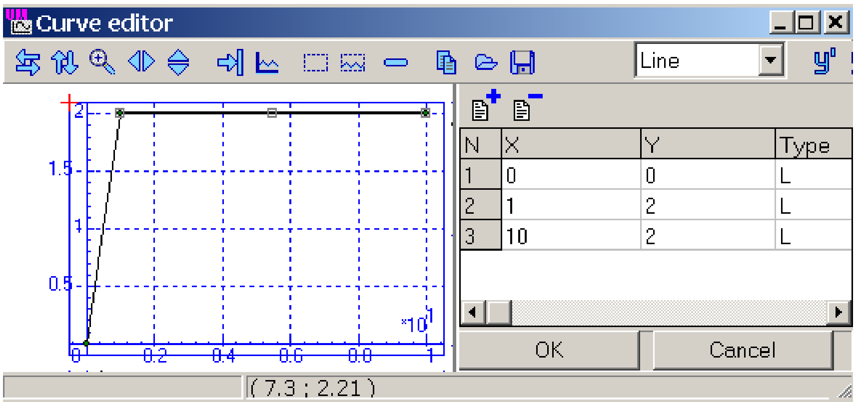


Figure 26.30. Setting functions with the curve editor

Use the buttons to read/save data from/to file.

Remark. If initial speed is zero, dependence of the speed on time must be used (not on distance).

26.6.1.3. Creating beam section profile

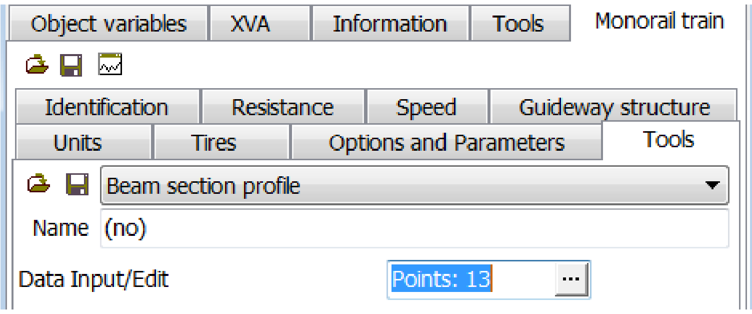


Figure 26.31. Tool for setting beam section

Use the **Road vehicle | Tools** tab of the **Object simulation inspector** to specify the desired guiding *beam section profile*. Click on the button to open the Curve editor. The profile is described by a closed line be a set of points.

