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8. General information

**UM Loco** is an additional UM module that is aimed at simulation of dynamics of rail vehicles (RV): locomotives, cars, trains.

The **UM Loco** module includes a number of additional tools in **UM Input** and **UM Simulation** programs. 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 8.1.

![Figure 8.1. UM Loco module is available](image)

In addition to the standard UM configuration it includes the following items:

- Wheelset as a standard subsystem;
- Algorithms of forces computation in wheel/rail contact including the FASTSIM algorithm, the model by W. Kik and J. Piotrowski, the interface to the Kalker’s CONTACT model.
- Specialized graphical interface for animation of contact forces;
- Interface for creating rail and wheel profiles and track irregularities;
- Interface for setting curve and switch parameters;
- Standard list of variables, which characterize wheel/rail interaction (creepages, total, normal and creep forces in wheel/rail contacts, angle of attack, wear factors, etc.; more than 30 variables for each wheel of the vehicles);
- Database of profiles and track irregularities;
- Models of various vehicles.

**UM Loco** allows the user:

- to calculate the critical speed of a vehicle;
- to analyze 3D dynamics of a vehicle or a train in time domain in tangent track or in curves with/without irregularities;
- to analyze vehicle dynamics in dependence on wheel and rail profiles;
- to include 3D vehicles in a train model;
- to create scanning projects for scanning the vehicle/train dynamics depending on any parameters;
- to compute natural frequencies and modes, eigenvalues and eigenforms as well as root locus of linearized equations of motion;
- to create hybrid rigid-elastic models of vehicles.
Simulation of vehicle dynamics is performed in time domain by means of numeric integration of automatically generated differential or differential-algebraic equations of motion.

**UM Loco** allows the user to create *fully parameterized models* of vehicles. Geometrical, inertia, force parameters may be specified using identifiers and symbolic expressions. The parameterization of model is the base for its optimization.

More general information about use of UM for simulation can be found in the PowerPoint presentation at [http://www.universalmechanism.com/download/docs/eng/umloco.ppsx](http://www.universalmechanism.com/download/docs/eng/umloco.ppsx).

Below in the current chapter we consider some features of description of a RAIL VEHICLE in UM as well as some useful notions and special utilities.
8.1. Creating models of rail vehicles

User creates UM models of rail vehicles (RV) similar to any other multibody systems, see Chapter 3. The vehicle is considered as a system of rigid or flexible bodies connected by means of joints and force elements. Usually a model of a rail vehicle contains the following rigid bodies: vehicle body, bogie frames, wheelsets, axle-boxes (often can be removed from the model) etc. In the case of a locomotive, a motor model consists often of two bodies: a motor case and a rotor.

See the gs_UM_Loco.pdf file with detailed information about process of a rail vehicle model development.

8.1.1. Type of object – Rail Vehicle

To get an UM model of a vehicle the user should create a new UM object by clicking the File | New object menu item, and at least one wheelset must be added to the object. After that the standard identifier v0 for the initial speed of the vehicle is added to the list of identifiers Figure 8.2; more precisely, this identifier specifies the initial value of speed in the neutral and constant speed modes of longitudinal motion, Sect. 8.4.2.2. "Modes of longitudinal motion of vehicle", p. 8-140.

![Figure 8.2. Identifier of speed](image)

8.1.2. Base coordinate system

Base coordinate system (SC0, Base0) is the system of coordinate in which the object is described and simulated. For a rail vehicle, the SC0 satisfies the following requirements:

- Z-axis is directed vertically upwards;
- X-axis is horizontal along direction of motion at the vehicle initial position;
- SC0 origin is usually located either at the level of the rail head or at the wheelset axes level at their ideal initial position (obsolete).

We consider an element of the vehicle model as a left one (left wheel, left spring etc.) if it has a positive Y-coordinate, i.e. if the element is on the left to the motion direction.
8.1.3. Wheelset and single wheel

8.1.3.1. Adding a wheelset or a wheel

Wheelset (WS) in UM is a *standard subsystem*. To add a wheelset or a single wheel, select the **Subsystem** item in the list of elements, add a subsystem by the [button] and select the **Wheelset** type of the subsystem, Figure 8.3.

![Figure 8.3. Adding a wheelset](image)

Two types of wheelsets are available in UM. These types differ in number of degrees of freedom as well as a separate wheel with an individual suspension, Figure 8.4:

- **Standard**: a WS with six d.o.f. and a rigid axle;
- **Independent rotation**: is used for modeling wheelsets with independently rotating wheels as well as for modeling torsion flexibility of the standard WS;
- **Single wheel (left)**;
- **Single wheel (right)**.

![Figure 8.4. Type of wheelset](image)

Templates of the subsystems are located in the directory `{UM data}\rw\wset:`

Standard.wst
Independent.wst
SingleRight.wst
SingleLeft.wst

Starting from UM 8.0 there is a possibility to use wheelset subsystems including inertial rails. Rails are considered as rigid bodies and named as leftrail and rightrail. Rails as rigid bodies might have three d.o.f. – two translational d.o.f. relative to lateral (Y) and vertical (Z) axes and one rotational d.o.f. relative to longitudinal X axis. All three degrees of freedom are optional. Every mentioned above degree of freedom may be turned off. Rest three degrees of freedom have no effect on simulation results since plane model of inertial rail is considered. Rails are connected with Base0 body through Bushing force elements that simulate road bed. To use wheelset subsystems with inertial rails turn on flag Inertial rail.

Wheelset subsystems can be modified by the user. It is strongly recommended not to change the number of coordinates as well as their sequence.

To edit a template
• create its backup,
• create a new UM object,
• read the template by the Edit | Read from file… menu command or by the button on the tool panel,
• apply modifications,
• save the template by the File | Save as component… menu command or by the button.

8.1.3.2. Wheelset with six degrees of freedom

The model of wheelset with 6 d.o.f. includes two bodies, two joints and a wheelset image (Figure 8.5). The first body presents the base of the wheelset with 5 degrees of freedom. This body lacks for the rotation around the wheelset axle. The standard name of the base is Wset. The second body with the standard name WSetRotat is a gyrostat. It has the only degree of freedom relative to the base – rotation about the axle. It is known that equations of motion of the base plus gyrostat completely coincide with equations of motion of one body with six degrees of freedom.

![Figure 8.5. Wheelset degrees of freedom](image-url)
One of the goals of introduction of two bodies for one wheelset is as follows. In many cases it allows avoiding the introduction of axle-boxes as separate bodies and reduces considerably CPU expenses while simulation of the vehicle dynamics. In fact, it is impossible to attach linear force elements that are usually used for the modeling the primary suspension (springs, dampers, guides etc.) directly to rotating wheelset with 6 d.o.f., axle-boxes are necessary. In contrary, it is possible to attach these elements to the wheelset base (it does not rotate about the axle!) and the axle-boxes can be omitted in the model.

The coordinates of the wheelset are numbered in the following sequence (Figure 8.5):
1 is transition X;
2 is transition Y;
3 is transition Z;
4 is rotation Z;
5 is rotation X;
6 is rotation Y.

Starting from UM 8.0 built-in Wheelset subsystem includes two rigid bodies that simulate inertia properties of rails. Default names of bodies are leftrail and rightrail. Both bodies have three d.o.f. – two translational relative to Y and Z axes and one rotational relative to X axes. Inertia rails are supported by Multipoint contact model only. Other contact models ignore inertia properties of the rails.

The subsystem contains identifiers, which parameterize inertia and geometrical parameters of the WS, Table 8.1.

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>mwset</td>
<td>Mass of WS</td>
</tr>
<tr>
<td>ixwset</td>
<td>Moment of inertia relative to the longitudinal central axis</td>
</tr>
<tr>
<td>iywset</td>
<td>Moment of inertia relative to the lateral central axis</td>
</tr>
<tr>
<td>axlelength</td>
<td>Standard identifier for the axle image length. It is not recommended to remove or rename this identifier</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameters for inertial rails</th>
</tr>
</thead>
<tbody>
<tr>
<td>mleftail, mrightail</td>
</tr>
<tr>
<td>cyleftail, cyrightail</td>
</tr>
<tr>
<td>dissyleftail, dissyrightail</td>
</tr>
<tr>
<td>czleftail, czrightail</td>
</tr>
<tr>
<td>diszleftail, diszrightail</td>
</tr>
<tr>
<td>cangleleftail, cangrightail</td>
</tr>
<tr>
<td>dissangleleftail, dissangrightail</td>
</tr>
</tbody>
</table>

8.1.3.3. Wheelset with independent rotation of wheels

This type of the WS is used for modeling of a WS with independent rotation of the wheels as well as for modeling an ordinary WS with the torsion flexibility of the axle, Figure 8.6.
In this case, the WS has seven degrees of freedom. In addition to six d.o.f., a rotation of the right wheel relative to the left one is introduced. The model of the WS consists of three bodies and three joints.

Two identifiers \( iywset\_l, iywset\_r \) parameterize the moment of inertia relative to the Y axis of the left and right wheels.

To introduce the torsion flexibility of the axle, the user should add a joint torque for the third joint \( jWSetRightWheel \). The torque must contain both elastic and dissipative parts.

![Figure 8.6. Wheelset with independent wheels](image)

### 8.1.3.4. Single wheel

This type of WS can be used for modeling wheels with independent suspensions, Figure 8.7. Subsystem description is similar to the WS with six d.o.f. An additional identifier \( ycg \) specifies the lateral position of the center of gravity.

![Figure 8.7. Single left and right wheels](image)
Two single wheels can be used for modeling torsion and bending of the WS axle. In this case, both the left and the right single wheels are to be added with the same longitudinal positions. After that a bushing force element is added describing flexibility of the axle. Values of stiffness and damping parameters of the bushing are evaluated similar to that in Sect. 8.1.3.7. "Setting torsion stiffness of axle", p. 8-17.

8.1.3.5. Wheelset geometry

Geometrical properties of a wheelset are fully set with the following data (Figure 8.8, Figure 8.9):

- wheelset semibase \((L/2)\);
- running circle radius \(r\);
- difference of running circles radii \(dr_l, dr_r\), Sect. 8.4.2.7.2. "Wheel radii difference", p. 8-184;
- deviation of the wheel form from the circle (flat, ellipse and so on, Sect. 8.4.2.7.1. "Deviation of wheel form from ideal circle", p. 8-179);
- tread (wheel) profiles for the left and right wheels, which should be given in a special coordinate system of profile.

The first two parameters are specified in the **UM Input** program as the parameters of the standard subsystem (wheelset). Differences of running circles radii \(dr_l, dr_r\) are specified both for the left and right wheels. They are the difference between the real values \(r_l, r_r\) of the wheel radii, and the nominal one \(r\), Sect. 8.4.2.7.2. "Wheel radii difference", p. 8-184,

\[
dr_l = r_l - r, \quad dr_r = r_r - r.
\]

Thus, one WS can have wheels with different radii. Besides, different WS can have different radii of wheels.

![Figure 8.8. Geometrical parameters of wheelset](image-url)
Profiles are chosen from the UM database or created by the user with a special tool in the UM Simulation program (Sect. 8.4.1.1. "Creation of wheel and rail profiles", p. 8-98).

Let us introduce the notion of system of coordinate of a wheel (SCW) profile Figure 8.9. The SCW origin is located at point K on the running circle (Figure 1.8) and corresponds to the middle point of the profile along abscissa. The abscissa axis (y) is parallel to the wheelset axle and is directed towards the flange. Z-axis is vertical. Coordinates of the profile points are set in mm.

Figure 8.9. System of coordinates of a wheel profile
8.1.3.6. Editing wheelset parameters

The following parameters are available in the inspector window (Figure 8.10):

- **Name** of the subsystem, e.g. Wheelset1;
- **Identifier** of the subsystem must consist of Latin letters and digits, e.g. Wset1. The identifier is used for access to the identifiers of the wheelset while programming in the UM environment. *The identifier should be unique within the object.*
- **Type of WS** (see. Sect. 8.1.3.1. "Adding a wheelset or a wheel", p. 8-9).

Further parameters of the wheelset:

- **Radius** of the running circle (Sect. 8.1.3.5. "Wheelset geometry", p. 8-13);
- **Semibase** of the wheelset (Sect. 8.1.3.5. "Wheelset geometry", p. 8-13).

Other parameters in the inspector window allow the user to modify the wheelset image:

- **Axle length** increases or decreases the length of the axle image
- **Gear** adds a simplified image of a gear for a traction wheelset (double if necessary) as well as the corresponding radius of the gear and its position on the axle;

![Figure 8.10. Wheelset parameters](image)

Changing geometric parameters of the wheelset results in automatic modification of its image (Figure 8.11).
Use the **Position** tab (Figure 8.10) to specify the longitudinal and vertical position of the wheelset. If the object is a bogie, the lateral position is set relative to the SC of the bogie. If the object is a vehicle, the lateral position is set relative to the corresponding SC. Position of the wheelset can be parameterized, i.e. specified by a symbolic expression (Chapter 3, Sect. Constant symbolic expression). Set the z coordinate of the wheelset equal to the wheel radius to locate the origin of SC0 at the rail head level (Sect. 8.1.2. "Base coordinate system", p. 8-8). Zero value of this coordinate corresponds location of the SC0 origin on the wheelset center level.

Use the **Edit subsystem** button to change inertia parameters or to modify the image (e.g. to add images of axle-boxes). This button opens the subsystem as a multibody system in a separate window where the necessary modifications of the wheelset such as changing parameters or renaming elements can be done in a usual manner (see Chapter 3, Chapter 9).

![Figure 8.11. Images of wheelset](image)

![Figure 8.12. Inertia parameters of WS base](image)
8.1.3.7. Setting torsion stiffness of axle

To set the axle torsion stiffness and damping in the case of a WS with seven d.o.f. (Sect. 1.1.3.3), a joint torque of the Linear type must be specified with proper values of stiffness and damping constants, Figure 8.13.

To evaluate the stiffness \( c \) and damping \( d \) constants in case of equal moments of inertia of the left and right wheels \( I_y \), it is recommended to use the value of the first torsion frequency \( f \) of WS as well as the damping ratio \( \beta \):

\[
c = \frac{I_y(2\pi f)^2}{2}, \quad d = 2\beta \sqrt{\frac{I_y c}{2}}.
\]

For instance, the recommended values for \( f=40 \text{ Hz, } \beta =0.02, I_z=150 \text{ kgm}^2 \) are

\[
c = 4.74 \times 10^6 \text{Nm, } \quad d = 754N \cdot m \cdot \text{rad/s}.
\]

8.1.3.8. Adding other wheelsets

To add all other wheelsets:

- use the operation of copying the described wheelset by clicking the \( \text{复制} \) button;
- change the name and identifier of the new wheelset;
- change the longitudinal position and other parameters (if necessary).
8.1.3.9. **Visual adding wheelset**

The **UM Loco** tab is used for visual adding wheelsets, Figure 8.14. The standard UM Loco configuration includes three components:

- standard WS with six d.o.f.;
- WS with independent rotation of the wheels;
- WS with torsion flexible axle; torsion stiffness and damping constants.

![Diagram of UM Loco components](image)

**Figure 8.14.** Visual components of UM Loco

Origin of system of coordinates is located on the rail head level. After changing the wheel radius, the vertical position of the WS must be modified on the **Position** tab.

Image of WS with torsion flexible axle is shown in Figure 8.15. Values of the torsion frequency and damping ratio can be modified in the **Identifiers** tab of the subsystem, Figure 8.16.
Figure 8.16. Identifiers parameterizing the WS with torsion flexible axle

Remark. The user can develop his/her own components and place them on the tab of visual components, see Chapter 3.
8.1.4. Modeling axle-boxes

Sometimes axle-boxes are not included in vehicle models as separate bodies (Sect. 8.1.3.2. "Wheelset with six degrees of freedom", p. 8-10), and the bogie frame is connected directly with the base of the wheelset (non-rotating part of the wheelset). In this case graphic images of axle-boxes can be introduced to make the vehicle model more realistic. The images of the axle-boxes are assigned to the base of the wheelset.

In other cases introduction of axle-boxes as separate rigid bodies is necessary to make the model correct. Some of these cases are listed below.

- Non-symmetric attachment and different stiffness of a pair of springs connected with the axle-box.
- Non-symmetric attachment of traction rods for traction wheelset;
- Lateral gaps in axle-box assembly for some locomotives with 3 axle bogies.

8.1.4.1. Axle-boxes as massless graphic images

Let us consider how we can add images of axle-boxes without adding them as rigid bodies. A simplified standard image for an axle-box can be obtained from the file

\bin\rw\images\axlebox.img

Make the following actions with a wheelset already added to the object.

- Run modification of the subsystem by clicking the **Edit subsystem** button (Figure 8.16).
- Read image of the left axle-box from the \bin\rw\images\axlebox.img file by the **»** button on the tool panel. Rename the image, e.g. **Axlebox L**.
- Copy the image of the left axle-box, rotate it on 180 degrees about the vertical axis and re-name the copy as **Axlebox R**.

Create a new graphic object with two graphic elements of the **GO** type, assign images of the axle boxes to the elements, Figure 8.17. Set lateral position of the axle-boxes and rename the image. The result is shown in Figure 8.18.
Finally, select the *Wset* body in the list of bodies (the base of the wheelset, Sect. 8.1.3.2. "Wheelset with six degrees of freedom", p. 8-10), and assign to it the created image, Figure 8.19.

![Image 8.18. Image of fictitious axle-boxes](image)

**Figure 8.18. Image of fictitious axle-boxes**

- Close editing the wheelset subsystem by clicking the *Accept* button in the dialog window or use the *X* button and confirm the acceptance of the modifications, Figure 8.20. As a result, the wheelset image will look like Figure 8.21.

![Image 8.19. Selection of the Wset body in the list and assignment of an image](image)

**Figure 8.19. Selection of the Wset body in the list and assignment of an image**

![Image 8.20. Close subsystem window](image)

**Figure 8.20. Close subsystem window**
Of course, the image of the axle-boxes cannot be assigned to the rotating part of the wheelset, because this assignment will lead to the corresponding rotation of the image during simulations.

### 8.1.4.2. Axle-box as a rigid body

If an axle-box should be considered as a separate body, the user should use the following instructions.

1. Do not open the wheelset for editing. Modify the object, which contains the wheelset as an included subsystem.
2. Create a new graphic object for the axle box image. In the simplest case, the standard image `\bin\graph\axlebox.img` could be used (read it by the button in the tool panel).
3. Add a new body for the axle-box, rename it, assign the image and set inertia parameters.
4. Adjust a joint to the axle-box by the button (Figure 8.22). If the axle-box has one rotational degree of freedom relative to the axle, the rotational joint should be assigned. After that
• change the first body (base of the wheelset instead of Base0);
• set axis of rotation (0, 1, 0) about Y-axis for each of the bodies;
• set the axle-box position on the axle (expression – *yaxle_box* in Figure 8.22 for the right axle-box).

![Figure 8.23. Wheelset with the right axle-box](image)

**8.1.4.3. Visual adding an axle-box**

Axle boxes can be added by visual components.

• Open the **UMLoco** tab of the visual component lists.
• Click on the axle-box button, then click somewhere on the grid for a temporary location of the axle-box.
• Assign a revolute joint using either method above or the visual component of the joint.

![Figure 8.24. Visual components of UMLoco module](image)
8.1.5. Modeling linear springs of primary and secondary suspension

The following types of force elements are used for modeling both linear and nonlinear springs.

- **Special force element Spring**
  The element is used for modeling linear springs.
  Mathematical model of the element is described in Chapter 2, Sect. Special forces/Spring, Generalized linear force element.
  Examples of description and/or usage:
  - Chapter 7, Sect. Models of Springs
  - Model: {UM Data}\SAMPLES\Rail_Vehicles\ac4

- **Generalized linear force element**
  The element allows modeling both the same springs as the previous one and more complicated or simplified cases, e.g. when the shear stiffness depends on direction of deflection. It can be used also for modeling bilinear springs.
  Mathematical model of the element is described in Chapter 2, Sect. Generalized linear force element.
  Examples of description and/or usage:
  - Chapter 7, Sect. Models of Springs;
  - Model: {UM Data}\SAMPLES\Rail_vehicles\Manchester_benchmarks\Vehicle1;
  - Model: {UM Data}\SAMPLES\Rail_vehicles\Manchester_benchmarks\Vehicle2.

- **Bipolar force element**
  The element can be used for modeling both linear and nonlinear springs, which produce force directed along the element attachment points
  Mathematical model of the element is described in Chapter 2, Sect. Bipolar force element.
  Examples of description and/or usage:
  - Model: {UM Data}\SAMPLES\Rail_vehicles\Manchester_benchmarks\Vehicle1;
  - Model: {UM Data}\SAMPLES\Rail_vehicles\Manchester_benchmarks\Vehicle2.

General recommendations:
1. models should be created near the equilibrium position at zero values of object coordinates; stationary values of vertical loads should be set for springs;
2. set the lower body as the first attachment body of a vertical spring and the upper as the second one; in this case the stationary vertical force is positive.

8.1.6. Modeling dampers, traction rods

As a rule, bipolar force elements are used for modeling dampers and traction rods.
Mathematic model of the element is described in Chapter 2, Sect. Bipolar force element.
Examples of description and/or usage:
- Model: {UM Data}\SAMPLES\Rail_vehicles\Manchester_benchmarks\Vehicle1;
- Model: {UM Data}\SAMPLES\Rail_vehicles\Manchester_benchmarks\Vehicle2;
Model: {UM Data}\SAMPLES\Rail Vehicles\ac4.
8.1.7. Some features of development of locomotive models

Features of locomotive models are traction systems.

8.1.7.1. Model of traction

Figure 8.25. Model of one unit of VL80 electric locomotive

Simplified modeling of traction motors and wheel driving systems is necessary for realization of traction mode. Specific features of the model depend on a type of the drive system. Here we consider the axle-hung traction motors taking the VL80 locomotive as an example, Figure 8.25.

8.1.7.1.1. Bodies and joints

Figure 8.26. Subsystems “bogie” and “wheel-motor assembly”

Model of one unit of the locomotive includes two subsystems “bogie”, which contain two subsystems “wheel-motor assembly” each. Traction system is realized within the “wheel-motor assembly” subsystem.
Model of the wheel-motor assembly contains a wheelset, two axle-boxes, motor and reducer casings as one rigid body, rotor with two pinions (drive shaft, Figure 8.27) as well as primary suspension force elements. All the suspension force elements are described as external ones (the External second body) and have activated the autodetection attribute.

Motor casing is connected to the wheelset base by a revolute joint. Another revolute joint connects the rotor with the motor casing. Joint axes are parallel to the lateral axis Y.

8.1.7.1.2. Traction torque

Driving torque is introduced as a joint torques in the revolute joint connecting the drive shaft with the motor casing, Figure 8.28. It is recommended to use the List of forces type of the joint torque. The list contains two elements. The first element of the List of characteristics type stands for modeling the torque value depending on the rotor angular velocity for different positions of the throttle. The second element of the Expression type includes a parameterized expression, and can be used for direct setting the traction torque if the locomotive model is included in a 3D model of a train.
In our example the traction torque is defined by the set of force-speed curves where the force is the total traction force of the vehicle, Figure 1.31. The curves are described in the sequence corresponding to the throttle position number (1…N).

The following parameters should be set for additional description of the element (Figure 8.28, left).

- **Curve identifier**: the identifiers which numerical value 0…N sets the throttle position and selects one of the curve; zero value of the identifier means zero torque. It is strongly recommended to use the `trottle_position` identifier, which automates the recognition of the identifier when the locomotive is included into a train 3D model.
- **Factor X**: the factor should differ from unity if abscissa in Figure 8.28 is not angular velocity of the rotor (e.g. the unit speed). It should be also used when the drive shaft rotates in the
negative direction, i.e. the corresponding joint velocity is negative. In the example in Figure 8.28 the expression $0.625/4.19 \times \text{rotation}_\text{sign}$ is used for the factor, which, first, converts the rotor angular velocity to the vehicle speed (0.625 is the wheel radius, 4.19 is the gear ratio), second, makes the velocity value positive by the rotation_sign identifier if the rotor rotates in negative direction. Thus, the rotation_sign should be +1 if the drive shaft rotates positively, and -1 in the opposite case (see Remark 2 in Sect. 8.1.7.1.4. "Computation of initial angular velocities by fixation file", p. 8-31).

- **Factor Y:** the factor should differ from unity if the ordinate in Fig. is not a torque applied to the drive shaft (e.g. the total traction force of the unit). It should be also used when the drive shaft rotates in the negative direction, i.e. the corresponding joint velocity is negative. In the example in Figure 8.28 the expression $\text{traction}_\text{to}_\text{torque} \times \text{rotation}_\text{sign}$ is used. The traction_to_torque multiplier converts the total traction force into the torque on the rotor for a single motor. In our case this identifier defined by the following expression: $\text{traction}_\text{to}_\text{torque} = 1/4 \times 0.625/4.19$ (4 is the number of wheelsets, 0.625 is the wheel radius, 4.19 is the gear ratio). The rotation_sign multiplier makes the sign of the torque equal to that of the joint velocity, which corresponds to the traction mode.

Now consider the direct setting the traction torque, which is necessary if the locomotive is included in the train 3D model, see. Figure 8.28. The torque is set by the expression $\text{traction}_\text{torque} \times \text{rotation}_\text{sign}$ where the rotation_sign factor takes into account the rotor rotation direction and the traction_torque identifier is equal to the torque value. The last identifier should be expressed in terms of the total traction force as

$$\text{traction}_\text{torque} = \text{traction}_\text{force} \times \text{traction}_\text{to}_\text{torque}.$$

**It is strongly recommended** to use the traction_force identifier for the total traction force to automate its detection if the locomotive is included in a train 3D model.

Finally, it is recommended to introduce the identifier $n_{\text{throttle}_\text{positions}}$ with numeric value equal to the number of the throttle positions. The identifier should be added to the identifier list of the locomotive model (not in the subsystems).

### 8.1.7.1.3. Gearing

Model of a gearing is the necessary part of the drive system. To add gears to the wheelset image, open the wheelset subsystem parameters in the object inspector, check the Gear key and if necessary Double key, as well as set the gear radius (0.45m in the Figure 8.30) and location on the axle (0.55 m in the figure).
A special force of the **Gearing** type is used for modeling the gearing. The force element connects the rotational part of the wheelset (the WSetRotat body) as the first body and the drive shaft as the second body. The following parameters specify the force element, Figure 8.31:

- **Attachment points** are coordinates of bull gear and pinion centers in system of coordinates of the wheelset and rotor respectively;
- **Axes of rotation** are unit vectors (0, 1, 0);
- **Gear ratio** is the bull gear radius divided by the pinion radius;
• **Clearance** is the value of possible teeth clearance due to wear (m);
• **Damping and stiffness coefficients** characterize the drive system compliance reduced to the gear teeth;
• The **External gearing** key must be checked.

![Figure 8.32. Visualization of the gearing force element](image)

Switch the animation window mode to the visualization of a single element by the button to control the correctness of geometrical parameters of the element. Red vectors in the window correspond to the gear axes, and red circles shows the central gear circles, Figure 8.32.

**Remark.** Use of gearing force elements requires creation of fixation file or setting constraints for initial velocities (see below).

### 8.1.7.1.4. Computation of initial angular velocities by fixation file

Use of gearing requires setting the correct initial angular velocities of some bodies. Neglecting this requirement leads to large forces in the drive system, to lifting wheels from rails at the beginning simulations. One of the main tools for automatic computation of initial angular velocities (more precisely, joint velocities) is the creation by the user of the so-called **fixation file**, that informs the program which joint velocities must be kept without change by computation of initial values.

To illustrate the fixation of a coordinate, consider the drive system of one of the wheelset of locomotive VL80 with the axle-hung suspension of motor. Due to the gearing, the following equation takes place:

\[ i \omega_w = - (\omega_r - \omega_m), \]

where \( \omega_m \) is the angular velocity of the wheelset rotation, \( \omega_m \) is the angular velocity of the motor casing relative to the wheelset base, \( \omega_r \) is the angular velocity of the rotor relative to the motor casing, \( i \) is the gear ratio. It is clear that this equation does not have a unique solution. The program cannot automatically choose which of three angular velocities should be computed from this expression and may choose any of them. Often this leads to a false solution: either the motor
casing has an angular velocity equal to the wheelset rotation velocity multiplied by the gear ratio or all angular velocities are zeroes. The fixation file allows the program to solve the equation correctly. Namely, if change of angular velocities of wheelset and casing \( \omega_w \omega_r \) is forbidden (or the corresponding coordinates are fixed), the program automatically selects the only velocity \( \omega_r \) to be changed and compute it according to the current values of angular velocities of wheelset and casing. Of course, the casing initial angular velocity must be zero.

![Object simulation inspector](image)

**Figure 8.33. Fixation of coordinates and creation of fixation file**

Fixation of a coordinate means that the coordinate and its time derivative (velocity) cannot be changed during computation of initial values of coordinates and velocities. The fixation file contains the list of fixed coordinates. Thus, in the case of locomotive VL80 it is necessary to fix coordinates of wheelsets corresponding to rotation of wheelsets about its lateral axis (joint coordinates in joints \( jWSetRotat \)) as well as coordinates in revolute joints, setting rotation of motor casings about wheelset axes (joints \( jMotor \) in the figure). The fixation file is created in the UM Simulation program on the Initial conditions | Coordinates tab of the object simulation inspector, Figure 8.33.

- Click the upper of two Message buttons. After this action, the program automatically computes angular velocities of wheelsets as well as longitudinal velocities of some of bodies (e.g. car body). This stage of creation of fixation file is not necessary, but it allows the user to see the current values of wheelset angular velocities which must be fixed.
• Fix the necessary coordinates by clicking on cells of the table column marked by the image on the top.
• Save fixation to the file with name of the model in the directory of the model (the default file name and path).
• If the first item of this list is executed, click the button to compute the initial velocities and to verify the correctness of the fixation (angular velocities of rotors must be computed).

Remark 1. For some types of traction motor suspensions (e.g. in case of quill drive) the fixation file is not sufficient for computation of all the necessary initial velocities. In such cases additional constraints on initial velocities must be used, see the next section of the manual.

Remark 2. The sign of the rotor angular velocity (i.e. the sign of the corresponding joint velocity) obtained from Figure 8.33 should be used for specifying the rotation_sign identifier value, see Sect. Traction torque.

8.1.7.1.5. Computation of initial angular velocities by constraints on initial values

Constraints on initial values are an alternative of the fixation file, and give the user more opportunities to control initial conditions.

A constraint is an equation of one of the following two types

\[ x_i = X_i, \]

\[ v_i = V_i, \]

where \( x_i \) is the joint coordinate, \( v_i = \dot{x}_i \) is the first time derivative of the joint coordinate (joint velocity). The right hand sides are arbitrary expressions created with the wizard of variables (see Chapter 4, Sect. Wizard of variables).

The following steps create a new constraint.

• Add a row to the table of constraints by the button.
• Open the wizard of variables with the help of the Tools | Wizard of variables... menu command or by the button on the tool panel.

Figure 8.34. Tools for setting constraints for initial values
Figure 8.35. Creating variable: velocity of drive shaft rotation relative to the motor casing

- Create a variable corresponding to a joint velocity for setting the initial value: open the **Coordinates** tab, select the necessary joint coordinate in the list located in the left part of the wizard. Set the variable type **Velocity** and send in to the container by the **button, Figure 8.36.

- Drag the variable by the mouse and drop it into the left cell of the constraint data row, Figure 8.35.
Figure 8.36. Creation of variables: angular velocity of wheelset and computed value of drive shaft angular velocity

- Create a variable corresponding to the desired value of the velocity and put it in the right cell of the constraint row. Let us consider the following example. Let the rotor angular velocity is equal to the wheelset angular velocity multiplied by the gear ratio 4.19. It is necessary to take into account that the wheelset and the rotor rotate in opposite directions, i.e. the joint velocities have different signs.
Create a variable corresponding to the angular velocity of the wheelset (more precisely, the derivative of the angle of rotation); this is the joint velocity in the joint $jWSe-tRotat$.

Open the Expression tab of the wizard. Add a multiplication operation by the button, Figure 8.36.

Set the wheelset angular velocity by the mouse as the first operand; enter the number ‘-4.19’ (negative!) by the clipboard as the second operand.

Set the variable name instead of the default value Expression.

Send the variable into container by the button and drag it into the constraint cell, Figure 8.34.

- When all the constraints are specified, save them in a file in the object directory. If constraint file has the name of the object, the constraints are automatically loaded at each load of the object in the simulation module. Constraints are used for automatic computation of initial conditions right before the start of the simulation process.

- To verify the correctness of the constraints, open the Initial conditions | Coordinates tab of the inspector, run the upper command Message, and compute the initial values by the button. Compare the computed values of velocities with the desired ones.
8.1.7.2. Example of development and analysis of locomotive model

Consider basic principles of development of a locomotive with two COCO bogies, Figure 8.37. Each of the bogie models contains three Wheelset-Motor assemblies (WMA). In a WMA, the motor is rigidly fixed relative to the frame, and the traction reducer is connected to the wheelset by a rotational joint.

The ready model of the locomotive is located in the directory \{UM Data\}\SAMPLES\Rail_Vehicles\Co-Co.

8.1.7.2.1. Development of model

Figure 8.37. Locomotive model

8.1.7.2.1.1. Development of wheelset-motor assembling

Let us consider some details of the WMA model. Run UM Input and open the model or click on the hyperlink \{UM Data\}\SAMPLES\Rail_Vehicles\Co-Co. Open the subsystem Bogie_1, and then the subsystem Wheelset_motor_assembling_1, Figure 8.38.

The WMA model contains several rigid bodies:
- two axle-boxes 3 (Axle-box L and Axle-box R),
- Reduction gearbox 7,
- Traction motor 5,
- Rotor,
- Gear wheel,
- Cardan shaft.

The wheelset is the standard subsystem, Sect 8.1.3. “Wheelset and single wheel”, p. 8-9.

Consider the structure of the model in more details, Figure 8.39. The traction motor casing is rigidly fixed to the bogie frame. The rotor is connected to the motor casing by the rotational joint jTraction motor_Rotor. The cardan shaft has two degrees of freedom relative to the rotor; see the joint jRotor_Cardan_shaft in which four degrees of freedom are disabled. The rubber annulus coupling is modeled by a bushing force element Rubber-cord coupler. The shaft transmits the traction torque by the coupling to the Gear wheel of the reducer. The Reduction gearbox is con-
connected to the wheelset by the rotational joint \( j\text{WS}et\_\text{Reduction gearbox} \) and suspended to the frame by the linear bipolar force element \( \text{Rod} \).

Figure 8.38. Model of wheelset-motor assembly: damper (1), primary suspension (2), axle-box (3), traction rod (4), traction motor (5), elastic coupling (6), reduction gearbox (7), reducer suspension rod (8)

Figure 8.39. Structure of WMA

**Remark.** Simple images are created directly in UM. Advanced images can be imported from CAD programs. In the case of our locomotive models some images are created in UM (Rotor, Gear wheel, Cardan, Spring, Damper), other images are imported from CAD.

The joint \( j\text{Base}_\text{Traction motor} \) with 6 degrees of freedom sets the position of the motor casing relative to SC0. This joint will be automatically removed when the motor will be fixed to the frame in the upper subsystem (the bogie model).

**Remark.** It is recommended to use the following names of joints for the better identification: \( \langle j \rangle \) + “Name of first body” + “_” + “Name of second body”.
A joint of the generalized type introduces the rotational degree of freedom of the rotor relative to the motor casing. A rotational joint could be used as well. The traction torque is described by the joint torque of the points (numeric) type.

The cardan joint is created with the “6 d.o.f” joint \( j_{\text{Rotor \_Cardan \_shaft}} \). The joint is specified by the joint points; four degrees of freedom of six are locked; rotations about the X and Z axes are allowed.

The rotational joint \( j_{\text{Reduction} \_gearbox \_Gear \_wheel} \) describes rotation of the gear relative to the reducer casing, which rotates about the wheelset axle \( (j_{\text{WSet \_Reduction} \_gearbox}) \).

Finally, the joints \( j_{\text{Axle-box L} \_WSet} \) and \( j_{\text{Axle-box R} \_WSet} \) connect axle-boxes to the wheelset axle. These joints differ for the front and rear WMA on the one hand, and for the middle WMA on the other hand. The joint are rotational in the first case (Figure 8.40), and the joints for the middle WMA has 15 mm gap relative to the axle in the lateral direction (Figure 8.41).

Figure 8.40. Joint \( j_{\text{Axle-box L} \_WSet} \) for the front and read WMA

Open the Wheelset\_motor\_assembling\_2 subsystem to see the description of the joint \( j_{\text{Axle-box L} \_WSet} \) with two degrees of freedom. The joint type is generalized and it has three elementary transformations (ET, see Chapter 2, Sect. Generalized joint):

- \( tc \) (translation constant) sets the lateral position of the box on the axle \( \text{ShiftAxleBox} = 1.085 \text{ m}, \) Figure 8.41a;
- \( tv \) (translational degree of freedom) specifies the lateral motion of the box;
- \( rv \) (rotational degree of freedom) introduces the rotation of the box relative to the axle.

Let us consider the ET of the \( tv \) type in more details.

The tab Force/Torque contains the description of forces acting on the box by its motion relative to the axle in the lateral direction. The type of torque is the List of forces with two elements:

- the Bump stop element describes the gap, Figure 8.41b;
- the AxleBox\_Friction element introduces the friction force, Figure 8.41c.
Bipolar force elements are used for modeling the reducer support and the inclined primary damper. It is important that the second body in the force elements is External (the second body will be assigned in the bogie subsystem), and the Autodetection mode is checked, see Chapter 3, Sect. “Interconnection of subsystem. Use of external elements” for more details.

A bipolar force of the Linear type describes the reducer suspension rod. An image is assigned to the rot for the visualization.

Characteristics of the hydraulic dampers Damper L and Damper R (Figure 8.43) are described by the expression

\[-(d_{Axlebox\_1part}\cdot v^2\cdot heavi(v\_damper-\text{abs}(v))+heavi(-v\_damper+\text{abs}(v))\cdot (d_{Axlebox\_1part}\cdot v\_damper^2+d_{Axlebox\_2part}\cdot (\text{abs}(v)-v\_damper)))\cdot \text{sign}(v)\].

See the list of identifiers for the values of the identifiers in the expression.
Springs and traction rods are often modeled by *Linear force* elements.

The *Rubber-cord coupler* is modeled by a *Special force* element of the *Bushing* type. Characteristics of the coupler are nonlinear. If the deflection is more than 0.06m, the stiffness of the bushing increases.
Remark. It is recommended to parameterize all elements of force description for the possible modification during the simulation.

### 8.1.7.2.1.2. Development of bogie model

Consider some features in description of the bogie model. Open the Bogie_1 subsystem. Development of the bogie model starts with creation of images. Image of a frame is imported from a CAD program, and all other images are developed in UM.

The subsystem includes two bodies Frame and Traction rod.

![Figure 8.44. Bogie model](image)

The joints jBase_Frame, jBase_Traction introduce six degrees of freedom of the frame and traction rod relative to SC0.

The model contains three included subsystems WMA, Sect. 8.1.7.2.1.1. "Development of wheelset-motor assembling", p. 8-37. Please note that the front and the read WMA are identical, whereas the middle of differs in description of axle-boxes degrees of freedom. The button is recommended for copying the subsystem. Longitudinal positions are parameterized by the identifiers x_Wheel_1, x_Wheel_3, r_Wheel. The rear WMA is rotated on 180 degrees about the vertical axis.

The jFrame_Wheelset_motor_assembling_1, jFrame_Wheelset_motor_assembling_2, jFrame_Wheelset_motor_assembling_3 joints fix motor casing to the frame. After introduction of these joints, the fictitious joints jBase_Traction motor are ignored for all of the three WMA. For fixation joints we have used the generalized type of joints. The position of the casings are set by the elementary transformations of the tc type. An additional rotation about the Z axis is assigned to the rear motor casing with the transformation of the rc type.

Bipolar forces DamperZ 1R, DamperZ 2R, DamperZ 1L, DamperZ 2L describe the vertical dampers; lateral dampers are Damper Y L and Damper Y R, and yaw dampers are Damper X L and Damper X R. In all three cases we have used the simplified linear model of the dampers. The second body for all forces is selected External, and the Autodetection key is checked.

The linear force elements describe six secondary suspension springs for a bogie. The stationary force in springs is vertical; it is equal to the product of the spring constant on the static spring
deflection. The stiffness matrix specifies the spring characteristics. Second body is the External one and Autocomputation for the second body key is checked.

Figure 8.45. Secondary dampers: vertical (a), lateral (b) and yaw (c)

An inclined traction rod is used in the bogie model for transfer of the traction efforts. The traction rod is connected with the bogie frame and car body by special force elements of the bushing type Joint_traction_1 and Joint_traction_2. The second bushing is the external one. The Autodetection key is checked for both of the bushings.

Figure 8.46. Assignment of connection points with the “Assign to all” menu command
To finalize the bogie model, we must assign connections to all of the external elements introduced in the WMA subsystems. Open the Connections tab of the inspector by the item in the element tree. In our model all external elements are described in the autodetection mode. All external elements are connected to the bogie frame, and the assignment of this body as the second one for the force elements can be done by the “Assign to all” command of the pop-up menu. It is necessary to have at least one connection point in description of the frame body. Select one of the external elements in the list by the mouse and call the pop-up menu, Figure 8.46. Select the “Assign to all” command and choose one of the connection point for the frame body. After this operation the frame body will be assigned to all external elements in the WMA subsystems, and coordinates of connection points to the frame body will be evaluated automatically.


8.1.7.2.1.3. Finalization of locomotive model

Let us consider the full locomotive model. Firstly, the new model must be created or the bogie model must be converted into a subsystem. After that, the car body image must be created. We have done it in a CAD program and imported to UM.

Remark. Each graphic element in UM has one color only. It is recommended to develop in CAD a car body image consisting of several parts to assign them different colors. In our case we have used six parts, which are joint in a single GO as a collection of references to the part images Figure 8.47.

Figure 8.47. Image as a collection of part images

The model includes one body corresponding to the car body, and one joint with six degrees of freedom jBody introducing coordinated of the car body relative to the SC0. If the bogie is not converted into a model subsystem, it must be added to the locomotive model as an included subsystem Bogie_1. The second bogie Bogie_2 is created as a copy of the first one. The first bogie longitudinal position is set by the expression vehiclebase/2. The second
bogie position has the opposite sine, and in addition the subsystem must be rotated about the Z-axis on 180 degrees.

Connection of external elements with the car body is done in the same manner as in the case of the bogie model, Sect. 8.1.7.2.1.2. "Development of bogie model", p. 8-42. The Summary tab in inspector informs us about possible errors in the model.

![Model of locomotive](image)

**Figure 8.48. Model of locomotive**

### 8.1.7.2.2. Simulation of locomotive dynamics

Open the locomotive model in the simulation program.

#### 8.1.7.2.2.1. Creation of fixation file

Notion of the fixation file is introduced in Sect. 8.1.7.1.4. "Computation of initial angular velocities by fixation file", p. 8-31. For correct automatic computation of initial values of angular velocities in the traction system of locomotive we must fix several coordinates. The kinematic scheme of the WMA is shown in Figure 8.49.
Figure 8.49. To computation of angular velocities

According to the scheme, we must fix angular coordinate of the reducer casing as well as the wheelset coordinate for rotation about the wheelset axle in each WMA.

The fixation file is created with the help of the Initial conditions | Coordinates tab of the inspector, Figure 8.50. Use the left mouse button to fix the necessary 12 coordinates by the mark in the first column of the coordinate table. The file with the model name is created corresponding by the pop-up menu command.
8.1.7.2.2.2. Creation of constraints on initial conditions

Fixation file allows computing correctly the gear angular velocities, but not the rotor rates. In addition to the fixation file, we must create six constraints on initial conditions to make the rotor angular velocity equal to that of the gear wheel, see Sect. 8.1.7.1.5. “Computation of initial angular velocities by constraints on initial values”, p. 8-33.

The variables corresponding to the angular velocities of rotors and gear wheels are created in the Coordinates tab of the Wizard of coordinates. After that, the variables corresponding to the rotor rates are dragged into the first column of the Constraints on initial conditions tab of inspector, Figure 8.51, and angular velocities of the gears are dragged into the second column, Figure 8.52. The list of constraints must be saved in the file with the name of the model.
To verify the correctness of the fixation file and the constraints, open the **Initial conditions** | **Coordinates** tab, click on the upper Message button to assign initial velocities to wheelsets,
frames and other bodies, and click button to compute other initial velocities according to fixation and constraints. Verify the results. For instance, rates of the rotors and wheels must be equal, Figure 8.53.

![Image of Object simulation inspector window](image.png)

Figure 8.53. Result of computations of initial conditions
8.1.7.2.3. Test for force start values

A very useful tool is available for verification of correctness of force description in the model. The tool computes the force values at start of the simulation. Usually this test is run for just developed models to find possible errors in description of force elements.

To run the test, open the Tools | Test tab of the inspector and click the Compute button. The program computes the forces and displays the force component values on SC0, Figure 8.54. The user compares the values with the expected ones.

![Object simulation inspector]

Figure 8.54. Test for forces

8.1.7.2.3. Analysis of some locomotive performances

The developed model allows analyzing dynamic performances of the locomotive in tangent sections and curves, with constant or variables speed and so on. Evaluated dynamic performances are usually the same as in the field tests: guiding and frame forces, derailment criteria, lateral and vertical accelerations, dynamic factors, wear factors in rail\wheel contacts, etc.

Consider the following list of simple tests.

- Computation of dynamic factors for the primary and secondary suspensions by different irregularities.
- Evaluation of the critical speed.
- Evaluation of wear factors by run in curves.
8.1.7.2.3.1. Computation of dynamic factors

Let us compute dynamic factors of the primary and secondary suspensions for different levels of track irregularities. To vary the level of irregularities, we change value of parameter *Factor* which in fact is multipliers to assigned irregularities, Figure 8.55.

Let the locomotive initial speed be 30 m/s, and the neutral speed mode is selected; track be a tangent section with assigned irregularities “UIC bad”, Figure 8.55. Simulation time is 10s.

Variables corresponding to dynamic factors are created with the wizard of variables, Sect. 8.4.3.1. "Some features of creation of variables", p. 8-186, see Chapter 4 for more details. The variables are dragged into graphical windows.

![Figure 8.55. Track irregularities](image)

**a)**

**b)**
Figure 8.56. Dynamic factors for the primary (a) and secondary (b) suspensions; irregularity factors are 1

![Figure 8.56](image_a.jpg)

Figure 8.57. Dynamic factors for the primary (a) and secondary (b) suspensions; irregularity factors are 2

The processing of the plots is usually done by the table processor, available by the Tools | Table processor menu command. Some results for the _4Max_Mean functional (Sect. 8.4.3.5, "Table processor", p. 8-214) are shown in Figure 8.58.

![Figure 8.58](image_b.jpg)

Figure 8.58. Maximal dynamic factors for the first and the second tests
8.1.7.2.3.2. Critical speed of locomotive

Evaluation of the critical speed is an important problem. The only way to do it on the design stage is the simulation.


In our case we evaluate the critical speed in the following steps.

- With the deterministic type of irregularities, we assign a single lateral irregularity; in the vertical direction rails are ideal, Figure 8.59.
- We run a series of simulations with increasing speed.
- Basing on the lateral displacements of wheelset, we estimate the critical speed.

Critical speed of the locomotive model is 70 m/s. Compare lateral motion of wheelsets for 60 m/s and 80 m/s in Figure 8.60.
8.1.7.2.3.3. Comparison of wheel wear factors by locomotive curving

In this test, we compare the wheel wear factor by motion of the locomotive in a curve $R = 300$ m with different speeds, with and without rail lubrication.

The wheel wear factor estimation will be based on the friction work in wheel/rail contact. The right curves are considered in UM by default. That’s why the wear is usually defined on the left (climbing) wheels. Let us consider the total friction work in the wheel/rail contact for all left wheels of the locomotive. You can create such variable using **Wizard of variables**. To do it select $AWear1$ (work of friction forces on tape circle) on the **Rail/Wheel** tab in the **Variables for wheel** group (see Sect. 8.4.3.1.1. "Rail/wheel contact variables", p. 8-186) and choose all left wheels, Figure 8.62. Make the same steps for the $AWear2$ (work of friction forces on flange) variable. Then use the **Expression** tab to sum works for all left wheels, Figure 8.63. Move the obtained variable $AWearSum$ to the graph window.
Figure 8.61. Creating "Work of friction forces" variable
We have compared the work of creep forces for the following cases:

- speed 6 m/s, without lubrication;
- speed 12 m/s, without lubrication;
- speed 6 m/s, with lubrication;
- speed 12 m/s, with lubrication.

Let the coefficient of friction without lubrication be 0.25, and with lubrication on the rail side face be 0.15. The values of the coefficients of friction are set in the Rail/Wheel | Contact | Friction tab of the inspector.

Such tests are usually made with the scanning tool if the UM Experiments module is available. After run of the experiments, we get the results in Figure 8.63.
Figure 8.63. Summarized frictional work for speed 6 and 12 m/s:
a) without lubrication, b) with lubrication
8.1.7.3. Support of braking mode

8.1.7.3.1. General information

Simulation of braking process is discussed in the Chapter 15 of UM user’s manual, which is devoted to the longitudinal train dynamics. Here we consider adding to a vehicle model (both car and locomotive) force elements only, which allows converting the braking force computed in the train module to the moments and forces acting between bodies of the rail vehicle. Using UM the user could realize a detailed model of mechanical part of the braking system, but here we consider a simplified force model, which is quite precise in many cases.

![Bilateral brake blocks](image)

Figure 8.64. Bilateral brake blocks

Let the total braking force for the vehicle is set by an identifier. It is recommended to use for this purpose the standard identifier `braking_force` to automate the process of its recognition in the train 3D models. Consider bilateral brake blocks, which are pressed symmetrically against the wheel tread, Figure 8.64. It is assumed also that all the wheelsets of the vehicle produce equal braking forces. In this case the brake force for each of the wheelsets can be realized by torque acting from the bogie frame on the wheelset opposite to its rotation

\[ \pm \frac{\text{braking_force}}{N_w} \times R_w \]

where \( N_w \) is the number of wheelsets, and \( R_w \) is the wheel radius. The + sign is set if the wheelset forward motion corresponds to the negative angular velocity (it is possible if a subsystem including the wheelset is rotated on 180 degrees about the vertical axis), see the sign of angular velocity of the wheelset in Figure 8.33.
Such a moment should be added for each of the wheelsets using the $T$-force element, Figure 8.65. The first body in this element is the bogie frame, the second one is the rotational part of the wheelset ($WSetRotat$), and the reference body must be the base of the wheelset. It is an error if the reference body is Base0.

The same model can be used in case of brake disks. If unilateral brake blocks are used, the force element must contain in addition a vertical force equal to the braking force; the user should take care of the signs of torque and force. The signs both depend on direction of rotation of the wheelset, and on position of the brake block relative to the wheelset.

8.1.7.3.2. Use of visual components

Visual components make faster the process of development of force elements that describe braking forces, Sect. 1.1.7.3.1.

The following steps are necessary if the visual components are used.

- Click a component button, Figure 8.66.
- Click by the mouse on the frame or other body attached to the braking mechanism; for instance, it is the bolster in case of freight three-piece bogie (the first body).
- Click on the wheelset (the second body).
- Click on the connection point in the center of the wheelset (reference body for the force).
Set desired values of identifiers in the **Initialization of values** window: number of wheel-sets and wheel radius, Figure 8.67. This initialization is not necessary if identifier is already introduced.

**Three components are used for modeling brakes.**

- **Bilateral brake blocks or disc brakes.** A brake torque is added to the frame and wheel-set. List of identifiers is shown in Figure 1.68.

  ![Initialization of values](image)

  Figure 8.67. List of identifiers parameterizing the bilateral brake

- **Unilateral brake blocks, rear position of the block.** The force summarizes action from two blocks of the wheelset.

  ![Loading scheme for rear unilateral brake block](image)

  Figure 8.68. Loading scheme for rear unilateral brake block

  Loading scheme is shown in Figure 8.68. Normal force $F_z$ and friction force $F_x$ satisfy the equation $F_z = f F_x$, where $f$ is the coefficient of friction. List of identifier includes coefficient of friction, Figure 8.69.

  ![Coefficient of friction for a brake block](image)

  Figure 8.69. Additional identifier for an unilateral brake
Forces $F_x, F_z$ are applied to the wheel tread, but T-force must be applied to a fixed point of a body. That is why the transformation of the force to the center of wheelset is done, and a brake torque is added

$$M_y = F_z r_w,$$

where $r_w$ is the wheel radius.

Unilateral brake blocks, front position of the block. The force summarizes action from two blocks that are installed on the wheelset.

Figure 8.70. Loading scheme for rear unilateral brake block

Description of the element is similar to the previous one.

Correction of signs of force and torque

In the case of a unilateral brake blocks, signs of the force $F_x$ and torque $M_y$ depend on the sign of wheelset angular velocity. If the velocity is negative, signs of the force and torque must be changed to opposite, Figure 8.71. For instance, if a wheelset is rotated on 180 about the vertical axis together with the bogie, its angular velocity will be negative. The sign of the wheelset can be obtained from Figure 8.33.
Figure 8.71. Standard description of force element that models braking forces
8.1.8. Railway test rig model development and simulation features

Roller rigs (Figure 8.72) are used for a wide range of studies which concern the stability of the rail vehicle, passengers comfort, braking systems, wear prediction. The Roller rigs are easy to use and require significantly less investment than the full-scale field tests.

![Roller rig (Hongik University, the Republic of Korea), reprinted from [1]](image.jpg)

To create a roller rig model take the following steps in the UM Input program:

1. Add bodies, which model the rollers, set their inertia parameters, assign the corresponding graphical objects and joints. One roller must be assigned to each of the wheels. The following requirements take place:
   - All rollers must be identical;
   - Each of the rollers has one rotational DOF relative to the Y axis below the wheelset. It can be done by a rotational joint (Chapter 2, Sect. "Translational and rotational joint"), which description includes:
     - Connecting bodies: Base0 as the first body and the roller as the second one;
     - Axis of rotation (0,1,0) for each of the bodies;
     - Roller position as the joint point for the Base0 body, see Figure 8.73.
2. Go to data inspector of the "Wheelset" subsystem window and activate the key "Test rig". The standard identifier r_roller corresponding to the roller radius is automatically added to the list of identifiers after this operation. Then the roller bodies must be assigned to the left and right wheels like in Figure 8.74.

Figure 8.74. Assigning roller-bodies to the wheelset
Let as consider briefly some features of specifying initial values for roller rotation speed by simulation. If initial rotation velocity differs from zero, it must be computed depending on the value of identifier \( v_0 \). This identifier corresponds to 'imaginary' longitudinal speed of the test rig. The initial rotation speed of a wheelset is equal to, \( v_0 / r_w \) where \( r_w \) is the wheel radius. Respectively, the roller angular velocity \( \omega_r \) is computed as:

\[
\omega_r = -\frac{v_0}{r_r},
\]

where \( r_r \) is the roller radius. Initial angular velocity can be assigned to the roller by the 'initial constrain' tool, see Chapter 4, Sect. "Constraints on initial conditions".

If the test rig starts with zero speed, the identifier \( v_0 \) value should zero.

Roller profiles are assigned on the Rail/Wheel | Profiles | Rails tab of the simulation inspector, see Sect. 8.4.2.3.1 "Assignment of rail profiles", p. 8-146.
8.2. Track

8.2.1. Track geometry

Track geometry includes the following components:
- geometry of rails in an ideal tangent track (track gauge, inclination of rail, rail profiles);
- macro geometry of curves;
- track irregularities.

8.2.1.1. Geometry of rails in an ideal track

The geometry of rails in an ideal tangent track includes:
- profiles of left and right rails,
- distance between centers of heads of rails,
- rail inclination.

A rail profile in UM should be set in a special system of coordinates (SCR), Figure 8.75. SCR origin is located at the profile top on its symmetry axis (i.e. the profile curve passes though the origin). The abscissa axis (y) is perpendicular to the rail profile axis and directed inside the track. The ordinate axis (z) is directed upwards. Unit for profile data is millimeter.