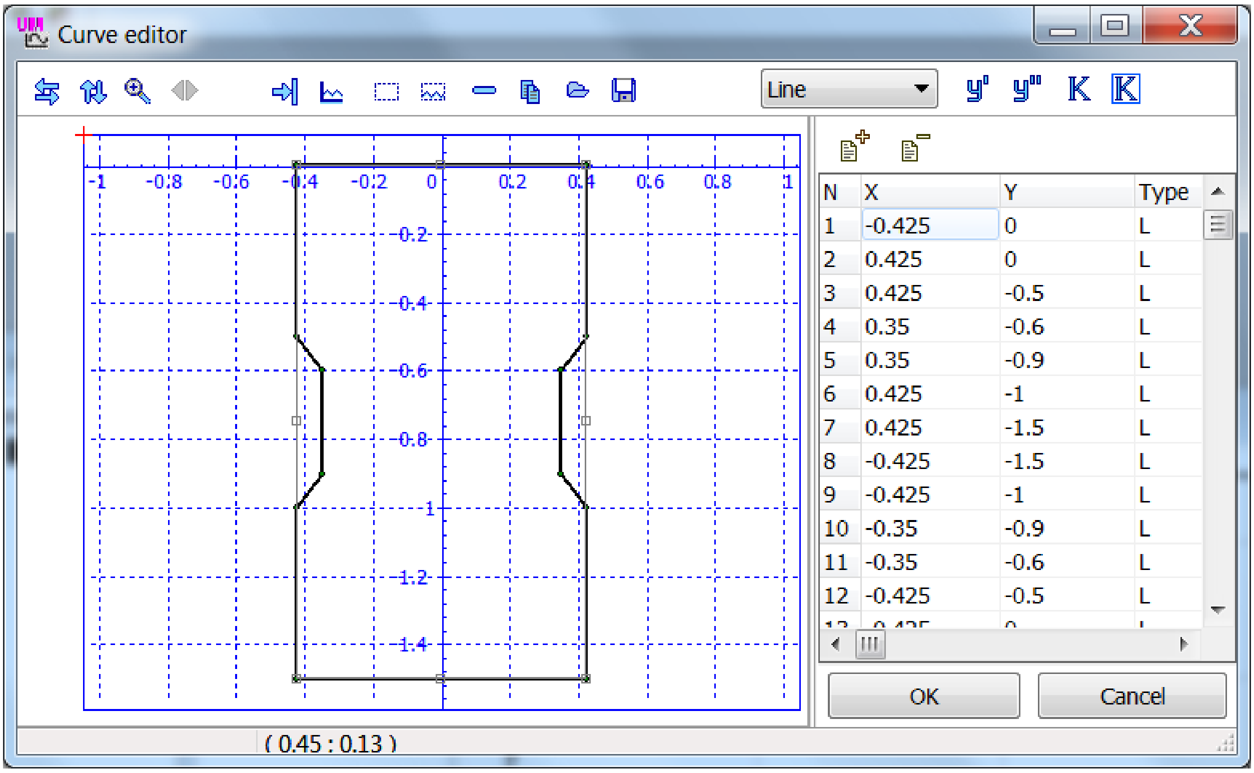


Figure 26.32. Beam section description

26.6.2. Modes of longitudinal motion of monorail

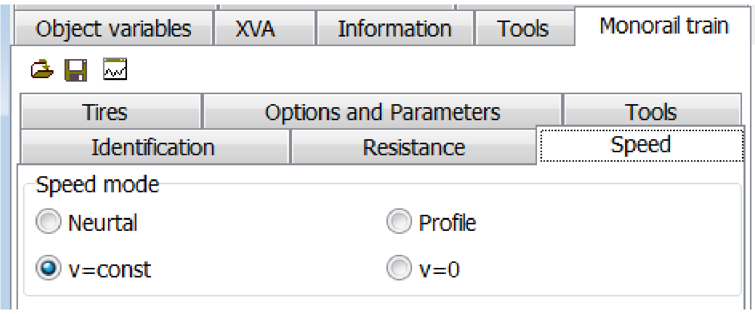


Figure 26.33. Longitudinal motion modes

Modes of longitudinal motion of the monorail are set on the **Monorail train | Speed** tab of the inspector.

26.6.2.1. Neutral

In this mode the initial speed value is set by the **v0** identifier, figure 26.34. The speed decreases due to resistance forces.

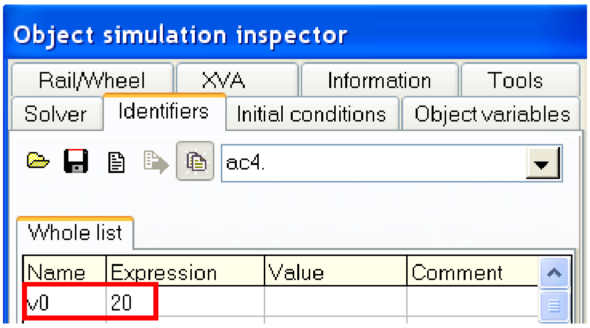


Figure 26.34. Identifier of speed

26.6.2.2. v=const

Constant speed mode. The nearly constant value of the vehicle speed is supported automatically by the torque applied to the driving wheel, see. Sect. 26.3.6, 26.6.1.1

$M = -K(v - v0)$,

where $v0$ is the desired speed, v is the current speed, and K is the amplifier.

In this mode the desired speed value is set by the **v0** identifier, figure 26.34.

26.6.2.3. Profile

The speed is controlled according to a dependence on a time or distance. The control force is similar to that in the previous mode (v=const). The buttons are used for reading previously created profiles (Sect. 26.6.1.2) and for saving the current curve.