![Figure 8.75. System of coordinates of rail](image)

Lateral position of rails in an ideal straight section is set by the SCR-SCW distance $\Delta y$ relative to the wheelset base (Figure 8.76)

$$\Delta y = \frac{L_r - L}{2},$$

where $L_r$ is the distance between the rail head centers, $L$ is wheel base (distance between running circles, Sect. 8.1.3.5. "Wheelset geometry", p. 8-13). In other words, the SCR-SCW distance is the lateral distance between the origins of two profile frames (wheel and rail) at ideal symmetric position of the wheelset.
Further expression for the SCR-SCW:

\[ \Delta y = \frac{S + h_r - L}{2} \]

where \( S \) is the gauge, \( h_r \) is the width of the rail head. Default value is \( \Delta y = 0.003 \) m.

Rail inclination \( \alpha_{r0} \) is the angle between the rail profile axis of symmetry and the vertical direction in an ideal straight track. Unit for the inclination is radian. The angle is positive for inclination inside the track. The default value is \( \alpha_{r0} = 0.05 \) rad.

The rail profile can be changed with the distance along the track (Sect. 0). To do this, enter a set of profiles as well as positions of each along the track. Let profiles R1 and R2 have positions S1 and S2 (S2>S1). Then the program computes an intermediate profile R(S) for every necessary position \( S \in [S1,S2] \) as a linear interpolation of profiles R1 and R2 such as \( R(S1)=R1, R(S2)=R2 \).

### 8.2.1.2. Geometry of curve

The following types of curves are available in UM (Figure 8.77):

- right curve
- S-curve (a right curve followed by a left one)
- left curve (can be obtained as a S-curve with a very short right curve section)

The following designations are used for the S-curve in Figure 8.77:

- \( L0 \) is the length of a straight section before the curve;
- \( P11 \) is the length of the first transition for the right curve;
- \( S1 \) is the length of steady curve;
- \( R1 \) is the radius of steady curve;
- $H1$ is the cant for the outer rail;
- $P12$ is the length of second transition for the right curve;
- $dy$ is the additional gauge widening in curve;
- $L$ is the length of a straight section between the right and the left curves (for S-curves only).

Other parameters for the second part of the S-curve have quite the same meaning.

**Note.** To get a left curve, small values should be set for $P11$, $S1$, $P12$, zero value for $H1$ and a large value for $R1$, e.g., $P11=0.01$, $S1=0.01$, $P12=0.01$, $R1=100000$.

Transient sections are formed by a cubic parabola or by clothoid, Sect. 8.4.2.4.1. "Track model choosing and parameters setting", p. 8-151. The curvature in transitions changes according approximately (for s cubic parabola) and exactly (for clothoid) linear law.

![Figure 8.77. On macro geometry of curve](image)

Cant increases/decreases at transient by linear function except the Curve type of macrogeometry, where the cant can be specified arbitrary by a set of points. It is possible to smooth the vertical junctions at ends of the transition by an arc.

*Additional widening of track in a curve (dy)* is proposed automatically: $dy = 10$ mm for $R \in [300,350]$, $dy = 15$ mm for $R < 300$ m. The widening is realized as a symmetric lateral shift of both the rails on a half of the widening. The widening in transient sections is the linear function of the position. The user may set his/her own widening, see Sect. 8.4.2.4.1. "Track model choosing and parameters setting", p. 8-151.

Let us introduce a number of designations for curve parameters computed by UM:
- $X(s)$, $Y(s)$ are equations for a curve, $s$ is the length along the curve;
- $\psi_x(s)$ is an angle between the X-axis and the tangent to the curve;
- $\rho(s)$ is a curvature radius;
- $S_0$ is a traveled distance.
Consider an example of an S-curve for the following parameters (Figure 8.78-Figure 8.82):

$L_0=10\text{m}$, $p_{11}=70\text{m}$, $s_1=150\text{m}$, $R_1=300\text{m}$, $p_{12}=60\text{m}$, $h_1=0.09\text{m}$,
$L=10\text{m}$, $p_{21}=50\text{m}$, $s_2=140\text{m}$, $R_2=330\text{m}$, $p_{22}=70\text{m}$, $h_2=0.1\text{m}$.

Figure 8.78. Angle between rail and $X$–axis

Figure 8.79. Curvature

Figure 8.80. Derivative of the curvature
Figure 8.81. Gauge widening

Figure 8.82. Cant for outer rail
8.2.1.3. Switch geometry

Motion in left and right switches is implemented in UM. The basic geometric parameters of a switch are shown in Figure 8.83. The following parameters are used for description of the switch.

$q$ is a stock rail overhang;
$\beta_n$ is an initial angle;
$\alpha$ is a switch angle;
$R_0$ is a radius of point;
$R$ is a radius of switch;
$b_r$ is a switch deviation for $R_0$;
\( m \) is a frog tail length; 
\( d \) is a track spacing.  
\( R_q \) is a radius behind frog.  
The parameters define fully the switch geometry and some additional parameters in Figure 8.83 like  
\( L_p \) is the full switch length;  
\( L_t \) is the theoretical length;  
\( k \) is tangent section before frog.  
UM includes the standard R65 1/11 and R65 1/9 exUSSR switches. The user can create files with any switch parameters.

**8.2.1.4. Track system of coordinates**

A track system of coordinates is introduced for each body of the vehicle (TSC). Its origin \( W_i \) coincides with the projection of the body fixed frame origin on the ideal central axis of the track. The abscissa axis \( x_i \) is the tangent to the ideal track centerline. The ordinate axis \( y_i \) lies in the track plane on the left to the motion direction.

![Figure 8.84. TSC axes in presence of a cant](image)

A cant of the outer rail \( h_i \) in Figure 8.85 gives the rotation of the track plane on the angle  
\[
\alpha_i = \arcsin \frac{h_i}{L_r}
\]

TSC is used for calculation of some dynamic performances of the vehicle in curves, Sect. 8.4.3.1.9. "Kinematic characteristics relative to track system of coordinates", p. 8-205.

**8.2.1.5. Track irregularities**

Vertical and horizontal irregularities of rails are stored in files *.way and assigned to rails. Step size of the irregularities is 0.1 m (Sect. 8.4.1.2. "Creation of track irregularities", p. 8-114).
It is possible to program user’s irregularities in the Control File (Sect. 8.4.1.2.2. "Programming irregularities in the Control file", p. 8-123).

**Note.** To avoid a force jump while going up the begin of an irregularity, the irregularity is set to zero on the first ten meters, and then irregularities are multiplied by a special factor that changes from 0 to 1 on the next 20 m. As an example consider an irregularity of a constant height of 1 mm. In fact the irregularity in Figure 8.85 will be applied. This is valid for file irregularity only, and not for the irregularities that are programmed in the Control File.

Figure 8.85. Smoothing an irregularity
8.2.2. Track models

Universal Mechanism supports three track models that consider track with different level of details:

- Massless rail;
- Inertial rail;
- Flexible track.

Massless rail track model treats rail as a massless force element. For such a rail model generalized coordinates are not introduced. Rail deflections are calculated as a result of solution of equilibrium equations (Sect. 8.3.1.2.1. "Method for computation of rail deflections and contact force", p. 8-84). This model is recommended to use for analysis/optimization of running gears of railway vehicles since intrinsic rail dynamics weakly effects on simulation results of rail vehicles. Massless rail model is used as the default track model.

Inertial rail track model considers rails as rigid bodies under each wheel, see Figure 8.86. Every rigid body that simulates inertial rails has three degrees of freedom: two longitudinal d.o.f. relative to lateral (Y) and vertical (Z) axes and one rotational d.o.f. relative to longitudinal (X) axis. Equations of motion for inertial rails are given in track coordinate system (Sect. 8.2.1.4. "Track system of coordinates", 8-72). Underrail base is modeled as a Special force of Bushing type. Inertial rail model is recommended to use for simulation of complex scenario of wheel-to-rail contact: railway track evolution in the switches and turnouts, flange-back and conformal contacts, simulation of vehicle derailment cases, prediction of wheel and rail wear, etc.

![Figure 8.86. Inertial rail track model](image)

The presence of rail bodies in a railway vehicle model is regulated by the flag Inertial rail in Wheelset subsystem settings in UM Input program (Sect. 8.1.3.1. "Adding a wheelset or a wheel", 8-9).

Flexible track model is a detailed 3D track model that includes flexible rails, fasteners, sleepers and sleeper foundation. UM Flexible railway track module is required for Flexible track model. See Chapter 27 how to work with UM Flexible track module. Flexible track
model is recommended for problems that are focused on dynamics of the railway track and railway track foundation.

Listed above track models Massless rail, Inertial rail and Flexible track treat sequentially more and more complex models and approaches to simulation railway track. In fact, more complex models provide more accurate results but require more CPU efforts. The following rough estimations of relative CPU efforts while using different track models might be given. Inertial rail is about 2-3 times slower and Flexible track model is about 50-80 times slower than Massless rail model.

Please note that the frequency range for Massless rail model is 0-20 Hz. Inertial rail provides reliable simulation in the frequency range up to 100 Hz, and Flexible track – up to 1000 Hz.

A railway vehicle model can simultaneously include all the track models listed above. You can choose a track model on the tab sheet Rail/Wheel | Track | Model and parameters, Figure 8.87.

Figure 8.87. Track model choosing
8.3. Wheel-rail contact

Three main parts of contact computation can be pointed out:

- contact geometry, i.e. computing locations of contact points for a given position of a wheel-set relative to rails;
- computation of kinematical characteristics at contacts (creepages and spins);
- computation of normal forces and creep forces at contacts according to geometrical and kinematical parameters.

As it is shown below, these problems are not solved independently; a general iterative procedure is necessary.

A large part of the results, presented in this section, is obtained in cooperation with V.S. Kossov. In exposition of this section we will mainly follow the results and algorithms presented in the thesis by V.S. Kossov, making some refinements, modifications and generalizations.

The main method of calculating the geometry of the wheel and rail contact interaction, considered in this section, is based on the account of the exact geometry of the curves (profiles) which are the wheel and rail cross-sections. The simplified method, based on the notion of efficient conicity and effective contact angle parameter value, is discussed in Sect. 8.3.1.1.3. "Simplified contact geometry. Equivalent conicity and contact angle parameter", 8-81.

To improve the reliability and speed of calculating the contact point position two basic ideas were realized. Firstly, if the rail profile is constant along the track, the calculation of the coordinates of contact points for the set of profiles is performed once before the first start of the modeling process. Contact points coordinates are arranged in the arrays depending on the wheel profile displacement relative to the rail profile. It is assumed that the wheel has two degrees of freedom relative to the rail: rotation around the longitudinal axis and transverse displacement. In the process of coordinate values movement modeling (at the current position of the wheel profile relative to the rail) are calculated via the mentioned precalculated arrays using interpolation. This lets significantly reduce the number of arithmetic operations and raise the speed of the process.

Secondly, computation of contact points on the profiles is based on a procedure, which computes the nearest point between two curves. These algorithms proved to be very fast and reliable, and do not depend on smoothness of the curves.

8.3.1. Computation of the contact between the wheel and massless rail

8.3.1.1. Algorithms for wheel-rail contact geometry

8.3.1.1.1. Algorithm for computation of nearest points between two profiles

Let us consider an arbitrary position of the wheel profile relative to the system of coordinates of the rail profile $Y_rZ_r$ (SCR, Sect. 8.2.1.1. "Geometry of rails in an ideal track", p. 8-66), Figure 8.88. Introduce a new SC (SCR0) $Y_0Z_0$, which origin coincides with the origin of SCR. The $Z_0$-axis is perpendicular to the track plane as if the inclination angle $\alpha_{t0}$ is zero. The SCR $Y_rZ_r$ is
inclined on $\alpha_{r_0}$ relative to SCR0. Position of SCW (system of coordinates of the wheel profile, Sect. 8.1.3.5. "Wheelset geometry", p. 8-13) $Y_w Z_w$ relative to SCR0 is defined by coordinates of the origin $\Delta y$, $\Delta z$, and the angle $\Delta \alpha$. Coordinates in Figure 8.88 are positive. All angles are considered to be small.

Figure 8.88. Relative position of profiles

It is necessary to find a pair of points on the profiles, which have the same $Y$-coordinate in SCR0 and the minimal difference in $Z$-coordinate in SCR0. Obviously, the solution does not depend on $\Delta z$.

Let us start with the algorithm for computing the value

$$\delta z = z_{w_0} - z_{r_0},$$

for two points having the same $Y$-coordinates in SCR0. The coordinate $y_r$ of a point on the rail profile in SCR ($Y_r Z_r$) has a given value. We should compute the coordinates $y_w, z_w$ of the corresponding point on the wheel profile in SCW as well as $\delta z$.

Firstly, here are the coordinates of the point on the rail profile in SCR0

$$y_{r_0} = y_r + z_r (y_r) \alpha_r,$$

$$z_{r_0} = z_r (y_r) - y_r \alpha_r,$$

where $z_r$ is the coordinate of the point in SCR.

Then a point on the wheel profile with coordinates $y_w$ and $z_w$ in SCW should be found, which has the following abscissa in SCR0: $y_{w_0} = y_{r_0} - \Delta y$, Figure 8.88. Since the angle $\Delta \alpha$ is small, the following nonlinear relation takes place:

$$y_{w_0} = y_w - z_w (y_w) \Delta \alpha,$$

or

$$y_w = y_{w_0} + z_w (y_w) \Delta \alpha.$$

To solve this nonlinear equation relative to $y_w$, direct iterations
can be applied.

As it is known, direct iterations converge if the condition
\[
\left| \frac{dz_w}{dy_w} \Delta \alpha \right| < 1.
\]
takes place. Since \( \Delta \alpha \ll 1 \), this condition is always valid for real profiles.

Finally, the coordinate \( z_{w0} \) is computed from the formula
\[
z_{w0} = y_w \Delta \alpha + z_w(y_w) + \Delta z.
\]
and the value of minimized function \( \delta z(y_r) \) is evaluated.

In this way the algorithm allows us to compute a pair of points and the distance between them. The main advantage of the algorithms is its simplicity, reliability and independence on smoothness of profiles.

Computing the minimal value \( \delta z_{\text{min}} \) is executed according to the following algorithm. Consider a sequence of values of coordinate \( y_r \) with a contact step size \( h = 1 \text{ mm} \) and select the points with the minimal value \( \delta z \). After that the process is repeated near the found point with smaller step size (0.1 mm).

8.3.1.1.2. Computing tables of contact points

As it is already mentioned, computation of tables of contact geometry information is executed before start of the simulation, if the rail profile does not change along the track. This information is obtained in dependence on the wheel profile position relative to the rail profile. If we consider a rail as a massless element, there may be two possible contact types: one-point and two-point contact, (Figure 8.89).

![Figure 8.89](#)

Figure 8.89. Pairs of profiles allowing two-point contact (left) and one-point contact only (right)

In a one-point contact mode the contact point position depends on the lateral shift \( \Delta y \) and the angle \( \Delta \alpha \), Figure 8.88. Coordinates of the contact point correspond to the profile point with the minimal distance in the vertical direction (Sect. 8.3.1.1.1. "Algorithm for computation of nearest points between two profiles", 8-76). Thus, the table contains coordinates of the contact point in SCR and SCW for a discrete set of variables \( \Delta y_i, \Delta \alpha_j, i = 1,2 \ldots N_y, j = 1,2 \ldots N_\alpha \) with a proper step size of discretization.
Computation of one-point contact is realized according to the algorithm in Sect. 8.3.1.1.1. "Algorithm for computation of nearest points between two profiles", 8-76. Here we consider some features of computing a two-point contact.

Figure 8.90. Types of contact for a pair of profiles allowing two-point contact: one-point contact, two-point contact and creeping up

Considering that in case of one-point contact the coordinates computing is implemented using the algorithm, given in the previous paragraph, let us discuss the two-point contact computation aspects. Fix the value $\Delta \alpha$ and give the maximal value of the lateral displacement (Figure 8.90, left). In this position of the profile we have obviously a one-point contact. Now decrease $\Delta y$ without changing $\Delta \alpha$, i.e. shift the wheel profile to the left. There exists some critical value of the lateral coordinate $\Delta y^*$ for which a two-point contact occurs, if the profiles allow it (Figure 8.90, center). Further decreasing $\Delta y$ does not change coordinates of contact points, the rail profile will move to the left together with the wheel profile. This mode of the two-point contact can disappear in two different ways. Firstly, the wheel will move to the right and the flange contact disappears (Figure 8.90, left). Secondly, the contact on the running surface disappears (the corresponding normal force becomes zero) and the wheel goes to the creeping up state (Figure 8.90, right). This mental experiment is the base of an algorithm for computing the two-point contact. Let us consider the algorithm in details.

Let us choose the uniform discretization of the real change area of $\Delta \alpha$ and $\Delta y$ parameters. Now for each fixed value $\Delta \alpha_j$, $j = 1, 2, ..., N_\alpha$ compute coordinates of contact point on the running surface according to Sect. 8.3.1.1.1. "Algorithm for computation of nearest points between two profiles", p. 8-76 successively decreasing the lateral shift $\Delta y_i$, $i = N_y, N_y - 1, ..., 1$. If the profiles allow the two-point contact, the position of the contact point for some $\Delta y_i$ will change by a large enough jump. This fact means that the flange contact occurs inside the latest change of $\Delta y$. Denote this value of $\Delta y$ as $\Delta y^*$. Two conditions formalize the notion of a ‘large enough jump’ and give a criterion of passing through the two-point contact:

$$y_{r,i} - y_{r,i-1} > \eta_y, \quad n_{r,y}/n_{r,z} > \eta_n,$$

where $y_{r,i}$, $y_{r,i-1}$ are the successive coordinates of the contact point on the rail (in SCR), $n_{r,y}$, $n_{r,z}$ are the projections on the normal to the rail profile at the contact point at the latest step, $\eta_y$, $\eta_n$ are some empirical criterion numbers, e.g. $\eta_y = 20 \, \text{mm}, \eta_n = 0.5$. Thus, the two-point contact is considered to be found, if the contact coordinate on the rail profile changes by a large jump, and the new coordinate of the contact point lies on the side of the rail. Value of parameters $\eta_y$, $\eta_n$ can be modified by the user, Sect. 8.4.2.7.3. "Rail/wheel contact options", p. 8-184.

After confirmation of the fact, that the state of the two-point contact is crossed, the interval $y_{r,i-1}, y_{r,i}$ is discretized on small subintervals (about 0.1 mm), and the critical value $\Delta y^*_j$ is defined more exactly.

To model the wheel climb process, the computation is continued for $\Delta y > \Delta y^*_j$. 
The computations are repeated for other values of the angle $\Delta \alpha_j$.

The contact tables contain coordinates of contact points for various values $\Delta \alpha_j, \Delta y_i$ as well as the critical values of the lateral shift $\Delta y_j^*$ for each value of the angle $\Delta \alpha_j$.

Computation of two-point contact geometry assumes evaluation of a wheel "overswing" $x_c$, i.e. the longitudinal coordinate of the flange contact for nonzero value of the angle of attack $\gamma$. UM uses an approximate analytic expression for obtaining the value of this parameter. To get it consider a simplified geometrical model of the flange-rail contact, Figure 8.91. In this model the side surface of the rail near the contact is replaced by a plane with the same normal, and the flange is replaced by a circle with a radius equal to the wheel radius at the contact.

![Figure 8.91. Simplified model of the flange contact for computing a overswing](image)

Let $\gamma$ be the angle of attack, $\varphi$ is the angle defining the flange contact with the overswing. The $\varphi$ value can be found from the condition that the tangent to the flange circle at contact is perpendicular to the plane normal $\mathbf{n} = (0 \quad -n_{ry} \quad n_{rz})^T$. The unit tangent vector in SC of the wheelset base is set by the following expression

$$\mathbf{\tau} = (r_w \cos \varphi \quad 0 \quad r_w \sin \varphi)^T$$

where $r_w$ is the wheel radius at the flange contact.

Introducing the direct cosine matrix corresponding to the angle of attack,

$$\mathbf{A}_{01} = \begin{pmatrix} \cos \gamma & -\sin \gamma & 0 \\ \sin \gamma & \cos \gamma & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

yields the following orthogonal condition

$$\mathbf{n}^T \mathbf{A}_{01} \mathbf{\tau} = 0$$

or, taking into account that angles $\gamma$ and $\varphi$ are small,

$$-n_{ry} \gamma + n_{rz} \varphi = 0$$

For small angles the overswing can be found as $x_c = r_w \varphi$, which results in the final formula

$$x_c = r_w n_{ry}/n_{rz}.$$
8.3.1.1.3. Simplified contact geometry. Equivalent conicity and contact angle parameter

Sometimes it is important to analyze the behavior of a vehicle depending on the wheel/rail profile wear level without exact profiles curves, and taking into account on the important notions of equivalent conicity and contact angle parameter.

Consider definitions of these parameters.

8.3.1.1.3.1. Equivalent conicity

Consider a pair of rail/wheel profiles in a contact. When the wheel profile shifts in the lateral direction on distance $y$, the contact point changes its position of the profile curves. Let $\Delta r_l(y)$, $\Delta r_r(y)$ be changes in radii of the left and right wheels. The value $\Delta r = \Delta r_l - \Delta r_r$ is noted as the Rolling Radius Difference (RRD), and its plot depending on the lateral shift is used for evaluation of the equivalent conicity of a pair of profiles.

![Figure 8.92. A pair of new profiles: R65 and Russian wagon wheel (left); the corresponding RRD (right)](image1)

![Figure 8.93. A Pair of profiles: R65 and DMetI (left), the corresponding RRD (right)](image2)

For the new R65 and wagon wheel profile the RRD is a straight line in the region of one point contact. The tangent of the line inclination angle is equal to the double wheel profile conicity $\lambda = 1/20$. Figure 8.92. Really, the wheel profile function is

$$r_l = r_0 + \lambda y, \quad r_r = r_0 - \lambda y,$$

and $\Delta r = 2\lambda y$
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RRD for worn of curved profiles are non-linear even for small shifts of the wheelset, Figure 8.93. In this case the notion of equivalent conicity $\lambda$ is introduced as a mean value for a definite lateral shift of the wheelset $\Delta y$, according to the formula

$$\min_{\lambda} \int_0^{\Delta y} f(y)(\Delta r(y) - 2\lambda y)^2 dy,$$

(8.1)

where $f_y$ is the distribution function for the lateral shift $y$. Thus, the equivalent conicity is computed to fit the nonlinear RRD by a linear function on the $\Delta y$ interval. Often $\Delta y$ is the shift of the wheelset corresponding to the start of the flange contact. The normal distribution

$$f(y) = \frac{1}{\sigma \sqrt{2\pi}} e^{\frac{y^2}{2\sigma^2}},$$

is used in Eq. (1.1) in the current UM version. The default value of the standard deviation is $\sigma = 2.5 \text{ m.m.}$.

Differentiating Eq. (1.1) with respect to $\lambda$ yields the formula for the equivalent conicity as

$$\lambda = \frac{\int_0^{\Delta y} yf(y)\Delta r(y)dy}{2\int_0^{\Delta y} f(y)y^2 dy}.$$  

### 8.3.1.3.2. Contact angle parameter

Contact angle $\beta$ is the angle between the normal to the profiles at the contact point and the perpendicular to the track plane, which is vertical for tangent sections, Figure 8.94.

The designation $\beta_l(y), \beta_r(y)$ are introduced for the contact angles of the left and right wheels depending on the wheelset shift. If the left and right pairs of profiles are equal, the value $\beta_l(0) = \beta_r(0) = \beta_0$ corresponds to the contact angle for symmetric position of the wheelset.

![Figure 8.94. Contact angle](image)

The dependence
 \[ E(y) = \frac{\beta_l(y) - \beta_r(y) S}{2} \]

on the lateral shift is used for definition of the contact angle parameter. Here \( S \) is the distance between the wheelset rolling radii, Figure 8.8.

The contact angle parameter \( \varepsilon \) is used for linear approximation of the function \( E(y) \) on the interval \( \Delta y \) of the lateral shift of the wheelset.

\[ E(y) = \frac{\beta_l(y) - \beta_r(y) S}{2} \approx \varepsilon y. \]

The formula is similar to the equivalent conicity is used for evaluation of \( \varepsilon \)

\[ \varepsilon = \frac{\int_0^{\Delta y} yf(y)E(y)dy}{2 \int_0^{\Delta y} f(y) y^2dy}. \]

### 8.3.1.3.3. Simplified geometry of contact

The following simplified formulae are used for evaluation of wheel radii at contacts and for contact angles depending on the lateral shift of the wheelset in terms of the equivalent conicity and contact angle parameter:

\[ r_l = r_0 + \lambda y_l, \quad r_r = r_0 - \lambda y_r, \]
\[ \beta_l = \beta_0 + \frac{2\varepsilon y_l}{S/2}, \quad \beta_r = \beta_0 - \frac{2\varepsilon y_r}{S/2}. \]

Here \( y_l, y_r \) are lateral shifts of the left and right wheels relative to the corresponding rails, which are in general different due to the elastic deflections of rails.

If the lateral shift of a wheel towards the rail is greater than some given value \( y^* \) then a double contact takes place. The contact point position on the side of the rail is specified by the coordinates of in the SCR \( (y^*_l, z^*_l) \) and by flange angle \( \beta^* \). The longitudinal contact overswing is computed according to the results of the previous section.
8.3.1.2. Contact forces

8.3.1.2.1. Method for computation of rail deflections and contact force

A rail model as a massless element is based on the following assumptions:

- deflections of a rail for different wheelsets are independent and can be computed separately;
- deflections of the left and right rails are independent;
- rail deflections include independent lateral $\Delta y_r$, vertical $\Delta z_r$ deflections (Figure 8.96), which are parallel to the corresponding SC of the track;
- the rail as a linear force element both in the lateral and vertical directions; the lateral dissipation is taken into account for two-point contact mode only.

![Figure 8.96. Rail as massless force element](image)

Let $c_y, c_z$ be the lateral and the vertical stiffness of the rail, $d_y, d_z$ be the corresponding damping constants. Forces acting on the rail due to the deflections are the following:

$$
R_y = -c_{ry} \Delta y_r - d_{ry} \dot{\Delta y}_r, \\
R_z = -c_{rz} \Delta z_r - d_{rz} \dot{\Delta z}_r,
$$

(8.2)

where $c_{ry}, c_{rz}, d_{ry}, d_{rz}$ are stiffness and damping coefficients of rail in lateral and vertical directions correspondingly.

Because the rail has no mass, these forces must be balanced by contact forces acting on the rail from the wheel. The contact forces acting on the wheel for one- and two-point contacts are shown in Figure 8.97. Longitudinal forces are not shown in this figure.
Equilibrium equations for one-point contact written in SC of the track are

\[ R_y - F_1 \cos \beta_1 + N_1 \sin \beta_1 = 0, \]
\[ R_z - N_1 \cos \beta_1 - F_1 \sin \beta_1 = 0. \] (8.3)

Analogous equations are valid for a two-point contact

\[ R_y - F_1 \cos \beta_1 + N_1 \sin \beta_1 - F_2 \cos \beta_2 + N_2 \sin \beta_2 = 0, \]
\[ R_z - N_1 \cos \beta_1 - F_1 \sin \beta_1 - N_2 \cos \beta_2 - F_2 \sin \beta_2 = 0. \] (8.4)

Here \( \beta_1, \beta_2 \) are the angles between the normal to the rail at contact and the axis perpendicular to the track.

Eq. (1.3) for a one-point contact and (1.4) for a two-point contact are complicated systems of nonlinear algebraic equations relative to unknown deflections of the rail and normal reactions \( N_1, N_2 \). Consider the main ideas for their solving without going into details.

- Position of the wheel as well as the rail shift due to irregularities, gauge widening and cant are known by computing the contact problem; the only unknown are deflections \( \Delta y_r, \Delta z_r \) and their time derivatives. Note that the vertical deflection \( \Delta z_r \) is not an independent variable because when the lateral \( \Delta y_r \) deflection is known, the value of \( \Delta z_r \) can be obtained from the geometry of the contact. This value is equal to the value \( \delta z \), Sect. 8.3.1.1.1. "Algorithm for computation of nearest points between two profiles", p. 8-76.

- Calculation of the rail deflections and contact forces is an iterative process. Iterations include two cycles: internal and external. The internal iterations are used for solving equations (1.3), (1.4) for known values of tangential forces (lateral creep forces). External iterations calculate creep forces. Values of creep forces on the previous integration step are used as initial approximations. Thus, the contact computation looks like this: internal cycle of iterations computes lateral deflection of the rail and normal force/forces in contact/contacts, the lateral creep forces are taken from the previous step. After that the new values of creep forces are computed. When the new values differ from the previous ones more than an error tolerance, the external iterations start, and equations (1.3), (1.4) are solved for corrected values of creep forces.

Consider some features of realization of internal iterations.

1. Lateral deflection \( \Delta y_r \) is the sum of two components: \( \Delta y_r = \Delta y_{r1} + \Delta y_{r2} \).
• The first component corresponds to the rail deflection by forces at the first contact point, the second one differs from zero by the two-point contact and results from the forces at the flange contact $N_2, F_2$.
• The previous value of the $\Delta y_{t1}$ variable is used as the initial value for iterative solving the equilibrium equations. Iterations make the value more accurate.

2. Each of the iterations includes:
• Evaluation of the wheel profile position relative to the rail $\Delta y, \Delta \alpha$ according to the known data (position of the wheel, irregularities, gauge widening etc. These parameters are used for determination of the contact type (one- or two-point) as well as for interpolation of coordinates of the contact point (or points) with the help of the preliminary computed tables (Sect. 8.3.1.1.2. "Computing tables of contact points", p. 8-78), computing the vertical rail deflection $\Delta z_r$, the angle $\beta_1$ (and $\beta_2$ for the two-point contact). The second part of the rail deflection $\Delta y_{t2}$ is computed from the geometrical conditions.
• Forces $R_y, R_z$ are computed according to Eq. (1.2).
• The normal force $N_1$ for a one-point contact is obtained from Eq. (1.3); in the case of a two-point contact the normal reactions $N_1$ and $N_2$ are computed from Eq. (1.4).

3. The new value of the deflection $\Delta y_{t1}$ is computed and stored for the next iterations.

8.3.1.2.2. Algorithms for computing creep forces

![Image of Creepages, spin and creep forces](image)

Figure 8.98. Creepages, spin and creep forces

Modern models of tangential forces in a wheel-rail contact are based on nonlinear dependencies of the general form:

$$F_x = F_x(N, \xi_x, \xi_y, \varphi, f, p), \quad F_y = F_y(N, \xi_x, \xi_y, \varphi, f, p).$$

Here the following notations are used:
• $F_x, F_y$ are the longitudinal and lateral creep forces lying in the tangential plane of the rail;
• $N$ is the normal force in the contact;
• $\xi_x, \xi_y$ are the longitudinal and lateral creepages;
$\varphi$ is the spin;

$f$ is a friction coefficient in contact point;

$p$ is a set of geometrical parameters characterizing rail and wheel profiles, e.g. curvatures of contact surfaces in the case of the FASTSIM algorithm.

As it is known, the creepages and the spin satisfy the following relations:

$$\xi_x = \frac{v_x}{v_0}, \quad \xi_y = \frac{v_y}{v_0}, \quad \varphi = \frac{\omega_n}{v_0},$$

where $v_x, v_y$ are the corresponding components of sliding velocity at the contact point on the wheel relative to the rail; $v_0$ is the longitudinal velocity of the wheelset; $\omega_n$ is the projection of the wheel angular velocity on the normal to the rail at the contact point.

**Note.** For slow-speed movements up to the zero value initial velocity when $v_0 < v_0^*$ = 0.1 m/s the following formulae to compute creep and spin are applied:

$$\xi_x = \frac{v_x}{v_0^*}, \quad \xi_y = \frac{v_y}{v_0^*}, \quad \varphi = \frac{\omega_n}{v_0^*},$$

Parameter $v_0^*$ is the **critical speed for creep computation**, which value can be changes by the user, see Sect. 8.4.2.5. "Parameters for computation of rail-wheel contact forces", p. 8-168.

For the wheel contact model with the massless rail the following algorithms for creep forces computing are implemented: *Mueller’s method, Minov’s method, FASTSIM, FASTSIM_A.*

### 8.3.1.2.2.1. Mueller’s model

*Mueller’s* method is the simplest one for computation of the creep forces according to the following analytic expressions:

$$F_{xy} = \frac{1000k_c}{m} \sqrt{\frac{\xi}{1 + \frac{k_c\xi}{fP}^m}},$$

$$\xi = \sqrt{\xi_x^2 + \xi_y^2}, \quad P = 0.001N, \quad k_c = (235 - (2.4 - 0.01P)P)P$$

$$F_x = -\xi_x F_{xy}, \quad F_y = -\xi_y F_{xy}.$$ 

Thus, the model is very simple. In particular, forces do not depend on the spin. If the two-point contact is presented, forces at the flange contact are computed as simple friction forces in the sliding mode.

Some advantage of the algorithm consists in its simplicity. The disadvantage is its lower accuracy especially for a one-point flange contact where the spin is not small.

**Note.** Mueller’s method is also used to compute creep forces at a simplified profile setting using the equivalent conicity and contact angle parameter (see Sect. 8.3.1.1.3.3. "Simplified geometry of contact", p. 8-83).
8.3.1.2.2.2. Minov’s model

The method is used in simulation of locomotive in traction modes, and based on experimental dependence of adhesion force on creep. Figure 8.99. K.D. Minov supposed an analytic approximation for this curve consisting of three sections:

1. $0 \leq |\xi| \leq 0.0014$: linear section of elastic sliding
   
   $$ k = 359.6117|\xi| $$

2. $0.0014 \leq |\xi| \leq 0.025$: nonlinear section of elastic sliding
   
   $$ k = \frac{350|\xi| - 0.155}{0.195 + 336|\xi|} $$

3. $|\xi| > 0.025$: sliding
   
   $$ k = \frac{1}{1 - \chi v_0 (0.025 - |\xi|)} $$

where $k$ is the ratio of the force to its maximal value; $v_0$ is the vehicle speed, m/s; $\chi$ is the stiffness of the third section of the curve, s/m. The stiffness $\chi$ depends of the speed $v_0$ as in the Table 8.2.

<table>
<thead>
<tr>
<th>$v_0$, km/h</th>
<th>0-5</th>
<th>5-20</th>
<th>20-40</th>
<th>40-120</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi$</td>
<td>0.9</td>
<td>0.6</td>
<td>0.5</td>
<td>0.35</td>
</tr>
</tbody>
</table>

![Figure 8.99. Sticking coefficient versus creep in the Minov’s model](image)

Creep forces are computed according to the formulas

$$ F_{xy} = f \cdot N \cdot k(|\xi|), $$
In case of a two-point contact, the flange friction forces are computed as for the pure sliding.

Minov’s method allows to calculate creep forces for locomotives in traction mode (braking) and to simulate electro-mechanical processes in coupling failure. The advantage of the algorithm is in its simplicity and high-speed computing.

8.3.1.2.2.3. FASTSIM

FASTSIM algorithm, based on Kalker’s creep forces linear theory [2], has become a standard of creep forces computing in rail-wheel contact in the multibody dynamics software for rail vehicle dynamics simulation.

The following parameters and variables are the initial data for FASTSIM algorithm.

- **Rail and wheel material properties**, which are supposed to be equal (Young’s modulus and Poisson’s ratio) are set by the user;
- **Current geometric characteristics of the contact point**: principal curvatures of the contact surfaces are computed by the program;
- **The normal force** $N$ in the contact is computed by the program.
- **Semi-axis of the elliptic contact patch** are calculated by the program using Herz’s theory in the dynamic modeling process;
- **Longitudinal and lateral creepages and spin** are calculated by the program in the dynamic modeling process;
- **Friction coefficient in the contact point** is calculated by the program in the dynamics modeling process using parameters defined by user.

![Discretization of the contact patch](image)

Figure 8.100. Discretization of the contact patch

According to this data FASTSIM solves a system of differential equations (in the adhesion area of the contact patch) or a system of differential-algebraic equations (in the sliding area of the contact patch) relative to tangential stresses. For this purpose the contact ellipse is divided into a
number of narrow slices of the same width. In turn, each slice is divided into \( n \) elements of equal length within one slice (Figure 8.100). Number of slices \( m \) and elements \( n \) is set by the user. The default values are 10.

To compute the creep forces and to obtain adhesion and sliding areas of the patch, \textit{FASTSIM} solves the above equations for each of the slice successively. In fact, the discretization on elements gives the constant step size for numeric solving the differential equations by the explicit Euler method. Thus, CPU expenses are of order \( m \times n \) operations, and depend on the discretization level.

8.3.1.2.2.4. \textit{FASTSIM\_A}

\textit{FASTSIM\_A} is a semi-analytic modification of the classical \textit{FASTSIM} algorithm. For a slice it was found an exact solution of the \textit{FASTSIM} governing differential equations in the adhesion area of the contact patch and an approximate analytic solution for differential-algebraic equations in the sliding area. The solution was implemented in UM as \textit{FASTSIM\_A} (\textit{FASTSIM} – Analytic) procedure. The number of operation for computing creep forces is proportional to the number of slices \( m \). The procedure for \( m = 10 \) is at least two times faster than \textit{FASTSIM} and gives quite similar numeric results for computing creep forces in case of moderate spin values \((\varphi < 0.5)\) [3].

8.3.1.2.2.5. Non-elliptical contact model

Taking into account that the bodies in contact are quasi-identical, i.e. material properties of wheel and rail are the same, the contact problem can be divided into two independent ones: the normal contact problem and the tangential contact problem.

**Normal Contact Problem.** An approximate contact patch is defined in the following way. The wheel and the rail are considered as a body of revolution and a cylindrical surface, respectively. The surfaces are intersected in a depth \( \delta \) as rigid bodies, Figure 8.101. The function \( u(x,y) \) specifies the interpenetration of the surfaces at the point \((x, y)\). It satisfies the linearized equation

\[
    u(x, y) = \delta - z(x, y), \quad z(x, y) = \frac{x^2}{2R} + h(y),
\]

where \( z(x,y) \) is the function, which specifies the distance between the points of the bodies for \( \delta = 0 \), \( R \) is the wheel radius at the contact point, \( h(y) \) is the distance between the points of profiles in \( x=0 \) plane.

Edge of the approximate contact patch is determined as a line of intersection of the surfaces, Figure 8.101. The dependence of the intersection line on the lateral coordinate is

\[
    a(y, \delta) = \sqrt{2R(\delta - h(y))}
\]

The roots \( y_i \) of the equation

\[
    \delta = h(y)
\]

determine the length of the patch along the lateral axes. The number of separate zones of the contact is equal to a half of the number of the roots.

So the contact area is a function of the surfaces of the contacting bodies and the interpenetration \( \delta \). Since the surfaces are always given functions we have the only unknown value \( \delta \).
The materials of the bodies are assumed to be homogeneous, isotropic and elastic. Since the size of the contact patch is small in comparison to the characteristic sizes of wheel and rail, the contact stress does not depend on the shape of the contacting bodies distant from the contact patch. In this case, the contacting bodies can be considered as elastic half spaces. By using the half space method, the value of $\delta$ can be estimated. The deflection at point $(0, 0)$ can be found with the help of the Boussinesq's influence function as

$$w(0,0) = \frac{1 - \nu^2}{\pi E} \iint_\mathcal{C} \frac{p(x,y)}{\sqrt{x^2 + y^2}} \, dx \, dy$$  \hspace{1cm} (8.8)$$

where $p(x, y)$ is the distribution of the normal pressure, $\mathcal{C}$ is contact area. According to the assumption about materials, the wheel and rail deflections at contacting points are equal, thus $\delta = 2\omega(0, 0)$. But in reality, the bodies at contact cannot interpenetrate and deflections occur, so the interpenetration region encloses the contact patch if the influence function is unidirectional. Granting this fact, the bodies are interpenetrated in the depth $\delta_0 < \delta$, Figure 8.101.

To find the normal pressure distribution $p(x,y)$ in the contact area, the elastic Winkler foundation model, i.e. the assumption about proportionality between stress and interpenetration $u(x,y)$ was used. So the distribution of the normal pressure is set as

$$p(x,y) = k_p u(x,y)$$  \hspace{1cm} (8.9)$$

where $k_p$ is a proportionality factor.

In UM rail-track model, the rail is considered as a massless body on a viscous-elastic foundation and the normal force $N$ at the contact point is available from the solution of rail equilibrium equations. The interpenetration of the bodies is only used to compute the normal pressure distribution and the approximate contact patch, and its small value can be neglected in the dynamic equations. Thus, the normal force depends on the quite small vertical and lateral stiffness of the rail-track system and this model is not stiff.

Using Equations (1.5) – (1.9) the interpenetration in the case of single zone in the contact patch is
The normal contact force is calculated as

$$\delta = 2w(0,0) = 2 \frac{1 - v^2}{\pi E} k_p \sum_{i=1}^{n} \int_{y_{2i-1}}^{y_{2i}} \int (\delta - h(y)) \cdot \ln \left( \frac{a_i + \sqrt{a_i^2 + y^2}}{|y|} \right) - \frac{a_i}{4R} \sqrt{a_i^2 + y^2} \, dy.$$

Using Equations (1.10), (1.11) the following nonlinear equation are obtained:

$$N = \frac{\delta \pi E}{2(1 - v^2)} \cdot \int_{b_1}^{b_2} \left( \delta - h(y) + \frac{y^2}{4R} \right) \cdot \ln \left( \frac{a + \sqrt{a^2 + y^2}}{|y|} \right) - \frac{a}{4R} \sqrt{a^2 + y^2} \, dy.$$

The solution of Equation (1.12) is the interpenetration $\delta$. Taking into account that $\delta_0 < \delta$, the approximate contact patch is found and then using equation (1.11) the proportionality factor $k_p$ is calculated. Substituting the value of $k_p$ in equation (1.9) the distribution of the normal pressure over the contact area is obtained.

**Tangential contact problem.** The FASTSIM algorithm, which was adapted for non-elliptical contact area, is used to solve the tangential contact problem. To determine the value of flexibility an equivalent ellipse such, that the area of the non-elliptical patch is equal to the area of the ellipse, is calculated. The semi-axis of the ellipse in the rolling direction is set equal to the maximal half-length of the non-elliptical patch.

**8.3.2. Computation of contact between the wheel and the inertial rail**

When a rail is considered as an inertial element (rigid body or flexible beam) then in a wheel-rail contact the rigid interpenetration of wheel and rail profiles is allowed. At the same time, the amount of contact points is formally unlimited. The function of the distance between the undeformed profiles defines the form and size of the contact patches.

Modification of the algorithm, described in Sect. 8.3.1.1.1. "Algorithm for computation of nearest points between two profiles", p. 8-76, is used to define the points of intersection of profiles. It is obvious that the point of intersection of profiles is determined if the value $\delta z$ has changed its sign.

Coordinates of contact points in the profiles coordinate system are defined using the following system of equations:

$$\begin{cases} \mathbf{n}_w \times \mathbf{n}_r = 0, \\ \mathbf{n}_r \times \mathbf{d} = 0, \end{cases}$$

where $\mathbf{n}_w$ and $\mathbf{n}_r$ are the normals to the wheel and rail profiles in CSR0, $\mathbf{d} = \mathbf{r}_{p_r} - \mathbf{r}_{p_w}$, see Figure 8.102.
This system of vector equations defines the two points corresponding to the maximum interpenetration of the wheel and rail profiles. The first equation of the system defines the condition of collinearity of the normals to the profiles in the points. The second equation defines the condition of collinearity of the one of the normals to the radius vector which connects the points. System of vector equations forms the system of two non-linear algebraic equations relative to $y_r$ and $y_w$. A good initial approximation when solving the obtained system using Newton-Raphson algorithm is the two points that fit the minimum condition of the function $\delta z$ in the considered area of the profiles intersection. If smoothness of the profiles does not provide the convergence of Newton-Raphson's method, then the brute-force method for finding contact points is used.

It takes too much computational efforts (up to 60% of CPU time) to define the points of intersection of profiles and to search contact points. If the rail profile is constant along the track, the calculation of the coordinates of the potential contact points is performed once before the start of the modeling process. The coordinates of the potential contact points depending on the discreet shifting of the wheel profile relative to the rail profile are written in tables. At the same time it is considered that the wheel profile relative to the rail profile has two degrees of freedom: rotation around the longitudinal axis and lateral displacement. The potential contact points are the points in which the value $\delta z$ has the minimum, see Figure 8.103. In the simulation process for the current profiles position the potential contact points are computed with the help of the precalculated tables with interpolation usage.
After finding the contact points for each potential contact area, the local coordinate system of the contact patch (SCC) is introduced. SCC origin is located in contact point on the rail profile, Z-axis is directed along the normal to the wheel and rail profiles, Y-axis is directed along the tangent. The function of the distance between the undeformed profiles is defined in SCC, Figure 8.104.
Creeps and spin are computed according to the following formulas:

\[\xi_x = \frac{(v_w - v_r)\tau_1}{v_0}, \quad \xi_y = \frac{(v_w - v_r)\tau_2}{v_0}, \quad \varphi = \frac{(\omega_w - \omega_r)n}{v_0},\]

where \(v_w, v_r\) are the forward velocities of the contact point; \(\omega_w, \omega_r\) are the angular velocities of a wheelset and rail respectively. \(\tau_1, \tau_2, n\) are the tangents and normal to the contact point in CSR0; \(v_0\) is the longitudinal velocity of the wheelset.

Contact forces are computed using the models by W. Kik and J. Piotrowski [4] or CONTACT program [5]. In the model by W. Kik and J. Piotrowski FASTSIM algorithm, modified for non-elliptical contact patches, is used to compute creep forces.

Use the following formula to calculate the total normal reaction:

\[N = N_e + N_d,\]

where \(N_e\) is an elastic force (which is computed using the corresponding contact forces model), \(N_d\) is a damping force.

\[N_d = 2\zeta \sqrt{c_cm_w}\delta\left|\text{sign}\left(\delta\right) - 1\right| \frac{1}{2}\]

where \(\zeta\) is a damping ratio, \(c_c\) is a contact stiffness, \(m_w\) is a mass of the wheel, \(\delta = (v_w - v_r)n\) is a penetration velocity.
8.3.3. Coefficient of friction in wheel-rail contact

UM uses both variable and constant coefficients of friction in contacts of the wheel and rail. Two main coefficients of friction are introduced for each of two rails. The first one is the coefficient of friction on the rail running surface $f_r$, the second one is on the inward rail side $f_s$. These coefficients are defined either by numeric constants or by functions of the longitudinal coordinates along the track $f_r(x), f_s(x)$ or on time $f_r(t), f_s(t)$.

If the coefficients for a given longitudinal position have different values, i.e. $f_r \neq f_s$, the coefficient of friction is considered as a variable one on the rail profile in the lateral direction.

As a result, the profile is divided into three parts, Figure 8.105. The first one is the running surface with a constant coefficient $f_r$. The second part is the inward side of the rail with the coefficient $f_s$. Finally, a transient section between the previous two parts, where the coefficient changes continuously from $f_r$ to $f_s$. The transition is linear in the angle $\beta$. To divide the profile on these sections, the angles $\beta_r, \beta_s$ should be set.

Dependences of the coefficient of friction on the longitudinal coordinate allow the user to model e.g. an oil stain on a rail.

Different values of the coefficient on the running surface of the rail and on its side are used mainly for modeling lubrications in curves.

Dependence of the coefficient of friction on sliding velocity is implemented in UM 6.0 according to the model [6]

$$ f = f_0 \left( (1 - A) e^{-Bv_1} + A \right), $$

Here $f_0$ is the coefficient value for zero sliding, $A = f_\infty/f_0$ is the ratio of coefficient for infinite and zero sliding velocities, $B$ is the factor of exponential decrease of the coefficient of friction.

Decrease of the coefficient of friction is shown in Figure 8.106 for $A = 0.4$, $B = 0.6$ s/m.
Figure 8.106. Decrease of coefficient of friction with the growth of sliding velocity
8.4. Simulation of railway vehicles

8.4.1. Tools for preparing simulation process

8.4.1.1. Creation of wheel and rail profiles

Wheel and rail profiles are located in the \{UM Data\}\rw\prf directory in form of separate files with extension *\.wpf (wheels) and *\.rpf (rails). The profiles are described in a special systems of coordinates (Sect. 8.1.3.5. "Wheelset geometry", p. 8-13, Sect. 8.2.1.1. "Geometry of rails in an ideal track", p. 8-66) with the help of a special tool, which is available in the UM Simulation program by clicking the Tools | Railway wheel and rail profile editor. Creation of new profiles and modification of old ones are made with the help of the Curve editor (Figure 8.107). Detailed description of the editor can be found in Chapter 3, Sect. Object constructor/Curve editor. Creation of new profiles is possible in two modes:

- input as a set of points with successive spline approximation;
- input of profiles as a set of line segments and circle arcs.

The second type of the profile description is used mainly for new standard profiles.

![Figure 8.107. Editor of curves for creation of profiles](image)
8.4.1.1.1. Input as a set of points with successive spline approximation

Use either list of points in the left part of the editor window or clipboard for input of a profile as a set of points. The points must be ordered from the left to the right (according to increase their abscissa). The unit for data is millimeter.

Figure 8.108. Input as a set of points

For input from the clipboard points should be written as a text in two columns. The first column contains abscissa values, the second one – the ordinate values:

-68.9  11.7
-66.4  8.88
-63.9  6.98
-61.4  6.48
-58.9  5.99

To set points from the clipboard to do the follows:
- clear the editor;
- copy the new data to the clipboard from any text editor in a standard manner;
- activate the curve editor by the mouse and paste data from the clipboard (Ctrl+V or Shift+Insert).

When all the points are set into the editor, select the single profile by the mouse and set the B-spline interpolation type (Figure 8.110).

Save the profile with the help of the button on the toolbar of the editor.

Remark 1. It is not recommended to use step size for abscissa less than 1 mm. Otherwise the first derivative plot might look as a saw, and the curvature plot might have large overfall, see Figure 8.109. Such cases may lead to deterioration of the contact
Remark 2. Smoothed profile curvature is used by computation of creep forces with the help of the FASTSIM algorithm.

8.4.1.1.2. Input of profiles as a set of line segments and circle arcs

To create a profile as a set of line segments and circle arcs:
1. set coordinates of end points of line segments and arcs as a broken line from the left to the right (increasing abscissa);
2. select by the mouse a section of a sequence of sections, which should be replaced by circle arcs and set the Circle item as the type of sections (Figure 8.111);
3. save the profile.

Figure 8.111. Creation of profile as a set of line sections and circle arcs
8.4.1.1.3. Tool for analysis of pairs of profiles

The tool for analysis of profiles is available in the simulation program for the current values of the track gauge and rail inclination (Sect. 8.2.1.1. "Geometry of rails in an ideal track", p. 8-66). Use the Tools | Analysis of pairs of profiles menu command.

Container with profiles

The container contains lists of wheel (left) and rail (right) profiles located in the standard directory {UM Data}\rw\prf.

To add profiles from other directories to the list, click the right mouse button on the corresponding part of the container, select one of two menu commands (‘without sorting’ adds profiles to the end of the list ), and open the file with the help of the standard dialog window.

Selection of a pair of profiles

To choose profiles for analysis, select them in the lists by the mouse Figure 8.112, and click the Read button on the top of the window.
Analysis of results

The following results are available with the tool.

![Figure 8.113. Type of contact and flange clearance on a side](image)

- **Type of contact** (one or two-point contact), Figure 8.113.
- **Clearance** is the lateral shift of the wheel relative to the rail, which leads to double contact (for profiles allowing a two-point contact), Figure 8.113.

![Figure 8.114. Equivalent conicity and contact angle parameter](image)

- **$\lambda, \varepsilon$** – Equivalent conicity and contact angle parameter, Sect. 8.3.2. "Computation of contact between the wheel and the inertial rail", p. 8-92. The parameters are computed for given values of the standard deviation of the lateral shift (RMS, mm) and averaging interval, Figure 8.114.

The following graphic information is available depending on the option selected in the Draw group.

- **Position** shows contact points for different values of the wheel shift relative to the rail $dY$ as well as small wheel rotation angle relative to the longitudinal axis $dA$, Figure 8.111. To change values of $dY$ (mm) and $dA$ (degrees), use either track bars or direct input in the text boxes. After direct input in a text box, use the Enter key to redraw the contact. The angle $dA$ changes in the interval from -1.4 to 1.4 degrees.
Figure 8.115. All contacts of a pair of profiles

- **All contacts**: contacts on rail and wheel profiles for different values of lateral shift are connected by segments. The thick segment corresponds to the current value of the shift.
- **RRD** option draws the rolling radius difference curve, Sect. 8.3.2. "Computation of contact between the wheel and the inertial rail", p. 8-92.
- **dY/Y** is Y coordinates of contact point on rail and wheel profiles in SC of the corresponding profile depending on the lateral wheel shift.
- **Beta** is the contact angle versus lateral wheel shift, Figure 8.94.
- **(BL-BR)/2*L/2** plot of the function
  
  \[ E(y) = \frac{\beta_l - \beta_r}{2} S \frac{y}{2} \]

  used in computation of contact angle parameter, Sect. 8.3.1.1.3. "Simplified contact geometry. Equivalent conicity and contact angle parameter", p. 8-81.
8.4.1.1.4. Automatic generation of new rail profiles

New (not worn) rail profiles can be easily created with a special tool. To open the tool, use the Tools | Rail-profile generator… menu command or the button on tool panel followed by the same command, Figure 8.116. The default numerical data in the table of the generator correspond to the new Russian rail R65.

To create a profile, the following steps are necessary.

- Set values of geometric parameters, which sense is clear from Figure 8.116b.
  
  If the type 1:n is chosen for the angle unit, a conicity should be set instead of the angle, i.e., the tangent of the corresponding angle. For instance, the value 0.25 corresponds to the conicity 1:4 in Figure 8.118, and the value 0.05 corresponds to the conicity 1:20.

- Use the button in Figure 8.116a to see the generated profile, and the button for saving. The button sets back the profile scheme in Figure 8.116b.
Remark. Generator creates both *.rpf file with the rail profile data, and the *.img file for contact animation window, Figure 8.118.

Algorithm for computation of profile

Consider mathematical relations, which are used for computation of the rail profile by geometrical data in Figure 8.115. Computational scheme of the profile is shown in Figure 8.118.

Angles $\alpha_1$ and $\alpha_3$ are computed from the formulas
\[ \alpha_1 = \arcsin \frac{d}{2R_1}, \alpha_3 = \frac{\pi}{2} - \alpha. \]

Projections on abscissa and ordinate axes yield two main equations

\[ (R_1 - R_2) \sin \alpha_1 + (R_2 - R_3) \sin \alpha_2 + R_3 \cos \alpha + h \tan \alpha = \frac{D}{2}, \]

\[ R_1 - [(R_1 - R_2) \cos \alpha_1 + (R_2 - R_3) \cos \alpha_2 + R_3 \sin \alpha] + h = H - \frac{D}{2} \tan \beta \]

relative to the unknown parameters \( \alpha_2 \) and \( h \). Shift of known terms into the right hand side of equations leads to

\[ (R_2 - R_3) \sin \alpha_2 + h \tan \alpha = \alpha_1, \]

\[ -(R_2 - R_3) \cos \alpha_2 + h = \alpha_2, \]

Where

\[ a_1 = \frac{D}{2} - (R_1 - R_2) \sin \alpha_1 - R_3 \cos \alpha, \]

\[ a_2 = H - \frac{D}{2} \tan \beta - R_1 + (R_1 - R_2) \cos \alpha_1 + R_3 \sin \alpha. \]

Eliminating the parameter \( h \) from the first equation gives the following expression for evaluation of \( \alpha_2 \):

\[ \sin(\alpha_2 + \alpha) = \frac{a_1 \cos \alpha - a_2 \sin \alpha}{R_2 - R_3}. \]

Defined parameters allow estimating coordinates of points A, B, C, D, which are sufficient for the creation of profile.
8.4.1.1.5. Import wheel profiles from CAD

If image import from CAD of STEP, IGES format is available in the current UM configuration, the user can create a wheel profile in a CAD program and import it into UM Format.