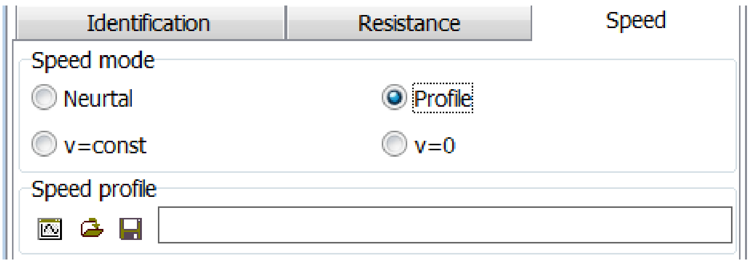


Figure 26.35. Speed profile mode

26.6.2.4. v=0

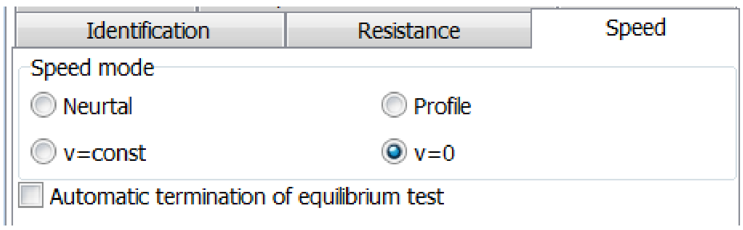


Figure 26.36. Zero speed test

Zero velocity mode.

If the key **'Automatic termination of equilibrium test'** is checked, the simulation runs until the kinetic energy decreases to the minimal value specified by the user, Sect. 26.6.1, the parameter **Kinetic energy for stop**. After success of the test, the program automatically accepts the coordinate values as standard ones and stored static deflections of tires and static tire loads, figure 26.37. It is recommended to run this equilibrium bests before other simulations.

If the key **'Automatic termination of equilibrium test'** is **not** checked, automatic actions are skipped. In this simulation, the user can e.g. apply periodic excitations to get the system response.