The following steps are necessary.
1. A sketch of the profile is created in a CAD program; the length unit must be millimeter.
2. Based on the sketch, a thin part is created; extrusion width in both directions must be about 0.001 mm, Figure 8.120.
3. If KOMPAS, SolidWorks or Inventor is used, the profile is imported directly from the CAD program. Otherwise, the part must be saved in STEP or IGES format.
4. In UM Input program, the profile is imported by the Tools | Import wheel profile from CAD menu command, Figure 8.121.
5. Path and file name for the profile in UM format is selected in the standard window.

Figure 8.120. Wheel profile in CAD KOMPAS

Figure 8.121. Wheel profile import in UM Input
8.4.1.1.6. Loading MiniProf wheel and rail profiles

UM supports direct loading the MiniProf *.whl, *.mpt, *.ban files. MiniProf is a rather popular tool for wheel and rail profile measurement. You can find more information about MiniProf at [http://www.greenwood.dk/miniprof.php](http://www.greenwood.dk/miniprof.php).

To load MiniProf files open a tool for development of wheel and rail profiles by clicking the Tools | Create wheel/rail profile menu command. Then click Load from file button and select one of the supported file formats in the dialog window, see Figure 8.122.

Along with direct reading the MiniProf files one can import such files manually using built-in UM tools. How to do that is shown in the Sect. 8.4.1.1.7 "Conversion of MiniProf wheel and rail profiles", p. 8-110.

![Figure 8.122. How to load MiniProf files into profile editor](image-url)
8.4.1.1.7. Conversion of MiniProf wheel and rail profiles

Let us consider a wheel profile file *.whl. Similar process is recommended for conversion of the rail profiles from MiniProf to UM format.

1. Open the *.whl file in the text editor and delete information lines from the top of the file. The file must contain numeric data only.
   
   
   0.5264 14.3366 1.4173 -0.107470274760285 1
   0.5279 14.4724 1.4173 -0.107470274760285 31
   0.5720 14.7482 1.3878 -0.101892819434936 92
   
   ...

2. Open **MS Excel** and read the file. If necessary, shift columns to set X and Y data in the neighboring columns (the first column must be X, the second one Y).

3. Run **UM Simulation**. Open a tool for development of wheel and rail profiles by clicking the **Tools | Railway wheel and rail profile editor** menu command.

4. Copy the XY profile data from **MS Excel** to clipboard, make the profile creation tool in UM active and paste the data (Ctrl+V), see Figure 8.123.

5. Open **Transformation** window by clicking the marked tool button, see Figure 8.123. **Transformation** window appears, see Figure 8.124.

![Creating profiles](image)

Figure 8.123. MiniProf file right after pasting from clipboard
Figure 8.124. Profile transformation tool

6. Click the **Reflect X** button to reflex the profile relative horizontal axis, see results in Figure 8.125.

Figure 8.125. Profile after clicking **Reflect X** button

7. Click the **Reflect Y** button to reflect the profile relative to vertical axis, see results in Figure 8.126.
Figure 8.126. Profile after clicking **Reflect Y** button

8. Set **Move to** vector, in the considered example it is (67.5, 0), and click the **Apply** button, see Figure 8.127. Operation result is shown in Figure 8.128.

Figure 8.127. How to move the profile
9. The profile conversion is over. Close the transformation window and save the wheel profile.

Figure 8.128. Final profile
8.4.1.2. Creation of track irregularities

Three variants of track irregularities description are available in UM:
- track irregularity files;
- deterministic functions;
- programming in the Control file of the model.

Irregularity files and deterministic functions are the most often used approaches. At the same time, programming of the irregularities can be more effective in some cases; as soon as it enables parameterization and modification of irregularity data (such as irregularities height, length, etc.) during simulation. All the variants enable study of the dependencies of dynamic properties of a vehicle on the irregularity parameters by a scanning project, Sect. 8.5.1. "List of internal identifiers parameterizing operation conditions of rail vehicles", p. 8-225.

8.4.1.2.1. Creation of irregularity files

Irregularities are stored in *.way files located by default in the {UM data}\rw directory. A file contains a sequence of irregularity values in meters with the constant step size (0.1 m) along the track; single accuracy format (4-byte floating point numbers) is used.

Figure 8.129. Tool for creation of track irregularities
A new file of irregularities can be generated by the special tool, which is available in the UM Simulation program by clicking the Tools | Irregularity editor | Railway track menu command.

**Note.** Within this tool the longitudinal coordinate is measured in meters but the irregularities should be given in millimeters.

Let us consider the structure of the tool and the meaning of its parts. The resultant track irregularity can be defined as a combination of single irregularities of various types; resultant irregularity profile is plotted in the top part of the tool window, see Figure 8.130. The list of single irregularities is located in the left top part of the window. Deleting or switching off an element of the list removes the corresponding component from the resultant profile.

![Figure 8.130. Railway track irregularities](image)

Buttons and parameters in the **Resultant profile** section are described below.

- **Parameter Length** defines the length of the record in meters.
- **Parameter Step** defines the interval between next points of the record. By default step is 0.1 m.

Tab sheets in the right bottom part are used for creation separate irregularities as components of resultant ones. The corresponding plot is located in the left bottom part of the window.
Buttons and parameters in the **Single profile** section are described below.

- **Button**  adds the current single irregularity to the resultant track profile.
- **Button**  saves the current single irregularity to file.
- **Buttons**  clears the current single irregularity.
- **Parameter**  *Factor* is the multiplier which is used for current single irregularity scaling during adding to the resultant profile. In an example, the user wants to convert irregularity profile defined in text format in UM data format. The source data points can be loaded by the tool placed on **Points** tab. By the way if the source file contains values of irregularities in meters, the 1000 scaling *Factor* value should be defined for correct conversion of the loaded data to millimeter units during adding to the resultant profile.
- If the **Autocorrection of length** check box is checked, the length of the resultant profile is automatically increased to match the adding separate irregularity. Otherwise the resultant profile length is defined by the **Length** control on the top panel.
- One can use **Start** parameter to define the start point of the resultant profile the first point of the adding single irregularity will be placed to. Note that the plot of the separate irregularity in the bottom graphic window always starts with zero abscissa value.
- The **Finish** parameter sets the end point of the adding irregularity record on the resultant profile. In other words, the part of single record between **Start** and **Finish** points is added to the resultant profile.

Consider types of irregularities.

**8.4.1.2.1.1. Irregularities as analytic expression (the Expression tab)**

Set an analytic expression $f(x)$ in the **Function of irregularity** edit box and press the **Enter** button or click  button. Standard functions can be used in the expression ([Chapter 3, Sect. Standard functions and constants](#)). Standard expressions can be assigned from the drop down list as well.

**8.4.1.2.1.2. Irregularities as slump**

This is a special and often used irregularity. Set its position and length using the **Start** and **Finish** parameters.

**8.4.1.2.1.3. From file**

Here an existing files of irregularities *.way* can be read. To do this, use the  button. A part of the irregularity, which length and position is determined by the **Start** and **Finish** parameter may be added to the resultant track profile.

**8.4.1.2.1.4. Irregularities as points**

Here an irregularity is created as a set of points with the help of the curve editor ([Chapter 3, Sect. Object constructor/Curve editor](#)). To call the editor, click the  button. In particular, here
the user can convert an irregularity given in a text format into UM format. For this purpose the irregularity should be open in any text editor in a two-column format. The first column should contain abscissa values in meters, i.e. the longitudinal coordinate starting with zero value. The second column should contain the irregularities in millimeters, e.g.

0 0
0.05 11
0.10 21
0.15 17
.....

To input this data with the help of the clipboard do the follows:
- delete all previously added points
- copy data into clipboard from any text editor in a standard manner;
- activate the curve editor by the mouse and paste the data from the clipboard (Ctrl+V or Shift+Insert hot keys).

Spline interpolation can be applied to the data.

8.4.1.2.1.5. Generation irregularities by spectrum

Track irregularities can be generated in accordance to PSD (spectral power density) function. The Rice-Pearson algorithm is used to generate the irregularity values by the equation:

\[ x[n\Delta s] = \sum_{m=0}^{M} \sqrt{2S_c(m\Delta \omega)} \Delta \omega \cos[m\Delta \omega n\Delta s + \varphi(m\Delta \omega)], \]

where
- \( \Delta s \) is the irregularity step size, m;
- \( M \) is the total number of harmonics in the sum;
- \( S_c(\omega) \) is the PSD function, m\(^2\)/(rad/m);
- \( \Delta \omega \) is the frequency increment, rad/m;
- \( \varphi(m\Delta \omega) \) is the phase uniformly distributed on interval \([-\pi, \pi]\).

The PSD can be function of frequency measured both in rad/m (circular frequency) and in oscillation/m. Use the **Circular frequency** check box to specify the PSD function abscissa units.
8.4.1.2.1.5.1. Spectrum: Points

Consider generation of irregularities by the PSD function shown in Figure 8.131. Open the curve editor by the button and specify four points on the PSD curve. Generated irregularities are given in Figure 8.132.

Note that this example illustrates the sequence of steps of the process, and cannot be used as a realization of irregularities by simulation of rail vehicles.
Federal Railroad Administration (FRA) of the United States Department of Transportation uses 9 (nine) classes for the description of railroad quality (first class is the worst one, ninth class is the best one). First five classes (1 … 5) correspond to normal-speed railroads, and the last ones (6…9) are used for high-speed railroads, with speed over 90 mile/h (145 km/h) for passenger trains and over 80 mile/h (130 km/h) for freight ones.

PSD functions of the first six classes (1 … 6) PSD functions are stated below [7]:

- PSD of half-sum of horizontal track irregularities:
  \[ \Phi(\Omega) = \frac{A_a \cdot \Omega_c^2}{\Omega^2 \cdot (\Omega^2 + \Omega_c^2)}, \quad \Omega > 0 \]

  \( \Omega \) – circular frequency, rad/m

- PSD of half-sum of vertical track irregularities:
  \[ \Phi(\Omega) = \frac{A_v \cdot \Omega_c^2}{\Omega^2 \cdot (\Omega^2 + \Omega_c^2)}, \quad \Omega > 0 \]

- PSD of half-difference of horizontal track irregularities:
  \[ \Phi(\Omega) = \frac{4 \cdot A_v \cdot \Omega_c^2}{(\Omega^2 + \Omega_c^2) \cdot (\Omega^2 + \Omega_c^2)}, \quad \Omega > 0 \]

- PSD of half-difference of vertical track irregularities:
  \[ \Phi(\Omega) = \frac{4 \cdot A_v \cdot \Omega_c^2}{(\Omega^2 + \Omega_c^2) \cdot (\Omega^2 + \Omega_c^2)}, \quad \Omega > 0 \]

<table>
<thead>
<tr>
<th>Class</th>
<th>Parameter</th>
<th>( A_v ), cm² rad/m</th>
<th>( A_a ), cm² rad/m</th>
<th>( \Omega_c^2 ), rad/m</th>
<th>( \Omega_c^2 ), rad/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (worst)</td>
<td></td>
<td>1,2107</td>
<td>3,3634</td>
<td>0,6046</td>
<td>0,8245</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>1,0181</td>
<td>1,2107</td>
<td>0,9308</td>
<td>0,8245</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>0,6816</td>
<td>0,4128</td>
<td>0,8520</td>
<td>0,8245</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>0,5376</td>
<td>0,3027</td>
<td>1,1312</td>
<td>0,8245</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>0,2095</td>
<td>0,0762</td>
<td>0,8209</td>
<td>0,8245</td>
</tr>
<tr>
<td>6 (best)</td>
<td></td>
<td>0,0339</td>
<td>0,0339</td>
<td>0,4380</td>
<td>0,8245</td>
</tr>
</tbody>
</table>
Create track irregularities tool enables generation of track irregularities corresponded to first six FRA track quality classes. The Lmin and Lmax parameters specify the minimal and the maximal length of irregularity wave in the realization (m).

Vertical and horizontal irregularities of the left and right rails can be generated by FRA spectrum in manual and automatic modes. The following sequence can be used for manual generation of vertical irregularities of the left and right rails:

a) select the Z+ option in the Type group, which denotes a PSD for a half sum of the vertical irregularities of the left and right rails;

b) generate realization by the Compute button and add it to the resultant irregularity by the \[\uparrow\] button;

c) select the Z- option in the Type group, which denotes a PSD for a half difference of the vertical irregularities of the left and right rails;

d) generate realization by the Compute button and add it to the resultant irregularity by the \[\uparrow\] button keeping Factor = 1, Figure 8.129; save the result to file for the left rail;

e) remove or switch off the second part of the resultant function corresponding to the difference in the irregularities of the left and right rails;

![Figure 8.133. Standard FRA spectrum generation](image)

![Figure 8.134. Resultant profile with a half difference realization](image)
f) subtract the half difference realization from the resultant irregularity by the button setting \textbf{Factor} = -1; save the result to file for the right rail.

As an alternative, one can use \textbf{Generate horizontal and vertical track irregularities} button to generate horizontal and vertical irregularities of left and right rails by one click. Four track irregularity realizations are generated automatically and added to the resultant profile in the following sequence:

- Vertical irregularities of the left rail (…\_Z\_Left)
- Vertical irregularities of the right rail (…\_Z\_Right)
- Horizontal irregularities of the left rail (…\_Y\_Left)
- Horizontal irregularities of the right rail (…\_Y\_Right)

The sequence above corresponds to the sequence of track irregularities files in irregularity group files *.tig. The following captions are used for the files by default: FRA_< Class_I >\_Z\_Left, where I is a number from the interval [1…6].

One can save the set of irregularity realizations (four items of the resultant profile list) as a group with the \textbf{Save irregularities group} *.tig popup menu command. New *.tig file and corresponded directory with irregularities files *.way will be created on a hard drive.
Create track irregularities tool enables generation of track irregularities corresponded to tracks of good and bad quality according to experts of International Union of Railways. PSD functions corresponded to tracks of different quality are stated below [7]:

- **PSD of horizontal track irregularities:**
  \[
  \Phi(\Omega) = \frac{a_h \cdot \Omega_c^2}{\Omega^2 + \Omega_R^2 \cdot (\Omega^2 + \Omega_c^2) \cdot \Omega > 0}
  \]

- **PSD of half-sum of vertical track irregularities:**
  \[
  \Phi(\Omega) = \frac{a_v \cdot \Omega_c^2}{\Omega^2 + \Omega_R^2 \cdot (\Omega^2 + \Omega_c^2) \cdot \Omega > 0}
  \]

- **PSD of half-difference of vertical track irregularities:**
  \[
  \Phi(\Omega) = \frac{1}{b_A^2} \cdot \frac{\Omega^2}{\Omega^2 + \Omega_R^2} \cdot \frac{a_v \cdot \Omega_c^2}{\Omega^2 + \Omega_R^2 \cdot (\Omega^2 + \Omega_c^2) \cdot \Omega > 0}
  \]

<table>
<thead>
<tr>
<th>Track quality</th>
<th>Parameter</th>
<th>a_v , cm² rad/m</th>
<th>a_h , cm² rad/m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bad</td>
<td>1,08e-6</td>
<td>0,6125e-6</td>
<td></td>
</tr>
<tr>
<td>Good</td>
<td>0,4032e-6</td>
<td>0,2119e-6</td>
<td></td>
</tr>
</tbody>
</table>

Note that the description of vertical irregularities is similar to that used in FRA standards, but horizontal irregularities for the left and right rails are equal.

![Generate horizontal and vertical irregularities](image)

**Figure 8.137. Generation of irregularities by UIC spectrum**
8.4.1.2.1.5.4. Spectrum (Expression)

Set an analytic expression \( f(w) \) in the **Function** edit box and press the **Enter** button or **Compute** button. Use the **Circular frequency** check box to specify the frequency type used in the expression. **Wmax** and **Wmin** labels show bounds of the frequency interval evaluated from **Lmin** and **Lmax** values. Click \( \text{Compute} \) button to plot or edit the spectrum function. Standard functions can be used in the expression (**Chapter 3**, Sect. **Standard functions and constants**). Standard expressions can be assigned from the drop down list (**Example spectra**) as well.

![Figure 8.138. Setting PSD function as an expression](image)

Let’s consider the sequence of irregularities generation according to the following data:

- \( F(w) = 1E^{-4} \sin(3.14w) \)
- **Circular frequency** is off;
- **Start** = 0 m; **Finish** = 2000 m.

8.4.1.2.2. Programming irregularities in the Control file

Control file is one of the main tools for the user programming in UM environment (**Chapter 5**). The control file for railway vehicles contains the following function:

```plaintext
begin
  Result := 0;
end;
```

The user may compute any vertical or horizontal irregularity within this function.

**Input:**

- **position** is longitudinal coordinate for which the irregularities are computed.

**Output:**

- **result** returns function value. If the return value is equal to 1 the programmed values will be taken into account, otherwise they are ignored.

**LeftZ, RightZ** are vertical irregularities of the left and right rails in meters;
**LeftY, RightY** are horizontal irregularities of the left and right rails in meters; 
**derLeftZ, derRightZ** are derivatives of vertical irregularities of the left and right rails w.r.t. longitudinal coordinate; 
**derLeftY, derRightY** are derivatives of horizontal irregularities of the left and right rails w.r.t. longitudinal coordinate.

Irregularities computed in the function are added with those assigned to rails from files. If it is necessary to take into account the programmed irregularities only, the *NoIrregularities.way* file should be assigned to the corresponding rails.

![Figure 8.139. Slump](image)

Let us consider a separate irregularity of the *Slump* type, Figure 8.139. The irregularity of the **left rail** and its derivative are defined by the formulae

\[
    h = -\frac{H}{2} \left(1 - \cos \frac{\pi(x - x_0)}{L}\right);
\]

\[
    h' = -\frac{\pi H}{2L} \sin \frac{\pi(x - x_0)}{L},
\]

\[x \in [x_0, x_0 + L].\]

Here \(H, L, x_0\) are the depth and length of the slump as well as the start position along the track. Let the same irregularity for the **right rail** be moved along the track in the longitudinal direction on \(dx\) relatively to the left rail. It is supposed that all of these four parameters are included in the list of identifiers of the corresponding UM model (Chapter 3, Sect. Basic elements of constructor).

```plaintext
begin
    Result := 1;
    LeftY:=0;
    RightY:=0;
    derLeftY:=0;
    derRightY:=0;

    // Irregularities for the left rail
    if (position>_pzAll[1].x0) and (position<_pzAll[1].x0 + _pzAll[1].L) then begin
        LeftZ:=-0.5*_pzAll[1].H*(1-cos(pi*(position-_pzAll[1].x0)/_pzAll[1].L));
        derLeftZ:=-0.5*pi*_pzAll[1].H*sin(pi*(position-_pzAll[1].x0)/_pzAll[1].L))/_pzAll[1].L;
    end else begin
```

...
LeftZ:=0;
derLeftZ:=0;
end;

//Irregularities for the right rail
if (position>_pzAll[1].x0+dx) and (position<_pzAll[1].x0 +
_pzAll[1].L+_pzAll[1].dx) then begin
  RightZ:=-0.5*_pzAll[1].H*(1-cos(pi*(position-_pzAll[1].x0 -
_pzAll[1].dx)/_pzAll[1].L)));
  derRightZ:=-0.5*pi*_pzAll[1].H*sin(pi*(position-_pzAll[1].x0 -
_pzAll[1].dx)/_pzAll[1].L))/_pzAll[1].L;
end else begin
  RightZ:=0;
  derRightZ:=0;
end;
end;
8.4.1.3. Creation of macrogeometry files

The macrogeometry files *.mcg are used in the following cases:
- Track macrogeometry differs from tangent section, curve, S-curve or switch;
- Vertical track macrogeometry is taken into account.

A macrogeometry file can include any number of curves, tangents, switches, variable friction conditions along the track as well as an arbitrary vertical profile.

Use the **Tool | Macrogeometry editor | Railway or monorail track** menu command to start the window where the track is described.

![Macrogeometry window](image1)

**Figure 8.140. Macrogeometry window**

8.4.1.3.1. Track macrogeometry in horizontal plane

The upper part of the window in Figure 8.140 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.

![Section menu](image2)

**Figure 8.141. Section menu**
To edit the section parameters double click on the corresponding line of the section list or select the line and press Enter.

### 8.4.1.3.1.1. Tangent section

![Section parameters](image)

Figure 8.142. Parameters of a tangent section

Tangent section window contains values of section length and coefficient of friction.

### 8.4.1.3.1.2. Curve section

Curve parameter window includes (Sect. Geometry of curve)

- 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), cant of outer rail (H) as well as additional gauge widening in curve (dY);
- coefficients of friction on running surfaces of outer and inner rails, on the inward side of the outer rail (flange) as well as angles $\beta_r, \beta_s$, which specify the transient from the coefficients of friction on the running surface $f_r$ and of the rail inward side $f_s$ if $f_r \neq f_s$. Sect. 8.3.3. "Coefficient of friction in wheel-rail contact", p. 8-96.
Remark. Transient sections of curves are set by clothoid, i.e. by a curve with a uniform increase of curvature.

8.4.1.3.1.3. Switch section

Switch parameter window includes values of (Figure 8.137, Sect. 8.2.1.3. "Switch geometry", p. 8-71).

- $q$ is stock rail overhang;
- $g$ is gauge;
- $\beta_{\text{init}}$ is initial angle;
- $\alpha$ is switch angle;
- $R_0$ is radius of point;
- $R$ is radius of switch;
- $b_r$ is switch deviation for $R_0$;
- $m$ is frog tail length;
- $d$ is track spacing.
- $R_1$ is radius behind the frog.

The parameters define fully the switch geometry and some additional parameters:

- $L_p$ is full switch length;
- $L_{\alpha}$ is theoretical length;
- $k$ is tangent section before the frog.
Figure 8.144. Switch parameters

Additional parameters
- direction of motion (facing, trailing)
- type of switch (left or right);
- coefficient of friction.
Figure 8.145. Switch geometry parameters
8.4.1.3.1.4. Point curve

Point curve can be used for the description of track geometry (shape of curves, cant, widening, etc.) with arbitrary functions. Curve editor is used for description of functions. Click button for editing of the curve parameter, Figure 8.146.

- Curve XY

Curve editor is used for setting of track axis position in XY plane. Section length is evaluated automatically as a length of XY curve.

First point must have zero coordinates. Tangent 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 track data or analytically computed coordinates of nonstandard transient curve section.

![Point curve parameter window](image)

Figure 8.146. Point curve parameter window

The point list can be the following:

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>Y</td>
<td>X</td>
<td>Y</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>26</td>
<td>0.4394</td>
</tr>
<tr>
<td>2</td>
<td>0.0002</td>
<td>28</td>
<td>0.5488</td>
</tr>
<tr>
<td>4</td>
<td>0.0016</td>
<td>30</td>
<td>0.675</td>
</tr>
<tr>
<td>6</td>
<td>0.0054</td>
<td>32</td>
<td>0.8192</td>
</tr>
<tr>
<td>8</td>
<td>0.0128</td>
<td>34</td>
<td>0.9826</td>
</tr>
<tr>
<td>10</td>
<td>0.025</td>
<td>36</td>
<td>1.1664</td>
</tr>
<tr>
<td>12</td>
<td>0.0432</td>
<td>38</td>
<td>1.3718</td>
</tr>
<tr>
<td>14</td>
<td>0.0686</td>
<td>40</td>
<td>1.6</td>
</tr>
<tr>
<td>16</td>
<td>0.1024</td>
<td>42</td>
<td>1.8522</td>
</tr>
<tr>
<td>18</td>
<td>0.1458</td>
<td>44</td>
<td>2.1296</td>
</tr>
<tr>
<td>20</td>
<td>0.2</td>
<td>46</td>
<td>2.4334</td>
</tr>
<tr>
<td>22</td>
<td>0.2662</td>
<td>48</td>
<td>2.7648</td>
</tr>
</tbody>
</table>
The list is prepared in MS Excel as a two-column table. Then it was copied to clipboard and insert to curve editor (all other points must be preliminary deleted from the curve editor list!). The curve shape is shown in Figure 8.147. B-Spline is recommended for curve shape approximation. Automatically evaluated curve length is shown in Figure 8.148.

**Remark.** Approximation with splines results in zero values of second derivatives at the first and the last points. It means that sometimes second derivative and curvature functions can have breaks at the points of connection of point curve with plane sections of other types. For example, if transient section described with point curve is sibling to a circular curve which is with standard curve with zero transient length there will be a break in curvature function, see Figure 8.149. In this situation first derivative is continuous. If points of point curve are set with a small step (1-2 meters), break in curvature doesn’t affect the simulation results. To exclude the problem of curvature breaking the user can describe the whole curve (all sections) with point curve element.
• **Cant functions of left and right rails**
  
  Cant functions for both rails are set with point curves from XY curve length. Left and right cants can be not zero simultaneously and get positive and negative values. Curve length values for each of XY points are shown at the last column of the curve editor table, see Figure 8.147.

• **Widening**

  Widening is set as a function from XY curve length.

• **Friction coefficients** are set the same as in Sect Curve section.

**Remark.** The user should control the continuity of cant and widening functions for the element, as well as for the areas of connection with sibling elements of horizontal track profile.

### 8.4.1.3.2. Track macrogeometry in vertical plane

The lower part of the window in Figure 8.140 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.
• To edit the section parameters double click on the corresponding line of the section list or select the line and press Enter.

**8.4.1.3.2.1. Constant slope section**

The following parameters can be set in Gradient window (Figure 8.151):

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

![Figure 8.151. Constant slope section parameters](image)

**8.4.1.3.2.2. Point section**

Point curve can be used for the description of vertical track axis coordinate with arbitrary functions from XY curve length. Curve editor is used for description of functions, see Figure 8.152. Curve editor opens when section editing starts.

![Figure 8.152. Parameters of point section](image)

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

**Remark.** Use zero smoothing radius value for constant slope section if point section is next to it. Vertical profile will have a break if not.
8.4.1.3.3. Import of measured track geometry

Track measurement is applied for getting of real geometrical characteristics of the railroad path relative to some basic point. Modern methods of measurements based on the usage of high-precision optical tachometers, GPS receivers and inclinometer provide list of data for each point of measurement like coordinates, track width, cant, etc.

Text files with measured data can be imported to macrogeometry model. The following format of text files is used by default:

<table>
<thead>
<tr>
<th>Track description</th>
</tr>
</thead>
<tbody>
<tr>
<td>N0</td>
</tr>
<tr>
<td>10000</td>
</tr>
<tr>
<td>10001</td>
</tr>
</tbody>
</table>

Mentioned designations are as follows:

- **N0** is a number of measured point (not used);
- **X, Y, Z** are coordinates;
- **Mark** is additional data (not used);
- **TW** is track width;
- **DZ** is curve cant;
- **Side** is curve side (used for cant setting).

The files can be prepared in Excel program and saved as text files with tab delimiters.

Press button at the top right corner of Macrogeometry form to import data. Track measured data loading form will appear (Figure 8.146). Select the file, set standard track width and curve approximation type.

![Figure 8.153. Track measured data loading form](image)

New point curve section will be added to the horizontal plane section list and vertical profile section list (see Sect. 8.4.1.3.1.4. "Point curve", p. 8-131, Sect. 8.4.1.3.2.2. "Point section", p. 8-134). Start point of the approximated curve will be placed at the last point of plane and profile correspondently. Section length is evaluated from XY curve length. The user can change curves or approximation type.

**Remark.** Remember that track widening, cant and Z coordinate of track are set relative to the track distance, which is evaluated from XY curve shape. Changing of the XY curve can result in data distortion. Therefore we recommend not to change XY curve after import and repeat import if it is necessary to change XY curve approximation type.
8.4.1.4. Creation of files with switch parameters

To create or edit a file with switch parameters use the Tools | Switch menu command. Switch parameters are saved in *.swt file. The upper text box contains the name of the switch (optional parameter).

See Sect. 8.2.1.3. "Switch geometry", p. 8-71 for more details.

![Switch window parameters](image)

Figure 8.154. Switch window parameters

8.4.1.5. Estimation of track quality

This tool corresponds to the Russian regulations and available for Russian version of UM only.
8.4.2. Setting parameters of rail vehicle simulation

Parameters for simulation of rail vehicle dynamics are available in the simulation inspector. To call the inspector use one of the following methods:

- **Analysis | Simulation** menu command;
- **F9** key.

A considerable part of the parameters can be set in a standard manner, Chapter 4, Sect. Preparing for integration. Here we consider some features of the parameters setting for a rail vehicle.

![Figure 8.155. Tab for rail vehicle simulation parameters](image)

Parameters and options related to rail vehicle are located on the Rail/Wheel tab, Figure 8.155. The tab contains the following buttons:

- is used for reading a rail vehicle configuration file *.rwc;
- is used for saving the current options and parameters in the configuration file *.rwc;
- is used to view the assigned rail irregularities in a graphic window;
- is used to view of selected rail and wheel profiles in a graphic window;
- is the tab navigator; click the button to get the menu for direct access of tabs related to rail vehicle, Figure 8.156.

![Figure 8.156. Menu of navigator](image)

A number of tabs are available on the **Rail/Wheel** tab. **Track**: assignment of macrogeometry, irregularities, stiffness, gauge, rail inclination and so on, Sect. 8.4.2.4. "Track parameters", p. 8-151,
Profiles: assignment of wheel and rail profiles, wheel forms, wheel radius differences, Sect. 8.4.2.3. "Assignment of rail and wheel profiles", p. 8-146, Sect. 8.4.2.7. "Additional parameters", p. 8-179,

Contact: selection of contact model and its parameters, coefficient of friction in rail/wheel contact, Sect. 8.4.2.5. "Parameters for computation of rail-wheel contact forces", p. 8-168,

Forces: setting forces in automatic couplers from files,

Speed: setting mode of longitudinal motion of vehicle (neutral, constant speed, zero speed, speed as a function of time or distance), Sect. 8.4.2.2. "Modes of longitudinal motion of vehicle", p. 8-140.

8.4.2.1. Configuration files

8.4.2.1.1. Configuration file of rail vehicle

![Figure 8.157. Key for automatic saving of rail vehicle configuration file](image)

All data entered in the Rail/Wheel tab are stored in a text file *.rwc by the button. The previously created files can be read by the button. All current options and parameters can be save in the file last.rwc on close of the UM Simulation program or on change of the model. The key Rail vehicle configuration in the Options window is user to activate or deactivate this function, Figure 8.157. The Tools | Options menu command calls the Options window.

Remark 1. If last.rwc file is presented in the model directory, it is read independently on value of automatic saving key in Figure 8.157, and the corresponding rail vehicle parameters are set. The same is valid for the file of identifiers last.par. That is why changes in identifier values made in the UM Input program are ignored if the last.par is available in the object directory. To accept the numeric value of identifiers from the input.dat file, the last.par file must be deleted before loading the object.
Remark 2. Rail vehicle configuration file can be read from the directory of another model.

8.4.2.1.2. Group of configuration files of rail vehicle

The current configuration of a rail vehicle is stored together with all other options by the File | Save configuration | All options menu command, Figure 8.158. As a result, a group of configuration files is created, which contain the full information about the current state of the model. Files in the group have equal names but different extensions. Later the user can read this group by the File | Load configuration | [Name of group] command, Figure 8.159.

For instance, we have completely prepared settings for analysis of stability of a rail vehicle numeric method is selected, simulation rime and accuracy is specified, a number of graphic and animation windows are prepared, numeric value of identifiers, wheel and rail profiles, rail inclination, and coefficients of friction and so on are assigned. After that we have made the analysis of stability of the vehicle and decided to store the successive options and parameters for later usage. We save all options by the File | Save configuration | All options command with the group name Stability. The following files are created:

Stability.icf (program desktop and parameters of numeric method), lists of disabled and non-stiff forces;
Stability.par (numeric values of identifiers);
Stability.rwc (rail vehicle configuration file);
Stability.xv (file of initial coordinate values);
Stability.sim (Matlab/Simulink interface options);

All this files will be read by the File | Load configuration | Stability command.
8.4.2.2. Modes of longitudinal motion of vehicle

Modes of longitudinal motion of vehicle are set on the Speed tab of the inspector.

8.4.2.2.1. Neutral

In this mode the initial speed value is set by the \( v_0 \) identifier, Figure 8.161. The speed decreases due to resistance wheel-to-rail forces.

8.4.2.2.2. \( v = \text{const} \)

It is a constant speed mode. The nearly constant value of the vehicle speed is supported automatically by the longitudinal force

\[
F = -k(v-v_0),
\]

where \( v_0 \) is the desired speed, \( v \) is the current speed, and \( k \) is the amplifier. The force is applied to a body selected by the user (usually to the car body) to a point which coordinates should be set in the body-fixed system of coordinates, Figure 8.162. Usually the point lies on the coupling level; the longitudinal coordinate of the point is not important if the body is rigid.

In this mode the desired speed value is set by the \( v_0 \) identifier, Figure 8.161.
8.4.2.2.3. Profile

The vehicle speed is controlled according to a dependence on a time or distance, the \textit{Abscissa type} group. The control force is similar to that in the previous mode ($v=\text{const}$). A curve editor is available by the button for setting the speed profile, Figure 8.163, Figure 8.164. The buttons are used for reading previously created profiles and for saving the current curve.

\textbf{Remark.} If initial speed is zero, dependence of the speed on time must be used (not on distance).
8.4.2.2.4. \( v=0 \)

Zero velocity mode. This mode is used to bring the vehicle to the equilibrium or load-induced oscillations simulation, defined depending on time. In the second case blocking of several degrees of freedom of wheelsets could be useful: longitudinal and lateral motions (X, Y) as well as rotations about the lateral and vertical axes (aX, aZ), Figure 8.165. To block a degree of freedom turn on the corresponding check box.

![Figure 8.165. Parameters of zero velocity mode](image)

To bring the vehicle to equilibrium position turn on Finish test automatically (Figure 8.165), then start the integration process and wait until the test finishes. As a rule, this is the first step when the work with a new railway vehicle model begins. The plot of vehicle summarized kinetic energy can be useful during the equilibrium test. The variable of kinetic energy is available in tab **Variables for group of bodies** of **Wizard of variables**. Equilibrium test is finished when kinetic energy value becomes small enough (Figure 8.166).
8.4.2.2.5. Motion of vehicles with different speed

It is possible to model of several vehicles or groups of vehicles moving with different initial speed. The following conditions are important.

- Each group of vehicles must be included in the model as an external subsystem, Figure 8.167. For instance, the user wish simulate two vehicles moving with different speed, so the vehicles must be included in the model as two external subsystems, see Chapter 2, Section Subsystems, Chapter 3, Section Subsystems.
Neutral mode of longitudinal motion must be selected.

Equal initial speed option must be unchecked, Figure 8.168.

Initial speed for each of the external subsystem is specified by the corresponding identifier \( v_0 \) in the corresponding subsystem, Figure 8.169.

8.4.2.2.6. Speed unit

Speed specification both by the identifier \( v_0 \) and by a function can be done either in km/h or m/s. To specify the unit, open the Option window by the Tools | Options menu command and set the desired unit, Figure 8.170. The selected option is stored in the registry of the local computer. This option can be used carefully, because errors possible due to transferring the model to another computer or by reading old configuration files.
Figure 8.170. Setting speed unit
8.4.2.3. Assignment of rail and wheel profiles

The Rail/Wheel | Profiles tab of the inspector is used for assignment profiles to the rail and wheels. References to files the assigned profiles are stored in a vehicle configuration file *.rwc.

8.4.2.3.1. Assignment of rail profiles

Use the buttons to assign profiles for the left and right rails (Figure 8.171). The set of rails is used both for the fast assignment of profiles, and for their internal parameterization in scanning projects, Sect. 8.5.1. "List of internal identifiers parameterizing operation conditions of rail vehicles", p. 8-225. The button helps the user to view the assigned profiles.

Figure 8.171. Assignment of rail profiles. Popup menu of the rail profile list.
The following rail profiles are delivered with UM Loco:

<table>
<thead>
<tr>
<th>File Name</th>
<th>Profile Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>115AREMA.rpf</td>
<td>NA profile, 115 lb/yd</td>
</tr>
<tr>
<td>119AREMA.rpf</td>
<td>NA profile, 119 lb/yd</td>
</tr>
<tr>
<td>132AREMA.rpf</td>
<td>NA profile, 132 lb/yd</td>
</tr>
<tr>
<td>133AREMA.rpf</td>
<td>NA profile, 133 lb/yd</td>
</tr>
<tr>
<td>136AREMA.rpf</td>
<td>NA profile, 136 lb/yd</td>
</tr>
<tr>
<td>141AREMA.rpf</td>
<td>NA profile, 141 lb/yd</td>
</tr>
<tr>
<td>BS113A_crv.rpf</td>
<td>European profile BS113</td>
</tr>
<tr>
<td>Chinese R60.rpf</td>
<td>Chinese profile R60</td>
</tr>
<tr>
<td>Chinese R75.rpf</td>
<td>Chinese profile R75</td>
</tr>
<tr>
<td>r50.rpf</td>
<td>Russian R50</td>
</tr>
<tr>
<td>r65new.rpf</td>
<td>Russian R65</td>
</tr>
<tr>
<td>r65old13.rpf</td>
<td>Russian R65 with 13 wear</td>
</tr>
<tr>
<td>UIC60new.rpf</td>
<td>European UIC60</td>
</tr>
<tr>
<td>UIC60_1.rpf</td>
<td>UIC60 (is used in Manchester tests)</td>
</tr>
<tr>
<td>UIC60r_1.rpf</td>
<td>UIC60 (is used in Manchester tests)</td>
</tr>
<tr>
<td>UIC60_crv.rpf</td>
<td>UIC60</td>
</tr>
<tr>
<td>UIC60_Worn.rpf</td>
<td>UIC60</td>
</tr>
</tbody>
</table>

**Gauge measuring interval** is a distance below a plane that rests across the top of the two rails which defines gauge measuring points taking the rail inclination into account (Figure 8.172). It is used to create *Gauge* variable, see. Sect. 8.4.3.1.2. "Variables related to the wheelset", p. 8-190.

![Figure 8.172. Gauge measurement](image)

### 8.4.2.3.2. Assignment of wheel profiles

Assignment of wheel profiles has two stages. At the first stage a list of wheel profiles is created (Figure 8.173). The list should include at least one profile. The button in the left panel is used to add a profile to the list. The button shows all profiles in the list.

To assign profiles from the list to the wheels:

- open the **Rail/Wheel | Profiles | Wheels | Profiles** tab, Figure 8.173;
- call the popup menu by clicking the right mouse button and select a profile to assign it to all the wheels;
• if different profiles should be assigned to different wheels, double click on the necessary wheel by the left mouse button and change the profile until the desired profile name appears.

**Remark.** List of profiles is used for internal parameterization of the profiles in scanning project, Sect. 8.5.1. "List of internal identifiers parameterizing operation conditions of rail vehicles", p. 8-225.

Figure 8.173. Assignment wheel profiles
UM database of wheel profiles includes the following files.

<table>
<thead>
<tr>
<th>File Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAR.wpf</td>
<td>NA profile AAR</td>
</tr>
<tr>
<td>Chinese LM.wpf</td>
<td>Chinese profile LM</td>
</tr>
<tr>
<td>Chinese LMA.wpf</td>
<td>Chinese profile LMA</td>
</tr>
<tr>
<td>dmeti30.wpf</td>
<td>Russian profile DMetI</td>
</tr>
<tr>
<td>newlocow.wpf</td>
<td>Russian new locomotive profile</td>
</tr>
<tr>
<td>newwagnw.wpf</td>
<td>Russian new car profile</td>
</tr>
<tr>
<td>s1002.wpf</td>
<td>European S1002</td>
</tr>
<tr>
<td>S1002l_1.wpf</td>
<td>European S1002 (Manchester benchmarks)</td>
</tr>
<tr>
<td>S1002r_1.wpf</td>
<td>European S1002 (Manchester benchmarks)</td>
</tr>
<tr>
<td>s1002worn.wpf</td>
<td>S1002, worn</td>
</tr>
<tr>
<td>s1002worn2.wpf</td>
<td>S1002, worn</td>
</tr>
</tbody>
</table>
8.4.2.3.3. Rail profile evolution along the track

To describe a changing profile of the left or/and right rail along the track (Sect. 8.2.1.1. "Geometry of rails in an ideal track", p. 8-66), the following steps should be done.

- Create the list of profiles with the Rail/Wheel | Profiles | Rails tab. Use the buttons or the popup menu to add and delete profiles.
- Use the list Rail profiles in control points to set a sequence of profiles \( R_i \) the track as well as their positions along the track \( S_i \) (Sect. 8.2.1.1. "Geometry of rails in an ideal track", p. 8-66), \( i=1,2,\ldots \). Add profiles to the sequence with the help of the popup menu. After that set their positions in the Track column, see Figure 8.174.

![Image](image_url)

Figure 8.174. Creation of sequence of profiles along the track

**Example.** Figure 8.174 shows a creation of sequence of profiles for the outer rail of a right curve with the following parameters (Sect. 8.2.1.2. "Geometry of curve", p. 8-67).

\[ \text{L0} = 10 \text{ m}, \text{P11} = 50 \text{ m}, \text{S1} = 200 \text{ m}, \text{P12} = 50 \text{ m}. \]

The new profile \( r65\text{new} \) (Figure 8.175) is used at straight sections. At the first 50 m transition (section from 10 m to 60 m) the new profile is transformed to the worn one \( r65\text{old} \). In the
steady curve (from 60 m to 260 m) the profile does not change. At the second 50 m transition (from 260 m to 310 m) the profile is transformed from the worn to the new one.

Figure 8.175. Profiles \textit{r65new} (left) and \textit{r65old}

\textbf{8.4.2.4. Track parameters}

The track parameters are defined on the tab sheet \textbf{Rail/Wheel | Track} in \textbf{Object simulation inspector}. The tab contains \textbf{Model and parameters}, \textbf{Macrogometry}, \textbf{Irregularities} and \textbf{Image} tabs. On the tab \textbf{Model and parameters} rail inclination and track gauge are set, track model and its parameters are chosen. On the \textbf{Macrogometry} tab track macrogeometry is set. On the \textbf{Irregularities} tab the irregularities of rail threads are set. You can set the track image in animation window on the \textbf{Image} tab.

\textbf{8.4.2.4.1. Track model choosing and parameters setting}

Rail inclination, track gauge, track model choosing and its parameters are set on the \textbf{Model and parameters} tab, Figure 8.176.

\textbf{Rail inclination} \(\alpha_{r0}\) is set in radians, Sect. 8.2.1.1. "\textit{Geometry of rails in an ideal track}" , p. 8-66.

Exact value of the gauge is specified by the distance between the systems of coordinates of rail and wheel \(\Delta y\) (SCR-SCW distance), Sect. 8.2.1.1. "\textit{Geometry of rails in an ideal track}" , p. 8-66.

The track models are described in Sect. 8.2.2. "\textit{Track models}" , p. 8-74.
8.4.2.4.1.1. Track stiffness and damping

8.4.2.4.1.1. Massless rail

Vertical and lateral stiffness of a rail can be specified in two different forms.

- **Constant stiffness along the track.**
  
  In this case the stiffness constants are equal for the left and right rails. Their numeric values are set in the boxes **Vertical stiffness**, **Lateral stiffness**, **Torsional stiffness**, Figure 8.176. The torsional stiffness is taking into account if the corresponding option is active, Figure 8.176.

- **Variable stiffness along the track**, Figure 8.177.

  The variable rail stiffness is described by sets of points in dependence on the longitudinal coordinate separately for the left and right rails. Use the button **Curve** to call the curve editor for entering the variable stiffness. In the case of variable vertical and lateral stiffness, the constant torsional stiffness can be applied.
Damping constants (Ns/m) are equal for the left and right rails, Figure 8.176.

To get track stiffness and damping, which is variable in the longitudinal direction, as well as set different values of these parameters for the left and right rail, the user should use the programming in the Control file (Chapter 5, Sect. 5.1). The following procedure in the Control file is used for programming the track parameters.

```pascal
function TrackStiffness( position : real_; var cLeftZ, cRightZ, cLeftY, cRightY, dLeftZ, dRightZ, dLeftY, dRightY : real_ ) : integer;
begin
  Result := 0;
end;
```

**Input:**
*position* is longitudinal coordinate for which the irregularities are computed.

**Output:**
*Result* returns function value. If the return value is 1, the programmed values will be taken into account, otherwise they are ignored.

- *cLeftZ*, *cRightZ* are vertical stiffnesses of the left and right rails, N/m;
- *cLeftY*, *cRightY* are lateral stiffnesses of the left and right rails, N/m;
- *dLeftZ*, *dRightZ* are vertical damping coefficients of the left and right rails, Ns/m;
- *dLeftY*, *dRightY* are lateral damping coefficients of the left and right rails, Ns/m.

**Remark 1.** If the function returns 1, parameters entered in Figure 8.176 are ignored except the cases in the Remark 2.

**Remark 2.** Zero values of stiffness coefficients *cLeftZ*, *cRightZ*, *cLeftY*, *cRightY* are ignored and replaced by values entered in Figure 8.176.

### 8.4.2.4.1.1.2. Inertial rail

Stiffness and damping properties of railway track for Inertial rail model are defined by the identifiers (Sect. 8.1.3.2, Wheelset with six degrees of freedom, p. 8-10). To change the identifier use Identifiers | List of Identifiers tab in the Object simulation inspector is used. To define var-
variables along the track stiffness and dissipation identifiers control is used (Object Simulation Inspector | Identifiers | Identifier control).

8.4.2.4.1.3. Flexible track

You can define or change the track stiffness and damping of Flexible track model in Wizard of flexible railway track. Chapter 27, Sect. 27.5.5.

8.4.2.4.2. Track macrogeometry

To define track macrogeometry use the Rail/Wheel | Track | Macrogeometry tab in the object simulation inspector, Figure 8.178.

![Figure 8.178. Choice of track macrogeometry](image)

8.4.2.4.2.1. Track type: tangent

Motion in a tangent section of unlimited length.

8.4.2.4.2.2. Track type: curve

Motion in a right curve (Figure 8.179) including a tangent section before the curve (L1), transient sections (P11, P12), steady curve of radius R1 and length S1, a positive cant for the outer rail, and an additional widening in the curve dY1. All parameters of the curve including the additional widening dY1 should be set in meters, see Sect. 8.2.1.2. "Geometry of curve", p. 8-67 for more details.

The L is equal to the full length of the curve including the tangent section L1. The V’ is equal to the vehicle speed (m/s) in case of zero value of the uncompensated acceleration.

**Smoothing** parameter is used for smoothing the vertical junctions at ends of the transition by arc of circle. The parameter here sets the meters length of the smoothed section.
8.4.2.4.2.3. Track type: S-curve

S-curve is a combination of a right curve followed by the left curve.

Remark. Transient sections of a curve and S-curve are cubic parabolas. It is assumed that the ratio of length of the transient section to the curve radius is small, and does not exceed 0.5. In the case of long transients, geometry type **From file** must be used, where the clothoid is implemented for transient sections.

8.4.2.4.2.4. Features of setting cant values in curve and in S-curve

In case of motion in a right curve and in S-curve (Figure 8.179, Figure 8.180) the cant value can be assigned for the **outer** rail by two different ways.
The first method is used if the cant value is positive and constant in steady part of the curve, and increases/decreases uniformly in the transients. In this case the numeric cant value should be set directly in the boxes H1, H2.

The second method is used if the conditions of the first one do not take place, e.g. when the cant value is not constant in the steady curve. The variable cant value along the track both for the first (right) and for the second (left) curves is set by the button in the right hand side of the H1 box, Figure 8.179, Figure 8.180. The curve editor appears, and the cant value (m) versus curve distance can be specified by a sequence of the points, Figure 8.181. After that the box looks like \[ \text{Profile} \]. To set a constant cant back, the user should delete all points in the list in Figure 8.181.

![Cant versus track distance](image)

Figure 8.181. Cant versus track distance

The user should take into account the following important remarks concerning usage of the variable cant value.

1. The cant function should be always zero at tangent sections of the track (before the first right curve, between the curves, after the second curve). Violation of this requirement leads to discontinuities in the vertical rail position.

2. The cant function starts since begin of the first transient section, and does not include the tangent section before the curve. For example, the point (0, 0) in Figure 8.181 corresponds to the start of the curve (not to the start of the track!). The cant function in S-curve takes into account the length of the tangent section between the curves, the L1 section is ignored only!

3. In case of S-curve, the cant function is valid for both of the curves, not for the first one. In particular it means that the cant value entered in the H2 edit box is ignored.

8.4.2.4.2.5. How to model the motion in a left curve?

S-curve can be easily used for simulation of motion in a left curve if lengths corresponding to the first (right) curve are small, cant is zero, and the radius is large.
Remark. In this mode, the smoothing length is ignored.

8.4.2.4.2.6. Track type: switch

Use the button to open a *.swt file with the switch parameters, Figure 8.183 (see Sect. 8.4.1.3. "Creation of macrogeometry files", p. 8-126). Other parameters allow the user to simulate both facing and trailing movements in the left and right switches. The **Tangent section** parameter sets the length of a tangent section before the switch.
Figure 8.184. Switches: a, b are facing and trailing movements in the right switch; c, d are facing and trailing movements in the left switch

8.4.2.4.2.7. Track type: from file. Set of macrogeometry files

A preliminary created file with track macrogeometry is assigned by the button, Figure 8.185, see Sect. 8.4.1.3. "Creation of macrogeometry files", p. 8-126.

View and modification of the file data are available by the button.

Set of macrogeometry files is used for a quick assignment of different files, as well for internal parameterization of files used in scanning projects, Sect. 8.5.1. "List of internal identifiers parameterizing operation conditions of rail vehicles", p. 8-225. Double click on the element of the set to assign it as the current one.
8.4.2.4.3. Assignment of track irregularities

The Rail/Wheel | Track | Irregularities tab is used for assignment of rail irregularities. The irregularities can be assigned in two forms: from files or deterministic, the Type of irregularities group, Figure 8.186. If the Even track state is activated, simulation runs in an ideal track without irregularities.

8.4.2.4.3.1. Irregularities from file. Group of irregularities

Database of UM includes a number of files with irregularities located in the {Path to UM}\bin\rw directory. See Sect. 8.4.1.2.1. “Creation of irregularity files”, p. 8-114 for creation of files with irregularities. The NoIrregularities.way file is used if a rail has no irregularities or the user programs the irregularities in the control file.

To set both the vertical (Z) and the horizontal (Y) irregularities to the left and right rails use the corresponding button (Figure 8.186).
The **Group of irregularities** section contains buttons, which are used for reading and writing groups of four files. For example, the user creates four files with irregularities assigns them to the track as above. After that the user saves names of files in a group file *.tig by the button, and can assign later the whole group by the button without opening all of them separately.

**Example.** The file UIC_good_1000.tig contains list of four files with irregularities corresponding to good condition according to UIC, length of realization is 1000m:

- D:\UM80\bin\rw\uic_good_1000_zleft.way
- D:\UM80\bin\rw\uic_good_1000_zright.way
- D:\UM80\bin\rw\uic_good_1000_y.way
- D:\UM80\bin\rw\uic_good_1000_y.way

The **Factor** parameter is used for increasing or decreasing the both assigned and computed in the control file irregularities. For example if the Y factor is 0.7, the decrease the horizontal irregularities to 30%.

### 8.4.2.4.3.1.1. List of irregularity groups

List of irregularity groups is used for a quick assignment of irregularities by double clicking as well as for internal parameterization of the irregularities used in scanning projects, Sect. 8.5.1. "List of internal identifiers parameterizing operation conditions of rail vehicles", p. 8-225.

![Figure 8.187. List of irregularity groups](image)

Figure 8.187. List of irregularity groups
8.4.2.4.3.2. Deterministic irregularities

Two types of vertical deterministic irregularities are available, Figure 8.188.

1. **Hump or deep**
   
   This type of irregularities is computed according to the formula
   \[
   \Delta z = \frac{H}{2} \left( 1 - \cos \frac{2\pi x}{L} \right),
   \]
   where \( H \) is the height of the wave (negative for a deep); \( L \) is the wave length, \( x \) is the longitudinal coordinate.

   Along with the length and height of the wave, the following parameters should be set:
   - start position of the left irregularity \( x_0 \);
   - shift of the right irregularity relative to the left one \( \Delta x \);
   - number of waves \( N \).

2. **Absolute value of sinus**
   
   This type of irregularities is computed according to the formula
\[ \Delta z = H \left| \sin \left( \frac{\pi x}{L} \right) \right| \]

The same parameters as they were for the "Hump" type irregularity are used. Figure 8.190 shows irregularities with the same values of parameters as in Figure 8.189.

![Figure 8.190. Example of irregularities ‘absolute value of sinus’](image)

Lateral deterministic irregularities are described by the same formula as the ‘hump’. Phase between the left and right lateral irregularity is not supported.
8.4.2.4.3.3. Setting irregularities by identifiers

Horizontal and vertical irregularities can be set for each of the wheel independently with an 'Identifier control' tool and with the Matlab/Simulink interface. This method has some additional features compared to the irregularity files:

- Arbitrary and variable step size for irregularity functions
- Rail vertical and horizontal motion as function of time.

Remark 1. Irregularities are set in meters
Remark 2. When pointwise description of irregularity functions is used, the derivative of the curve is recommended to be smooth, which can be achieved by a spline interpolation.

Consider a workflow for setting irregularities by identifiers.

**b) Adding standard identifiers for irregularities to the model**

Open a model in the Input program, click by the right mouse button on the list of identifiers and select the **Add identifiers for irregularities** command, Figure 8.191.

The number for adding identifiers is four times more than the number of wheelsets in the model, Figure 8.192. Syntax of the standard identifiers is as follows:

```
irr[type of irregularity][side][index of wheelset].
```
Figure 8.192. Standard irregularity identifiers for a model with four wheelsets

c) **Selection of irregularity type in simulation program**

![Image of selection process](image.png)

Figure 8.193. Setting type of irregularity

Select **Identifiers** type of irregularity description in the simulation inspector, Figure 8.193. If a user specifies identifiers, which names differ from the standard ones, he can assign them on this tab by double click of the mouse on the corresponding row and column of the table.
d) Setting irregularity by points as a function of wheelset position

Consider first setting an irregularity as a function of wheelset position. Add a new control element on the **Identifiers**|**Identifier control** tab, Figure 8.194:
- Click on the button to add a new identifier control;

![Figure 8.194. Identifier control tab](image)

- In the appeared window, click on the button to select an identifier.

![Figure 8.195. Window for control description](image)

- Set **Variable** type of abscissa; create a variable corresponding to the longitudinal position of the wheelset in track with the Wizard of variables and drag the variable to the corresponding box of the identifier control description, Figure 8.196.
e) Position of rail under wheel as a function of time

One of the purposes for setting a rail displacement under the wheel as a function of time consists in modeling of a test rig, when a kinematic excitation is assigned to wheelsets. In this case, the zero speed mode is recommended, Section 8.4.2.2.4 $v=0$. Another purpose of this irregularity type consists in setting the rail displacement obtained from other sources such as field tests or from FEA programs.

Figure 8.197. Example of irregularity function in the curve editor

- Use the $\text{button}$ button to describe the irregularity function in the curve editor, Figure 8.197. The function can be described point by point or read from file.

Figure 8.198. Harmonic rail oscillation

Rail displacement as a time function can be specified either pointwise with the curve editor or by a variable created with the Wizard of variables. Figure 8.198 shows assignment of the right rail oscillations according to the expression

$$z_1(t) = 0.02 \sin 2\pi t.$$
8.4.2.4.4. Track image in the animation window

Track image in the animation window is set on Rail/Wheel | Track | Image tab, Figure 8.199. If the Show rails check box is active, rails and sleepers are drawn in animation window. If Show Irregularities check box is active, rails are drawn taking into account irregularities. The rail is drawn along a polyline with a constant step size specified in Rail-image step box. Graphical image parameters of the sleepers are separated in Sizes of sleepers group.

![Figure 8.199. Track image in the animation window setting](image)

Figure 8.199. Track image in the animation window setting
8.4.2.5. Parameters for computation of rail-wheel contact forces

Contact and creep forces models can be chosen on the Rail/wheel | Contact | Contact forces tab. Different contact and creep forces models correspond to the different track models.

Parameter Critical speed for creep is used for every model of contact. The parameter allows the user to change the value of the critical speed $v_c^0$, Sect. 8.3.1.2.2. "Algorithms for computing creep forces", p. 8-86, Figure 8.201.

8.4.2.5.1. Parameters of massless rail contact

A method for creep forces computation in wheel-rail contact when rail is a massless element is described in Sect. 8.3.1.2.1. "Method for computation of rail deflections and contact force", p. 8-84. The following creep forces models are available: Mueller’s, Minov’s, FASTSIM, FASTSIM_A, Non-elliptical, External, see Figure 8.200.