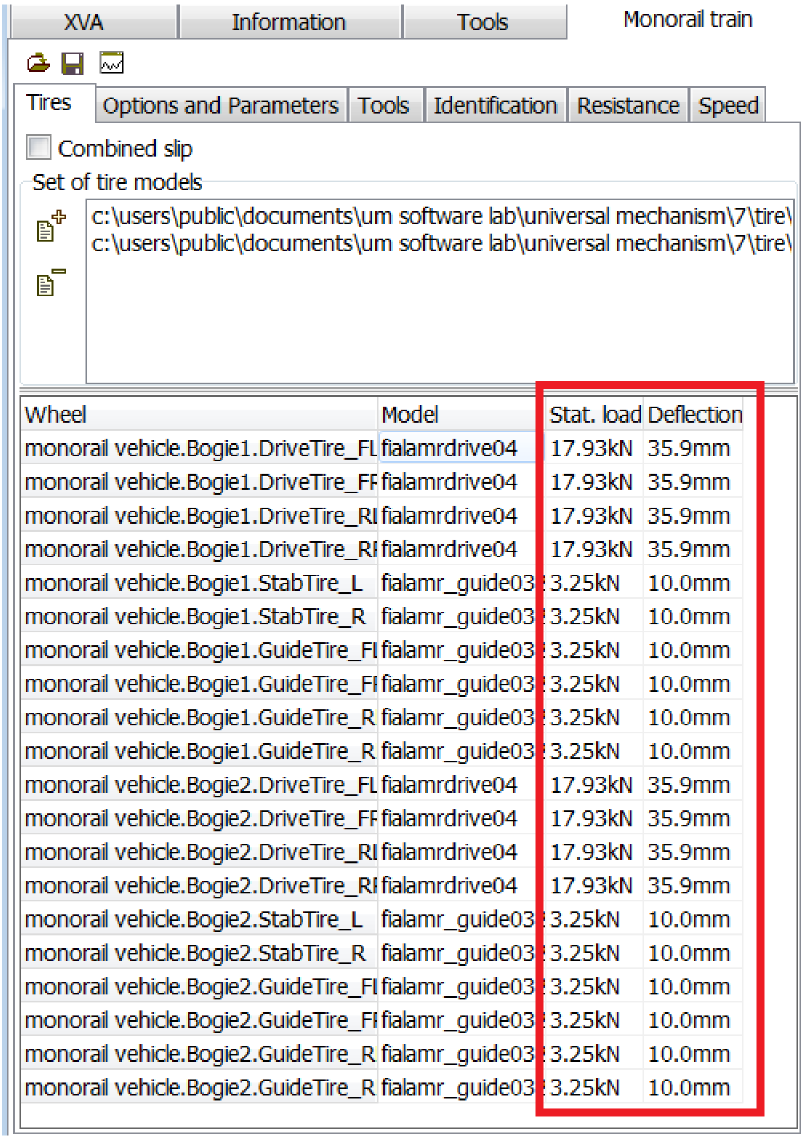


Figure 26.37. Tire static deflections and loads

26.6.3. Monorail train specific variables

26.6.3.1. Tire/road contact variables

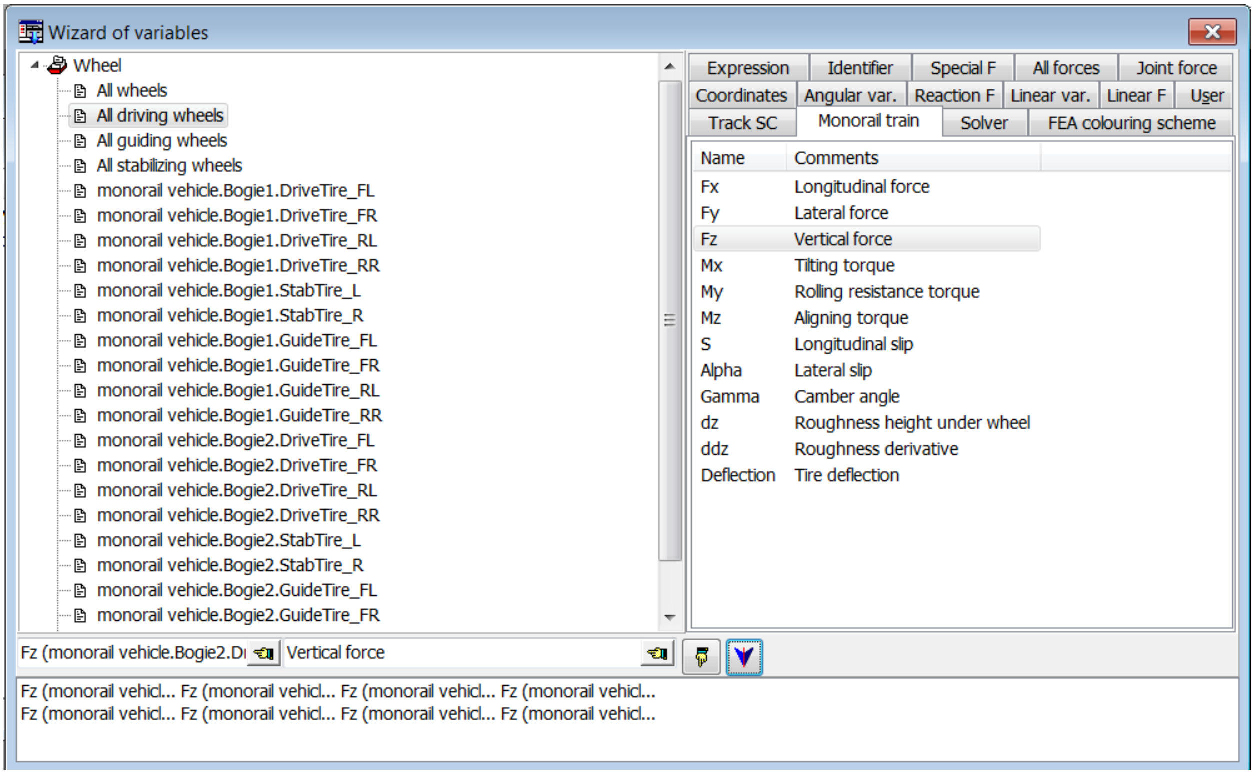


Figure 26.38. Variables related to tire/beam interaction

Variables related to the tire/beam interaction are available on the **Monorail train** tab of the **Wizard of variables**, figure 26.38. Use the **Tools | Wizard of variables…** menu command to open this window. Use other tabs of the wizard to create kinematic and dynamic variables different from the tire variables.

By default, the train travel distance variable is the user variable number 999. It can be added with the help of **Tools | Wizard of variables | User | UserVars** tab.