- Mueller’s model
  The only parameter is $m$, the default value is 3, see Sect. 8.3.1.2.2.1. "Mueller’s model", p. 8-87.

- Minov’s model
  Computation of creep forces according to empirical analytic expressions. The model is used for simulation of locomotives in traction mode. See Sect. 8.3.1.2.2.2. "Minov’s model", p. 8-88.

- FASTSIM, FASTSIM_A
  See Sect. 8.3.1.2.2.3. "FASTSIM", p. 8-89 and Sect. 8.3.1.2.2.4. "FASTSIM_A", p. 8-90 for description of the models. The model parameters are: Young's modulus and Poisson's ratio, Number of strips and Number of elements, Figure 8.202.
• Non-elliptical contact model
  This model is used for calculation of non-Hertzian wheel-rail contact, Sect. 8.3.1.2.2.5. "Non-elliptical contact model", p. 8-90. Non-elliptical contact model is supported by UM Loco/Non-elliptical Contact Model tool.

• External
  The usage of the alternative algorithms of creep forces computation, which are performed in the external DLLs, (see Chapter 5 Sect. 5.2 and Figure 8.203). UM Loco/External Contact Model tool is required.

The simplified model of the pair of profiles is used when the flag Simplified contact geometry is activated, Figure 8.204, see Sect. 8.3.1.1.3. "Simplified contact geometry. Equivalent conicity and contact angle parameter", p. 8-81.
There are following parameters of the simplified contact model:

- **Equivalent conicity** $\lambda$ (non-dimensional value);
- **Equivalent contact angle parameter** $\epsilon$ (non-dimensional value);
- **Nominal contact angle** $\beta_0$ (degrees);
- **Maximal displacement** is a maximal lateral wheel-rail deflection before the $y^*$ (mm) two-point contact starts;
- **Flange contact angle** is a flange contact angle with the rail lateral area in the $\beta^*$ (degrees) two-point contact;
- **Contact2** are the coordinates of flange contact for the two-point contact in the $y_f^*$ and $z_f^*$ (mm) rail coordinate system.

**Note.** In the simplified contact model of wheel-rail pair of profiles Mueller’s method is used for computation of creep forces.

### 8.4.2.5.2. Parameters of inertial rail contact

A method for computation of the wheel-inertial rail contact is described in Sect. 8.3.2. "Computation of contact between the wheel and the inertial rail", p. 8-92. For **Inertial rail** track model the contact forces models by W. Kik and J. Piotrowski and Kalker's CONTACT model are applicable, see Figure 8.205. **UM Loco/Multi-point Contact Model** tool is required for the model by W. Kik and J. Piotrowski. **UM Loco/CONTACT add-on interface** is a required tool for using CONTACT program. Note that the only interface for CONTACT is included in UM. Licenses for the CONTACT add-on for UM are provided and supported by VORtech CMCC, www.kalkersoftware.org. You may request for trial license by e-mailing to um-addon@kalkersoftware.org. In your e-mail request please specify your name, position and a company/university. After you get the license copy the license file in UM set-up folder C:\Program Files\UM Software Lab\Universal Mechanism\8\bin (by default) and restart the UM.
Figure 8.205. Choice of contact forces model for Inertial rail track model

The Interpenetration factor and Damping ratio are added in the model by W. Kik and J. Piotrowski, apart from the already considered parameters, see Figure 8.206.

Interpenetration factor \(k_\delta\) is a coefficient between the area of rigid interpenetration of profiles and the contact patch [4]. For example, if \(k_\delta = 1\), the whole area of the rigid interpenetration will be accepted as the contact patch; if \(k_\delta = 0.5\), then the area of the rigid interpenetration, obtained by profiles shifting on the penetration value decreased by a factor of 2, will be accepted as the contact patch. The recommended value of the interpenetration factor is 0.55.

Damping ratio \(\zeta\) is included in the formula of normal reaction in the contact patch computing, Sect. 8.3.2. "Computation of contact between the wheel and the inertial rail", p. 8-92.

Tables of contact points when computing a contact are used when the flag Use tables of contact points is turned on.

Note. The usage of the contact forces model by W. Kik and J. Piotrowski or CONTACT model leads to the stiff equations of motion. For these models it is recommended to turn on the Jacobian for wheel/rail forces flag, see Sect. 8.4.4.1. "Solver: Park method", p. 8-219.

8.4.2.5.3. Parameters of flexible track

Flexible track model is supported only by the contact forces model by W. Kik and J. Piotrowski.
8.4.2.5.4. Setting coefficients of friction in rail/wheel contact

The **Rail/Wheel | Contact | Friction** tab is used for setting the coefficient of friction, Figure 8.207.

![Figure 8.207. Setting of friction coefficients in the rail-wheel contact](image)

See Sect. 8.3.3. "Coefficient of friction in wheel-rail contact", p. 8-96 for the detailed information about the coefficient of friction.

To set the constant friction coefficients on the running surface \( f_r \) of the left and right rails, the corresponding fields of the **Rail head** group are used, Figure 8.207. If a coefficient of friction is variable, choose the function type first (either **Distance** or **Time**) and then click the ... button. The curve editor to set the curve dependence of the friction coefficient on the chosen parameter will appear.

![Figure 8.208. Setting of friction coefficients on rail side](image)

**Rail side face lubrication**

If lubrication of the rail side face is modeled, activate the **Lubrication of rail side face** key, (Figure 8.208), and set the value of \( f_s \) friction coefficient on rail side. The angles \( \beta_r \) and \( \beta_s \), which define the transition section should be set in the **from** and **to** edit boxes.

**Dependence of the friction coefficient on sliding velocity**

Parameters A, B in Figure 8.209 are included in dependence of the friction coefficient on sliding velocity, Sect. 8.3.3. "Coefficient of friction in wheel-rail contact", p. 8-96:

\[
 f = f_0 \left( (1 - A)e^{-Bv_1} + A \right).
\]
Figure 8.209. Dependence of the friction coefficient on sliding velocity. Dependence models.

If $A = 1$, $B = 0$, the coefficient of friction is constant. Parameter $A$ is the ratio of coefficient of friction for infinite sliding velocity to that for zero sliding. For example, $A = 0.4$ corresponds to the case when the coefficient of friction decreases in 2.5 times for large sliding. Parameter $B$ determines the rate of decrease of the coefficient, Figure 8.210.

![Dependence of the friction coefficient on sliding velocity](image)

Figure 8.210. Examples of decrease of coefficient of friction with growth of sliding velocity

Drop down menu in Figure 8.209 allows the user to choose the values of parameters $A$, $B$ from the database [6], Table 8.3.

Table 8.3

<table>
<thead>
<tr>
<th>Locomotive</th>
<th>State of rail</th>
<th>$A$</th>
<th>$B$ (s/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical</td>
<td>Dry</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>Typical</td>
<td>Wet</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>SD45X</td>
<td>Dry</td>
<td>0.44</td>
<td>0.6</td>
</tr>
<tr>
<td>DB127</td>
<td>Dry</td>
<td>0.38</td>
<td>0.7</td>
</tr>
<tr>
<td>S252</td>
<td>Dry</td>
<td>0.36</td>
<td>0.55</td>
</tr>
<tr>
<td>SBB460</td>
<td>Wet</td>
<td>0.5</td>
<td>0.16</td>
</tr>
<tr>
<td>12X</td>
<td>Wet</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>SD45X</td>
<td>Wet</td>
<td>0.38</td>
<td>0.18</td>
</tr>
</tbody>
</table>
8.4.2.6. Setting in-train forces

Use the Rail/Wheel | Forces tab to specify in-train forces acting on the vehicles (Figure 8.211).

8.4.2.6.1. Assigning forces

Forces can be obtained from experiments or from UM Train module (the module for analysis of longitudinal train dynamics). Both front and rear forces can be applied to a vehicle or to a group of vehicles. Each of the forces is specified by the following sets of data.

- Body, which the force is applied to, as a rule is a car body.
- Force application point. Coordinates X and Y set in the body-fixed SC, whereas the Z coordinate is measured from the rail head level.
- Files with force component descriptions. The force is described by three components in the body-fixed SC. To set a component, a preliminary created file should be selected by the buttons, Figure 8.211. File format description can be found in the next section.
- Use the On key to switch on/off the forces.
- If the Function of distance key is on, the forces are functions of the vehicle travel along the track otherwise they are functions of time.
- The Change sign key is used if it is necessary to change the sign of the front force to the opposite one. For instance, if the force is obtained from simulation of longitudinal train dynamics with UM Train, this key must be activated because the in-train forces in the coupling in UM Train are considered to be applied to the front vehicle in a coupling.

If files do not assign to some components of forces, they are zeroes.

The button is used for plotting the assigned functions.

Two methods are used to delete the file assignment.

- Locate the text cursor in the box with the name of file and press Delete;
8.4.2.6.2. Creating files with force description

Forces in Sect. 8.4.2.6.1. "Assigning forces", p. 8-174 must be preliminarily stored in files, which contain forces versus time or distance histories in projections on the car body system of coordinates. Units are N, s, m.

A linear interpolation is used to get a continuous dependence.
Two different formats are used for description of the force.

- Format *.frc, obsolete
  A binary force file contains successive force values with step size 0.1m (0.1s) starting from zero distance (time). Single binary format is used for force values (4 byte floating point numbers).
  It is recommended to use the window for development of track irregularities, which uses the format of files *.way (Sect. 8.4.1.2.1. "Creation of irregularity files", p. 8-114). After creating the file its extension should be renamed to frc instead of way. It is recommended to store files in the model directory or in the ../rw directory.

- Format *.txt
  In this case the text file contains two columns. The first column is the time or distance, the second one is the force. Example:

<table>
<thead>
<tr>
<th>Time</th>
<th>Force</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td>70</td>
<td>30000</td>
</tr>
<tr>
<td>150</td>
<td>30000</td>
</tr>
<tr>
<td>170</td>
<td>0</td>
</tr>
<tr>
<td>180</td>
<td>0</td>
</tr>
</tbody>
</table>

8.4.2.6.3. Plotting and visualization of forces

The variables for creation of forces plots in the railway vehicle simulation process with the aim of controlling the task correctness are available on the tab Railway vehicle of Wizard of variables (See 8.4.3.1.3. "Variables related to the railway vehicle", p. 8-191).

To visualize the force vectors in animation window, move the mouse cursor to the car body, click the right mouse button, and select the Show forces for [Name of Body] popup menu command Figure 8.212. If the forces are invisible during the simulation, either the force application coordinates are not correct, or scale factor for forces is too large. In the last case use the Scale of vectors command of the popup menu to decrease the scale factor, Figure 8.212.
8.4.2.6.4. Example of in-train forces

Consider lateral forces applied to the front and rear couplers, Figure 8.213. The forces are zero on the first 50 m of the vehicle travel, and then they grow uniformly to 3000 N on the interval from 50 m to 70 m. The forces are constant till 150 m, and decreases uniformly on the 20 m interval. The front force is positive, the rear one is negative.

Open the window for development of files with irregularities by the Tools | Create irregularities | Railway track menu command, open the Points tab and start the curve editor by the button.
Add 6 points by the button, and set their coordinates as in Figure 8.214. Optimize the polygon view by then button.

Close the editor by the OK button and save the result in a file by the lower button  . Rename the file extension manually to frc instead of way.

Let us consider an alternative method for adding points, which is highly useful if the force description includes many points. The polygon should be presented by two columns in any text editor. The first column corresponds to the abscissa (distance or time), the second one contains the force values.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>50</td>
<td>0</td>
</tr>
<tr>
<td>70</td>
<td>30000</td>
</tr>
<tr>
<td>150</td>
<td>30000</td>
</tr>
<tr>
<td>170</td>
<td>0</td>
</tr>
<tr>
<td>180</td>
<td>0</td>
</tr>
</tbody>
</table>

Copy data into the clipboard by Ctrl+C and paste into the curve editor Figure 8.214 by Ctrl+V. In this manner large data can be converted into the necessary format in the case when forces are obtained from experiment or from simulation of longitudinal train dynamics with UM Train. In the last case the corresponding variable should be saved in a text file from a graphic window.

To create a file with the force having the reverse sign, set -1 (minus unit) in the Factor box, send the plot to the upper part of the window by the button, save it by button, and rename the extension.

The created files can be immediately assigned to the force components, Figure 8.211, and used in simulation process.

Remark. It is recommended to use an alternative format of force description in *.txt files, Sect. 8.4.2.6.2. "Creating files with force description", p. 8-175.
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8.4.2.7. Additional parameters

8.4.2.7.1. Deviation of wheel form from ideal circle

The **Rail/Wheel | Profiles | Wheel forms** tab is used for specifying deviations of wheel forms from an ideal circle. A direct access to this tab is available with the **Form of wheels** button by the **Form of wheels** command, Figure 8.215. The list of wheelset is located in the left part of the tab. Icon image for a wheelset depends of the form type. For instance, in Figure 8.215 it has a rail vehicle with two wheelsets. A flat is assigned to the first WS, the second one has the form of an ideal circle.

Click a WS icon in the list to get access to the form of its wheels. **Forms of the left and right wheels of a WS are the same. Form of the wheel must be convex.**

Form of the wheels influences dynamically the normal force in contact as wheel as the longitudinal position of the contact.

8.4.2.7.1.1. Flat

The following parameters specify the flat geometry.

- **L** is the initial length of a flat (length of a flat section for zero value of wear parameter L1), Figure 8.217;
- **L1** is the decrease of the deformed part length due to plastic deformation (for a side);
- **Order of smoothing curve.** Either square \((y = ax^2)\) or cubic \((y = ax^3)\) parabola are used for smoothing the flat ends, Figure 8.218. The factor \(a\) of parabola is computed from the
condition that tangents to the circle and to the end point of parabola B coincide (Figure 8.217, the abscissa value is L/2 + L1). In this case, the initial point A of the parabola is computed automatically. Abscissa value of point A is greater for the cubic order then for the square one for equal values of \( L1 \), Figure 8.218. By \( L1 = L(\sqrt{3} - 1)/2 \approx 0.44L \) the flat section disappears for the cubic parabola, that is why the condition \( L1 < 0.44L \) takes place in the case of smoothing.

Figure 8.217. To definition of flat parameters

Figure 8.218. Comparison of flat smoothing by square and cubic parabola

8.4.2.7.1.2. Ellipse

The form of an elliptic wheel is computed according to the formula

\[
\frac{x^2}{(R + dA)^2} + \frac{y^2}{(R + dB)^2} = 1,
\]
where parameters $dA$ and $dB$ set deviation of ellipse semiaxes from the ideal wheel radius $R$, which is specified for the given wheelset in the UM Input program, Sect. 8.1.3.6. "Editing wheelset parameters", p. 8-15, Figure 8.220.

![Figure 8.219. Parameters of elliptic wheel](image1)

![Figure 8.220. Example of elliptic wheel](image2)

### 8.4.2.7.1.3. Harmonic deviation

The form of the wheel is computed according to the formulas

$$
x = (R + A \sin N\varphi) \sin \varphi
$$

$$
y = (R + A \sin N\varphi) \cos \varphi
$$

$$
\varphi \in [0, 2\pi]
$$

where deviation of the variable radius from the constant value $R$ is set by the harmonic function the amplitude $A$, Figure 8.221. The number of humps on the curve is equal to $N$, Figure 8.222.
8.4.2.7.1.4. Points

The form of the wheel is computed according to the formulas...
where deviation $dr$ of the variable radius from the constant value $R$ is set by a curve, that must be specified by the user in a text file, Figure 8.224. The corresponding form of the wheel is shown in Figure 8.225.
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The text file contains two columns. The first column is the angle in degrees; the second one is the deviation of radius in mm. Example:

0 0
1 0.000456917
2 0.001827527
3 0.004111415
4 0.007307883
5 0.011415959
6 0.016434391
7 0.02236165
8 0.02919593
9 0.036935151
10 0.045576954
11 0.055118707
12 0.065557503
.............

The button is used for assignment of a file. Continuous function of $dr$ vs. $\varphi$ is obtained by use of the Lagrangian interpolation polynomial of the 3rd order.

8.4.2.7.2. Wheel radii difference

Defect of wheel radii is the difference between the real radius of running circle, and the radius of wheels specified in the UM Input program, Sect. 8.1.3.6. "Editing wheelset parameters", p. 8-15. This difference is specified in Rail/Wheel | Profiles | Wheels | Radii difference tab in millimeters. In Figure 8.226a, the radius of the left wheel is 2 mm less than that for the right wheel. In Figure 8.226b, the wheels of the first WS are 3 mm less than that for the second wheel.

Radii differences have internal parameterization for scanning projects, Sect. 8.5.1. "List of internal identifiers parameterizing operation conditions of rail vehicles", p. 8-225.

![Figure 8.226](image)

a b

Figure 8.226. Setting difference in radii

8.4.2.7.3. Rail/wheel contact options

If worn profiles defined by a set of points are created or if profile evolution is computed, some problems with the contact geometry computations might appear. Let us consider some of these problems as well as their solving with the help of parameters in Rail/Wheel | Profiles | Contact options tab.
Figure 8.227. Additional parameters for contact geometry computations

- **Jump of parameter and angle parameter in two-point contact criterion**
  These parameters are used in the procedure of computing contact coordinates for verifying the fact of the two-point contact (see the $\eta_y, \eta_\eta$ parameters in Sect. 8.3.1.1.2. "Computing tables of contact points", p. 8-78). Sometimes variation of this parameter can improve the detection of two-point contact.

- **Key X-rotation of wheel profile on/off**
  Sometimes worn profiles of wheel and rail are in a very close contact near the flange region so that a small relative rotations $\Delta \alpha$ of the profiles about the longitudinal X-axis may cause a big jump in coordinates of contact points or transfer from profiles with one-point contact only to the profiles, which allow a two-point contact and back. Such cases lead usually to large jumps in values of contact forces. To stabilize the simulation, switching off the variation of the contact positions in dependence on the $\Delta \alpha$ angle is useful very often (see Sect. Computing tables of contact points). Switching off the key means that the coordinates for $\Delta \alpha = 0$ are used.

- **Key Thin out profile points**
  A very small abscissa step size in defining profiles leads to violation of continuity of contact point positions in dependence on lateral displacements and relative rotations of profiles (see Sect. 8.3.1.1.2. "Computing tables of contact points", p. 8-78 and Sect. 8.4.1.1. "Creation of wheel and rail profiles", p. 8-98). If the key is checked, the step size is decreased up to the value, which is set as the Thin out step size parameter. The default value of the step is 1mm.

- **Contact jump limit**
  The table of contact coordinates verses relative lateral shift of profiles has a discrete nature. If a difference between the neighbor coordinate values exceed this parameter, a jump or discontinuity of the curve take place. Otherwise, a linear interpolation within the interval is used.
- **Stop simulation on wheel derailment**
  
  If the option is checked, the simulation is broken when the lateral displacement of a wheelset exceeds some definite value. This value is computed automatically according to the rail and wheel profiles. Usually it is about 100mm.

### 8.4.3. Tools for visualization and analysis of railway vehicle dynamics

#### 8.4.3.1. Some features of creation of variables

General information about creation and usage of variables as well as lists of variables can be found in [Chapter 4, Sect. Variables, Wizard of variables, List of variables](#). Here we consider variables, which are related to rail vehicles exclusively.

#### 8.4.3.1.1. Rail/wheel contact variables

For variables which describe wheel-to-rail interaction use the Rail/Wheel tab of the **Wizard of variables**, Figure 8.228. See [Chapter 4, Sect. Wizard of variables](#) for detailed information about the **Wizard of variables**.

![Figure 8.228. Variables for rail/wheel contacts](#)
Note. The wheelsets are numbered 1, 2… in compliance with the decreasing of their longitudinal coordinate.

The variables on Rail/Wheel tab are formed in two groups: Variables for contact point and Variables for wheel. The first group contains the variables which describe wheel-to-rail contact points. It should be noted that the Simplified and two-point contact forces models assume two contact points as maximum. In this case the first contact point corresponds to the one-point contact or a contact on a wheel rolling surface (Figure 8.229), and the second contact point corresponds to a contact on the ledge of profiles, allowing a two-point contact (Figure 8.229). Multi-point and CONTACT models allow an unlimited number of contact points. The points are numbered in order correspondent its lateral position on the rail, from outer side to inner side of the railway track (Figure 8.229). The variables in this group are described in Table 8.4. The second group contains variables for the wheel which are not directly connected with any of the contact points. The description of these variables is given in Table 8.5.

Figure 8.229. Contact points numeration

To create one variable corresponding to one of the wheel, the wheel should be selected in the tree located in the left part of the wizard. For example, selection of the ‘wset 1 left’ item corresponds to the choice of the left wheel, wheelset 1.

Figure 8.228 shows an example when the four variables in the container are created by a single click on the button.

A type of a variable is selected in the list located in the right part of the wizard. The first column of the list contains standard names of variables. An identifier of a variable is constructed from the name of the corresponding type by adding the number of a wheelset and the l (left) or r (right) for wheel identification. For instance, the YWContact1_1r identifier of a variable (coordinate Y of the first contact point in SC of the rail profiles – Y Wheel Contact 1) is obtained from the standard identifiers of the type YWContact1 and relates to the right wheel of wheelset 1.

If one variable for a separate wheel is created, the user may change both the identifier and the comment in a standard manner. However, if a group of variables is created, standard identifiers and comments are assigned automatically.
<table>
<thead>
<tr>
<th>Identifier</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Creep[i]x, Creep[i]y</td>
<td>(unitless) Longitudinal and lateral creepages $\xi_x, \xi_y$, the variables are used for computing creep forces, Sect. 8.3.1.2.2. &quot;Algorithms for computing creep forces&quot;, p. 8-86.</td>
</tr>
<tr>
<td>Spin[i]</td>
<td>(rad/m) Spin $\phi$. The variables are used for computing creep forces with the FASTSIM algorithm, Sect. 8.3.1.2.2. &quot;Algorithms for computing creep forces&quot;, p. 8-86.</td>
</tr>
<tr>
<td>Creep[i]</td>
<td>(unitless) Module of the creepage vector $\xi = \sqrt{\xi_x^2 + \xi_y^2}$</td>
</tr>
<tr>
<td>FC[ripe[i]x, FC[ripe[i]y</td>
<td>(N) Longitudinal and lateral creep forces, Sect. 1.3.3.2. The lateral creep force corresponds to the $F_1$ force in Figure 8.97.</td>
</tr>
<tr>
<td>N[i]</td>
<td>(N) Normal force $N_i$, Figure 8.97.</td>
</tr>
<tr>
<td>Beta[i]</td>
<td>(rad) Contact angle: angle $\beta_i$ between the normal force $N_i$ and the Z-axis of the track SC, Figure 8.97. The angle is positive for inclination of the normal forces inward the track.</td>
</tr>
<tr>
<td>YWContact[i], ZWContact[i]</td>
<td>(m) Coordinates Y (lateral) and Z (vertical) of the contact point in SC of the wheel profile (Sect. 8.1.3.5. &quot;Wheelset geometry&quot;, p. 8-13).</td>
</tr>
<tr>
<td>XRC[ontact[i], YRContact[i], ZRContact[i]</td>
<td>(m) Coordinates Y (lateral) and Z (vertical) of the contact point in SC of the rail profile (Sect. 8.2.1.1. &quot;Geometry of rails in an ideal track&quot;, p. 8-66).</td>
</tr>
<tr>
<td>MWear[i]</td>
<td>Wear factor is power of frictional forces (W): $M_{wear} = \int_A \mathbf{v} \mathbf{\tau} , dA$, where $\mathbf{v}$ is a &quot;true&quot; sliding, $\mathbf{\tau}$ are tangential forces.</td>
</tr>
<tr>
<td>Tgamma[i]</td>
<td>Wear factor is $T\gamma$ number (N): $T\gamma =</td>
</tr>
<tr>
<td>Iw[i]</td>
<td>Wear index (N/mm²): $I_w = \frac{T\gamma}{A}$, where $A$ is area of the contact patch.</td>
</tr>
<tr>
<td>Area[i]</td>
<td>(m²) Area of the contact patch.</td>
</tr>
<tr>
<td>Pressure[i]</td>
<td>(Pa) Maximal pressure in the contact.</td>
</tr>
<tr>
<td>TauMax[i]</td>
<td>(Pa) Maximal tangential traction in the contact.</td>
</tr>
<tr>
<td>a[i], b[i]</td>
<td>(mm) Longitudinal and lateral semi-axis of the elliptical contact patch or equivalent non-elliptical.</td>
</tr>
<tr>
<td>AdhArea[i]</td>
<td>(m²) Area of adhesion zone in the contact patch.</td>
</tr>
<tr>
<td>Penetration[i]</td>
<td>(mm) Maximal geometrical penetration.</td>
</tr>
<tr>
<td>FrFactor[i]</td>
<td>(unitless) Actual friction coefficient at contact point.</td>
</tr>
</tbody>
</table>
**Wheel variables**

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>C\textsubscript{Safety}</td>
<td>Derailment quotient (Russian version) $S_{RU}$, Eq. (1.16). If $S_{RU} &gt; 5$ then the value $S_{RU} = 5$ is accepted. The value $S_{RU} = 5$ is set if there is no contact between a wheel and a rail (a full separation). The motion is safe if $S_{RU} &gt; 12$.</td>
</tr>
<tr>
<td>CSaf\textsubscript{y}Re\textsubscript{fin}ed</td>
<td>Refined derailment quotient (Russian version), $S_{RU}$, Eq. (1.17). Usually $S_{RU, r} &gt; S_{RU}$.</td>
</tr>
<tr>
<td>Nadal</td>
<td>Nadal derailment criterion $S_{L/V}$, Eq. (1.14). According to UIC 518, $Y/Q &lt; 0.8$ for $R &gt; 250\text{m}$. Zero value is set if there is no contact between a wheel and a rail (a full separation).</td>
</tr>
<tr>
<td>Weinstock</td>
<td>Derailment criterion proposed by Weinstock $S_{W}$, Eq. (1.15).</td>
</tr>
<tr>
<td>S\textsubscript{FC}</td>
<td>Combined safety factor (Russian version), $\lambda_c$, Eq. (1.19). Is recommended for analysis of derailment accidents by simulation.</td>
</tr>
<tr>
<td>Z\textsubscript{lifting}</td>
<td>(m) Vertical lifting the wheel running surface, Figure 8.235. For profiles with one-point contact (Figure 8.89, left): raise of the wheel over the critical position.</td>
</tr>
<tr>
<td>ZL\textsubscript{ifting}</td>
<td>(unitless) Relative lifting of a wheel over the rail, Eq. (1.18).oda) Angle of attack: the yaw angle of wheels with respect to the rail.</td>
</tr>
<tr>
<td>psi</td>
<td>(rad) Angle of attack: the yaw angle of wheels with respect to the rail.</td>
</tr>
<tr>
<td>F\textsubscript{x}</td>
<td>(N) Total longitudinal force acting on the wheel along the X-axes of the track system of coordinates (Sect. 8.2.1.3. &quot;Switch geometry&quot;, p. 8-71).</td>
</tr>
<tr>
<td>Y\textsubscript{(L)}</td>
<td>(N) Total lateral force acting on the wheel along the Y-axes of the track system of coordinates (Sect. 8.2.1.3. &quot;Switch geometry&quot;, p. 8-71).</td>
</tr>
<tr>
<td>Q\textsubscript{(V)}</td>
<td>(N) Total vertical force acting on the wheel along the Z-axes of the track system of coordinates (Sect. 8.2.1.3. &quot;Switch geometry&quot;, p. 8-71).</td>
</tr>
<tr>
<td>dY\textsubscript{Rail}, d\textsubscript{Z}\textsubscript{Rail}</td>
<td>(m) Lateral and vertical deflection of rail under the wheel</td>
</tr>
<tr>
<td>d\textsubscript{Y}\textsubscript{Rail}, d\textsubscript{Z}\textsubscript{Rail}</td>
<td>(m) Lateral and vertical deflection of rail under the wheel</td>
</tr>
<tr>
<td>dy\textsubscript{W/R}</td>
<td>(m) Lateral displacement of the wheel relative to the rail.</td>
</tr>
<tr>
<td>D\textsubscript{ratio} (W/R)</td>
<td>Dynamic factor on the rail/wheel level. The value is computed according to the formula $(F_z - F_{z0})/F_{z0}$, where $F_z$ is the total vertical force in the track SC, $F_{z0}$ is the static load for a wheel.</td>
</tr>
<tr>
<td>dy\textsubscript{Track}, dz\textsubscript{Track}</td>
<td>(m) Horizontal and vertical rail irregularities at the wheel position.</td>
</tr>
<tr>
<td>Deriv\textsubscript{Y}\textsubscript{Track}, Deriv\textsubscript{Z}\textsubscript{Track}</td>
<td>(unitless) Derivative of lateral and vertical irregularities with respect to the longitudinal coordinate</td>
</tr>
<tr>
<td>dy\textsubscript{Rail}\textsubscript{Full}</td>
<td>(m) Lateral rail position taking into account flange clearance, flexible deflection and lateral irregularities, Sect. 8.4.3.1.8. &quot;Example: draw plots for lateral motion of wheelset in the rail gangway&quot;, p. 8-202.</td>
</tr>
<tr>
<td>MW\textsubscript{ear},</td>
<td>Summed on all contact points wear factors, namely, power (W), work</td>
</tr>
</tbody>
</table>
AWear, SWear (J), specific work (J/m) of friction forces.

\[ A_{\text{wear}} = \int_0^t M_{\text{wear}} dt \]

\[ S_{\text{wear}} = \frac{A_{\text{wear}}}{S}, \text{where } S \text{ is the traveled distance.} \]

### 8.4.3.1.2. Variables related to the wheelset

Variables related to the wheelset are shown on the Wheelsets tab (Figure 8.230). Variables description is in Table 8.6.