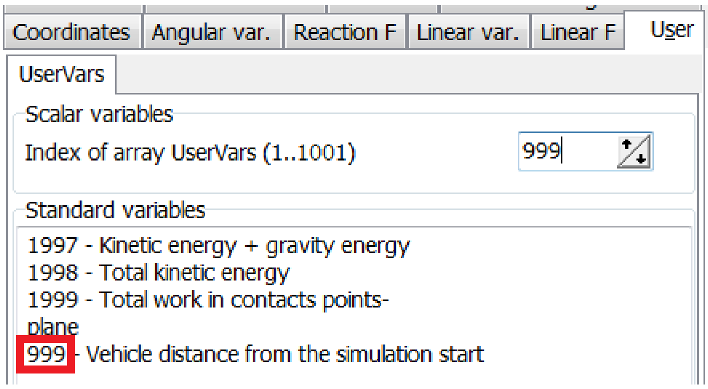


Figure 26.39. Wizard of variables: vehicle path variable

To get information about creating variables and their usage variables see Chapter 4.

26.6.3.2. Kinematic characteristics relative to track system of coordinates

Kinematical variables of bodies should be often projected on the track system of coordinates (TSC). The X-axis of the TSC is the tangent to the guiding beam centerline including the beam vertical slope, Sect. 26.4.3; the Y-axis is perpendicular to the X-axis taking into account the superelevation, Sect. 26.4.2.

Note that axes of the TSC and SC0 in a straight track are parallel, and projections of vectors on these SC are the same.

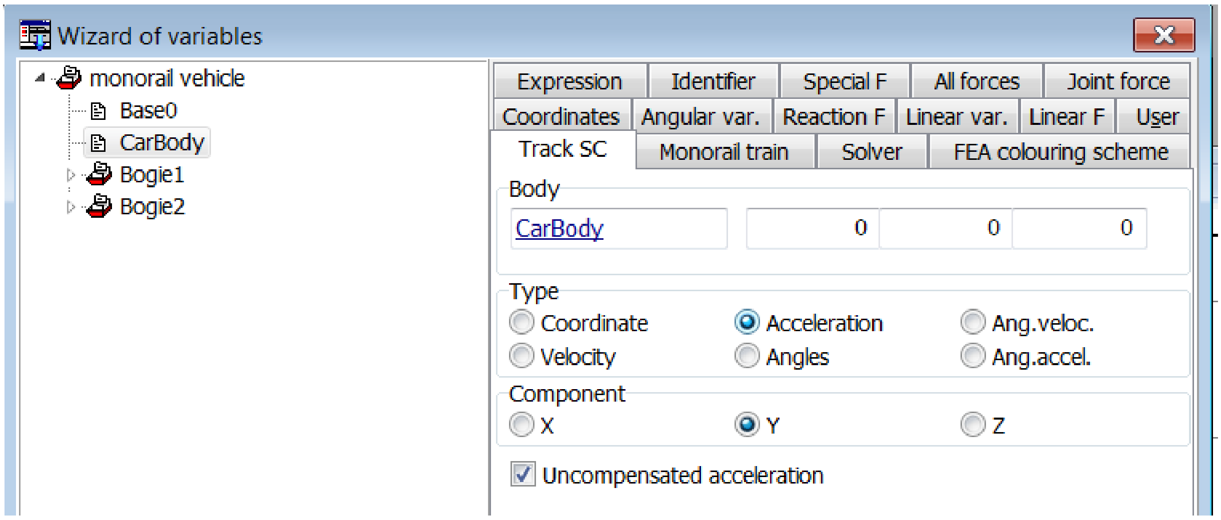


Figure 26.40. Kinematic characteristics of bodies in the track SC

Use the **Track SC** tab of the Wizard of variables to get any kinematic variable in projection of the TSC. To create a variable, perform the following steps:

- select a body in the list in the left part of the wizard;
- select the type of variable: a linear variable (Cartesian coordinates, velocity or acceleration) or an angular variable (angles, angular velocity and angular acceleration);
- set a point in SC of the body, which coordinate, velocity or acceleration should be computed, if a linear variable is selected;
- set an axis of the TSC for projection.

For the lateral component of acceleration, either the uncompensated acceleration or the usual acceleration is selected (figure 26.40).