![Wizard of variables](image)

Figure 8.230. Variables related to the wheelset

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position</td>
<td>(m) Wheelset position along the track</td>
</tr>
<tr>
<td>H</td>
<td>(N) Frame force. Frame force or total force acting on the frame from the wheelset, see Sect. 8.4.3.1.5. &quot;Lateral and frame forces&quot;, p. 8-197.</td>
</tr>
<tr>
<td>Ny</td>
<td>(N) Leading force: a projection of normal reaction of N on axis-related system of coordinates for the given wheel set. To compute the projection use a formula ( Ny = \pm N \sin \beta ), take minus sign for the left wheel.</td>
</tr>
<tr>
<td>yaw</td>
<td>(rad) Yaw angle of the wheelset</td>
</tr>
</tbody>
</table>
8.4.3.1.3. Variables related to the railway vehicle

The variables, which relate to the railway vehicle, are shown on tab Railway vehicle (Figure 8.231). The description of variables is shown in Table 1.4.

![Wizard of variables](image)

Figure 8.231. Related to the railway vehicle variables

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance</td>
<td>(m) A distance which vehicle has run since the start of simulation. The variable is used for plots construction of other variables depending on the distance.</td>
</tr>
<tr>
<td>Resistance</td>
<td>(N) Resistance force caused by creep forces. It is calculated as a summarized power of creep forces of all wheel sets divided by longitudinal velocity.</td>
</tr>
</tbody>
</table>
| VControlForce| (N) Speed control force (See Sect. 8.4.2.2. "Modes of longitudinal
8.4.3.1.4. Wheel climb derailment criteria

8.4.3.1.4.1. Nadal and Weinstock criteria

Derailment criteria are variables which allow estimating a level of derailment danger by wheel climb. Often these variables are different for field test and computer-aided simulations because of lack in data available for experimental evaluation, for example, friction coefficient.

![Diagram of wheel contact forces](image)

Figure 8.232. Wheel contact forces

Derailment criteria are mainly based on the following assessment of the ratio of the total lateral (L or Y) and vertical (V or Q) forces applied to a wheel from the rail in case of one-point flange contact, Figure 8.232:

\[
\frac{L}{V} = \frac{Y}{Q} = q(\delta, \mu_y) = \frac{\tan \delta - \mu_y}{1 + \mu_y \tan \delta}.
\]

(8.13)

Here \(\delta\) is the contact angle, \(\mu_y = F_y/N\) is the ratio of the lateral creep force to the normal force in the contact, \(L = F_y, V = F_z\).
If we suppose that the longitudinal creep force is small and a pure sleep in contact takes place, i.e. $F_y \approx \mu N$ with $\mu$ as the coefficient of friction, the formula is converted to the known Nadal criterion

$$S_{L/V} = \frac{L}{V} < q_0 = q(\delta_0, \mu) = \frac{\tan \delta_0 - \mu}{1 + \mu \tan \delta_0}, \quad (8.14)$$

where $q_0$ is the Nadal value computed for the maximal value of the contact angle on flange $\delta_0$ (flange angle), Figure 8.233. This criterion is very conservative for small and negative angles of attack. Nevertheless it is often used in field tests because of difficulties with measurement of angle of attack or the lateral creep forces.

Weinstock [8] proposed an alternative and less conservative derailment criterion based of evaluation of $L/V$ ratio for both left and right wheels

$$S_W = \frac{\left( \frac{L}{V} \right)_L - \left( \frac{L}{V} \right)_R}{\mu + q_0} < 1. \quad (8.15)$$

### 8.4.3.1.4.2. Safety factor in Russian railways. Refined and combined factors

A slightly different from Nadal derailment criterion is used by Russian Railways, the so called “safety factor” is

$$S_{RU} = \frac{V}{L} q_0 > 1. \quad (8.16)$$

It is clear that the criteria are correlated and satisfy the identity

$$S_{L/V} \cdot S_{RU} = q_0$$

Some advantage of the $S_{RU}$ factor is the independence of its critical value on the coefficient of friction and flange angle.
To make the assessment of derailment danger by simulation more realistic, wheel lift is often used as the main criterion of wheel climb derailment.

Figure 8.234. Critical positions for two- and one-point contacts

The refined safety factor is

\[ S_{RU,r} = \frac{V}{L} q(\delta_0, \mu_y) = \frac{V}{L} \tan \delta_0 - \mu_y \leq 1. \] (8.17)

Its value is exactly equal to the critical value 1 when the wheel ‘starts to climb’. In case of a pair of profiles allowing the two-point contact, this position corresponds to the two-point contact with zero value of contact forces on the top of rail, Figure 8.234 left. In case of profiles with one-point contact, the critical position corresponds to the flange contact in the point with the contact angle equal to the flange angle, Figure 8.234 right. In both cases the further lift of the wheel leads to increase of the contact angle which often results in the growth of the safety factor (1.17). Therefore, it cannot be used for assessment of wheel climb beyond the critical position shown in Figure 8.234.

Figure 8.235. Wheel lift over the rail head

Second, the relative vertical displacement of a wheel over the critical position is evaluated according to the formula

\[ S_z = \frac{z_{\text{max}} - z}{z_{\text{max}}} \in [0,1], \quad z > 0, \] (8.18)

where \( z \) is the lift of the wheel relative to the position in Figure 1.205. Like the refined safety factor \( S_{RU,r} \) the lifting factor \( S_z \) is equal to unity at the critical position, Figure 8.235.

The formula for the factor combination of \( S_{RU,r} \) and \( S_z \) in Eqs. (1.17), (1.18) is

\[ S_{\text{comb}} = \begin{cases} S_{RU,r} & \text{if } z \leq 0, \\ S_z & \text{if } z > 0. \end{cases} \] (8.19)

The combined safety factor decreases continuously by passing the wheel through the critical position and subsequent vertical displacement by climb. Zero value of the factor (1.19) corre-
sponds to the wheel flange position on the top of the rail in Figure 8.236 and, in fact, to the derailment.

![Figure 8.236. Wheel top climb](image)

Value of the combined factor below unity gives a quantitative estimation of the wheel lift. For instance, the value $S_{\text{comb}} = 0.85$ corresponds to 15% lift.

### 8.4.3.1.4.3. Simulation of motion of a freight car over dangerous combination of irregularities

Consider a simulation example. An empty freight hopper with three-piece bogies runs on a tangent section of a track with speed 20 m/s. Vertical and horizontal irregularities are shown in Figure 8.237. The horizontal irregularities are the same for the left and right rail. The corresponding wave has 20 m lengths and 22 mm height. Vertical waves of 20 m length and 20 mm height differ 9 m in phase. The horizontal irregularities begin 6m after the vertical left one. Coefficient of friction in wheel/rail contacts is 0.4. Flange angle is 600. The Nadal value in this case is $q_0 = 0.79$. 

![Figure 8.237. Track irregularities at longitudinal position of Wheelset 1](image)
Safety factors (1.14), (1.16), (1.19) for the wheelset 1 are drawn in Figure 8.238. All of them show a dangerous situation. The maximal L/V ratio 1.35 is much greater than the Nadal value 0.79, the Russian safety factor is less 1, and falls down to 0.58. Finally, the combined safety factor gives the most informative result showing that the maximal wheel lift over the rail is 18%, Figure 8.239. Lateral motion of Wheelset 1 is shown in Figure 8.240 by the thick line. Thin lines depict rail positions taking into account their elastic deflections. Constant lateral shifts of the rails are equal to the flange clearance so that touching the wheelset displacement curve and a rail line indicates the state of two-point contact. Shift of the wheelset curve outside of the gangway indicates the wheel lift over the critical position.
8.4.3.1.5. Lateral and frame forces

Lateral (Y or L) and frame (H forces) present important variables using for evaluation of load on the track from the vehicle in lateral direction.

Lateral force. Total lateral force acting on the wheel along the Y-axes of the track system of coordinates (Sect. 8.2.1.3. "Switch geometry", p. 8-71).

Frame force or total force acting on the frame from the wheelset (H-force according to UIC 518).

According to the Russian regulations, the allowed frame forces are:
- empty freight car $H_p/P_0 \leq 0.38$;
- loaded freight car $H_p/P_0 \leq 0.3$;
- locomotive $H_p/P_0 \leq 0.4$.

Here $P_0$ is the static axle load.

Allowed guiding forces should be less than 100 kN.

8.4.3.1.6. Example: creating variable $\Sigma Y$

Let us create a variable $\Sigma Y$ according to UIC 518 is, that in fact is the total force acting from the track on the wheelset in lateral direction. This force differs from the H (‘frame’) force on the value of lateral wheelset inertia force. Thus, these variables are nearly equal for small speeds.

1. Create three variables for the first wheelset in Wizard of variables | Rail/Wheel tab sheet:
   - two total lateral forces $Y(L)_1l$ and $Y(L)_1r$ and frame force $H$, Figure 8.241.
Figure 8.241. Total lateral and frame forces for wheelset 1

2. on the **Expression tab** (Figure 8.242):
   - add an operator by the button;
   - drag lateral forces to the operand boxes;
   - set a name of variable and comment \((F_{y1}\) in this example);
   - send the variable to container by clicking the button.
Comparison of the created variable with the corresponding H force for the rail car AC4 is shown in Figure 8.243.

8.4.3.1.7. Example: creating variable $\Sigma H$

To create a variable, that is the sum of H (frame) forces for the leading bogie, the following steps are required:

1. create $H$ forces for all of the wheelset of the bogie ($H1$, $H2$, $H3$ variables) with the help of Wizard of variables | Rail/Wheel tab, Figure 8.244;
2. on the **Expression** tab (Figure 8.245)

- add two sum operator by the \( + \) button;
- drag variables as operands;
- set name and comment for the variable;
- send the variable to container by the \( \text{①} \) button.

---

![Figure 8.244. Creating H forces for the leading bogie](image-url)
Figure 8.245. Creating a variable "Sum of H forces for leading bogie"
8.4.3.1.8. Example: draw plots for lateral motion of wheelset in the rail gangway

By simulation of the rail vehicle dynamics, a plot of lateral movement of a WS in the rail gangway is highly useful. The gangway is obtained by plots of lateral position of the rails under the WS taking into account flange clearance, elastic deflection and irregularities, Figure 8.246, Figure 8.247 (see Figure 8.240 as well).

In case of profiles with two-point contact, the states of contact in two points correspond to touching the WS and rail plots. In case of profiles with one-point contact, the touching of plots corresponds to the critical position of the wheel (see. Figure 8.234 right). For all types of profiles, shift of the wheelset curve outside of the gangway indicates the wheel lift over the critical position, Figure 8.240.

![Figure 8.246. Lateral movement of WS1 in the rail gangway. Profiles of two-point contact](image1)

![Figure 8.247. Lateral movement of WS1 in the rail gangway. Profiles of one-point contact](image2)
Figure 8.248. **Rail position** variables

Figure 8.249. **Distance** variable
To get such plots, the corresponding variables are to be created with the **Wizard of Variables**, Figure 8.248 (rail positions), Figure 8.249 (distance), Figure 8.249 (lateral movement of a wheelset). Note that the lateral shift of a wheelset must be computed relative to the track system of coordinates, Sect. 8.4.3.1.9. "Kinematic characteristics relative to track system of coordinates", p. 8-205. Z coordinate of the point on the wheelset base is equal to the wheel radius, Figure 8.248.

It is recommended to use **Distance** variable as an abscissa, Sect. 8.4.3.1.10. "Use of Distance variable", p. 8-205.
8.4.3.1.9. Kinematic characteristics relative to track system of coordinates

Kinematical variables of bodies should be often projected on the track system of coordinates (TSC, Sect. 8.2.1.4. “Track system of coordinates”, p. 8-72). 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 8.251. 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 (Figure 8.251). To create the 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 8.251).

8.4.3.1.10. Use of Distance variable

Distance variable is created on the Railway vehicle tab of the Wizard of variables, see Figure 8.252. It denotes the travel of vehicle since start the simulation. This variable has the standard name, which should not be modified by the user. Using this variable, simulation results ob-
tained for railway vehicles running with different speed can be easily compared. Consider variants of the variable usage.

Figure 8.252. Distance variable

8.4.3.1.10.1. Use of Distance variable in graphic windows

Drag the ‘Distance’ variable into the graphical window. Select the variable and click the right mouse button. Click the **Lay off variable as abscissa** command in the popup menu.
8.4.3.1.10.2. Use of *Distance* variable in list of calculated variables

It is strongly recommended that list of object variables for a railway vehicle always contains the ‘Distance’ variable. If it does not include this variable, add it to the list before simulation or scanning the object (Chapter 4, Sect. Assignment and usage of a list of automatically calculates variables). To get dependence of computed variables on the distance after the simulation, drag it into the box **Lay off as abscissa**. After that all the variables dragged from the list into the graphic windows, table processors, etc., are processed in dependence on the distance.

![Figure 8.253. Plotting variables versus the distance](image)

![Figure 8.254. Setting dependence of calculated variables on the distance](image)
8.4.3.2. Animation window

General information about usage of animation windows can be found in Chapter 3, Sect. Animation window, and in Chapter 4, Sect. Animation window in the UM Simulation program.

Figure 8.255. Diesel locomotive TEP70 in animation window

In addition to standard functions, visualization of rails and slippers is available for railway vehicles (the Show gauge check box in the Rail/Wheel | Track | Macrogeometry tab of the object simulation inspector.

Figure 8.256. Assignment of a body to be followed by the camera

In animation window, the camera can follow a body position during the simulation. To assign the body, move the mouse cursor to the body image and click the right mouse button; select the corresponding menu command, Figure 8.256.
Figure 8.257. Contact forces in animation window. The wheel is drawn in a wired mode

Rail-wheel contact forces can be drawn in the animation window, Figure 8.257. Use the All forces tab of the Wizard of variables to create the variable for the wheelset base, and drag it into the animation window, Figure 8.258. As a rule, vector scales for forces can be corrected to get a proper length of vectors, Figure 8.259.

Figure 8.258. Creating variable for vectors of contact forces
Figure 8.259. Call of window with vector scales using popup menu of animation window
8.4.3.3. Contact animation window

The Contact animation window (Figure 8.260, Figure 8.261) is a special animation window for visualization of relative positions of rail and wheel profiles as well as rail/wheel interaction forces while simulation of a vehicle dynamics. Use the Tools | Contact animation menu command or the Ctrl+N hot key to call the window.

Window parameters are located in the bottom part. These parameters allow the user to turn on/off visualization of contact forces, change vector scales and profile positioning (horizontal or vertical orientation).

Figure 8.260. Classification of contact forces in contact animation window
Pointing the mouse cursor at a vector allows the user to get its current value. Clicking the vertical positioning circles switch on/off profiles corresponding to one of wheelsets.

Figure 8.261. Direction of motion in the animation window
8.4.3.4. Contact patch animation window

Use the **Tools | Contact patch viewer** menu command to call the contact patch viewer window (Figure 8.262).

In the **Contact patch viewer** window in the process of simulation of vehicle dynamics the user can see the following variables:

- relative position of wheel and rail profiles in the track coordinate system;
- contact points;
- vectors of normal forces;
- contact patches;
- coordinate system of the contact patch;
- adhesion zone;
- distribution of tangential forces within the contact patch in the coordinate system of the contact patch.

![Contact patch viewer window](image)

Figure 8.262. Contact patches while a vehicle is in motion in a curve. The arrow shows the direction of motion.
8.4.3.5. Table processor

The following functionals are distributed along with UM Loco module.

<table>
<thead>
<tr>
<th>Functional</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>_3Min_Mean</td>
<td>Mean value of three minimums. All functionals are evaluated according to the same algorithms with some minor differences. Local minimums are taken for _3Min_Mean and _4Min_Mean, local maximums are taken for _3Max_Mean, _3Max_Zero, _4Max_Mean and _4Max_Zero. The window of 1/20 of the length of realization is used during creating the list of local extremums. Two adjacent extremums are added into a list of extremums if the plot intersects the abscissa axis (for functional with Zero postfix) or mean value (for functional with Mean postfix) between these extremums. Otherwise the only extremum is chosen. Then 3 or 4 extremums maximum/minimum extremums are extracted. For the _4Min_Mean, _4Max_Mean and _4Max_Zero functionals the smallest/biggest one is removed. Then the mean value for the rest extremums is calculated as a value of the functional.</td>
</tr>
</tbody>
</table>
8.4.3.6. Ride comfort functionals

The additional functionals for ride comfort evaluation are available with Ride Comfort Tool.

Passenger comfort according to UIC513

**Functionals: UIC513_Nmv_axyp95, UIC513_Nmv_azp95**

**Library:** Ride_Comfort_UIC513.dll

**UIC513_Nmv_axyp95** calculates \( a_{\text{x p}95}^W \) or \( a_{\text{y p}95}^W \) from the simplified ride comfort formula (1) (see p. 7.2.1 of [1]):

\[
N_{MV} = 6\sqrt{\left( a_{\text{x p}95}^W \right)^2 + \left( a_{\text{y p}95}^W \right)^2 + \left( a_{\text{z p}95}^W \right)^2}
\]  

(1)

**UIC513_Nmv_azp95** calculates \( a_{\text{z p}95}^W \) from the simplified ride comfort formula.

**Note.** The estimated variable must have time as abscissa and be not shorter than 5 seconds duration.

These functionals are intended for processing variables created in Wizard of variables which contain values of acceleration components of different points of railway vehicles. When calculating these functionals, the estimated variable is divided into segments of 5 seconds. So the estimated variable must have time as abscissa and be not shorter than 5 seconds duration. The respective effective accelerations \( a_{\text{w}d} \) are calculated for every segment by using the method from [9]. Since the high frequency of using filters is 100 Hz, the time step of the estimated variable must be not higher than 0.005 seconds (use Step size for animation and data storage parameter of the Object simulation inspector). After all effective accelerations are calculated, they are processed by using 95\(^{th}\) percentile. The value of the percentile is the result of the functional.

So user can calculate the ride comfort by using results of these functionals by formula (2):

\[
N_{MV} = 6\sqrt{\left( \text{UIC513_Nmv_axyp95}(a_x(t)) \right)^2 + \left( \text{UIC513_Nmv_axyp95}(a_y(t)) \right)^2 + \left( \text{UIC513_Nmv_azp95}(a_z(t)) \right)^2}
\]  

(2)

where \( \text{UIC513_Nmv_axyp95}(a_x(t)) \) is the result of **UIC513_Nmv_axyp95** functional for X component of the estimated acceleration,

\( \text{UIC513_Nmv_axyp95}(a_y(t)) \) is the result of **UIC513_Nmv_axyp95** functional for Y component of the estimated acceleration,

\( \text{UIC513_Nmv_azp95}(a_z(t)) \) is the result of **UIC513_Nmv_azp95** functional for Z component of the estimated acceleration.
Sperling’s ride comfort indices

**Functionals:** Vertical\_Sperling\_Index, Lateral\_Sperling\_Index

**Library:** Ride\_Comfort\_Sperling.dll

**Vertical\_Sperling\_Index** and **Lateral\_Sperling\_Index** calculate Sperling’s ride comfort indices for vertical and lateral directions [10]. The ride comfort index for the lateral direction is calculated as

\[
W_{z} = 10 \sqrt{\int_{0.5}^{30} a^3 B_{w}^3 df}, \quad (1)
\]

where \(a\) is acceleration in frequency domain (cm/s\(^2\)), \(f\) is the frequency (Hz), \(B_{w}\) is defined by the following equation:

\[
B_{w} = 0.737 \left[ \frac{1.911 f^2 + (0.25 f^2)^2}{(1 - 0.277 f^2)^2 + (1.563 f - 0.0368 f^3)^2} \right]^{\frac{1}{2}} \quad (2)
\]

The ride comfort index for the vertical direction is calculated as

\[
W_{z} = 10 \sqrt{\int_{0.5}^{30} a^3 B_{s}^3 df}, \quad (3)
\]

where \(B_{s}\) is defined as

\[
B_{s} = 0.588 \left[ \frac{1.911 f^2 + (0.25 f^2)^2}{(1 - 0.277 f^2)^2 + (1.563 f - 0.0368 f^3)^2} \right]^{\frac{1}{2}} \quad (4)
\]

**Note.** The estimated acceleration values in UM must be in m/s.

These functionals are intended for processing variables created in Wizard of variables which contain values of acceleration components of different points of railway vehicles. These variables must be in m/s. Since the high frequency of using filters is 30 Hz, the time step of the estimated variable must be not higher than 0.0167 seconds (use Step size for animation and data storage parameter of the Object simulation inspector).
Ride comfort factor according to Russian (exUSSR) standard 24.050.16-85.

**Functionals:** Ride_Comfort_G, Ride_Comfort_V

**Library:** Ride_Comfort.dll

Ride_Comfort_V and Ride_Comfort_G calculate ride comfort indices for vertical and lateral directions according to Russian (exUSSR) branch standard 24.050.16-85 [11]

These functionals are intended for processing variables created in **Wizard of variables** which contain values of acceleration components of different points of railway vehicles. These variables must be in m/s.

**Note.** Since the high frequency of using filters is 20 Hz, the time step of the estimated variable must be not higher than 0.025 seconds (use **Step size for animation and data storage** parameter of the **Object simulation inspector**).
8.4.4. Solvers

Park solver in its two implementations is the only solver recommended for simulation of a rail vehicle dynamics, Figure 8.263 (Left panel): without use of multithread computation (Park method) and with use of multithread computation (Park Parallel). Choice of the solver is made by comparison of computational efficiency of these two solvers on the local computer for a rail vehicle model.

Let us consider some general recommendations related to the choice of rational parameters of solvers.

The recommended value of the error tolerance in the case of Park solver is 4E-6...1E-7.

The Delay to real time simulation option is activated if simulation is faster than real time, and the user wants to see the motion in the real time in an animation window.

Step size for animation and data storage sets the time step size for refreshing animation windows, adding new points in graphic windows, and computing variables in the lists of variables. The recommended value is 0.005 s for rail vehicles. Note that the default value cannot be more than this value.

The recommended values of parameters for the Park solver are shown in Figure 8.263 (Right panel). For getting precise computation, it is recommended to set zero value for the Minimal step size.
8.4.4.1. Solver: Park method

Recommended values of parameters for the Park solver are shown in Figure 8.263 right. For getting precise computation, it is recommended to set zero value for the **Minimal step** size.

If equations of motion are stiff and/or error tolerance is not small enough, the Park method shows instable solutions. As a rule, if a solver is instable, plots of some of accelerations include large oscillations with a high frequency. In such cases, it is recommended to do the follows:

- activate use of **Jacobian matrices** (JM),
- set smaller **error tolerance**, 
- set **Minimal step size** to zero.

Use of **Jacobian matrices** leads to a considerable acceleration of simulation process in the following cases:

- low speed of vehicle (less 8-10 m/s); in this case the **Jacobian for wheel/rail forces** key should be activated; *this method helps in the case of motion with a nearly constant speed*;
- vehicle model includes stiff forces, i.e. forces with large gradients due to big stiffness and damping coefficients; examples: contact forces, force element with a successive connection of spring and damper (the viscous-elastic force element).

If computation of **Jacobian matrices** is on, simulation process can be often made faster with the help of **block-diagonal Jacobians** and switching off computation of **Jacobian matrices** for non-stiff forces such as suspension springs or dampers on the **Tools** | **Forces** tab of the **Object Simulation Inspector**, Figure 8.264.

![Object simulation inspector](image)

Figure 8.264. Switching on/off evaluation of JM for force elements

**Keep decomposition of iterative matrix** option is not used for simulation of rail vehicles.
Remark. The main criterion for use of Jacobian matrices is very simple. If simulation with this option is faster and stable, it should be used. It is recommended to optimize parameters and options of the solver for each of the rail vehicle models.

8.4.4.2. Solver: Park Parallel

The new solver Park parallel is implemented in UM 8.0, Figure 8.267. In fact, this method is a combination of a special algorithm for numeric-iterative generation of equations of motion, and the Park solver for stiff ordinary differential equations. One of the main features of this method is use of multi-core processors for parallel computations, which make simulation faster in many cases.

8.4.4.2.1. Conditions for use of Park Parallel solver

The Park parallel can be used if some requirements are met.

- Numeric iterative method of generation of motion equations must be set for the vehicle model in the UM Input program, Figure 8.265.
- Mass and moments of inertia relative to the X, Y, Z axes for all of the bodies must be positive.
- Using Park Parallel for simulation of hybrid models, which include flexible bodies (UM FEM) and interfaces with Matlab\Simulink is not supported.
- 3D contact elements are ignored (see Chapter 3 of the user’s manual).

Figure 8.265. Numeric-iterative method of generation of equations; the Object tab of the inspector in UM Input program

If the model does not satisfy these requirements, the corresponding message appears, and the list of violations is stored in a text file, Figure 8.266.
Figure 8.266. Message about impossibility of use the Park Parallel, and list of violations

8.4.4.2.2. Solver parameters

**CGM solution method**

CGM is iteration of Conjugate Gradient Method. The CGM is used for more precise solving stiff equations. If **Solution method** is set to **CGM**, the full JM are used otherwise the block-diagonal JM are applied. There are no exact recommendations for use of CG iterations. The user should follow the simple method: the key is activated if the simulation becomes faster.

If the CG iterations are used, the **CGM error** must be specified. As a rule, results are good even for low accuracy 0.1.

**Use of threads**

Threads can be used for computers with multi-core processors. The number of threads for parallel computations cannot exceed the maximal number of processor cores (physical and logical). Optimal number is determined by the experience. Nowadays, four- and eight-core processors are the most efficient. In some cases, use of parallel computations improves the solver performance by factor 2.5-3, see Sect. 8.4.4.3. "Comparison of solver performances in simulation of freight car with three-piece bogies", p. 8-222.
8.4.4.3. Comparison of solver performances in simulation of freight car with three-piece bogies

Consider an example of simulation of an empty hopper with three-piece bogies 18-100, Figure 8.268. The advanced model of a freight car is used compared to simplified one delivered with UM ([UM Data]SAMPLES\Rail_vehicles\simple_18_100). The advanced model includes friction wedges as rigid bodies with six degrees of freedom. The model has 114 d.o.f., and it is accepted by Russian Railways as the standard by safety problem analysis [9].
Remark. The model of a freight car \([\text{UM Data}]\SAMPLES\Rail\_vehicles\simple\_18\_100\) uses programming in UM environment for evaluation of friction wedge forces, and cannot be simulated with the Park Parallel solver.

Consider simulation of motion of the hopper in curve \(R=600\, \text{m}\) (Figure 8.269) speed 20 m/s, simulation time 15 s. Solver parameters and options correspond to Figure 8.263.

![Figure 8.269. Parameters of curve](image)

Comparison of solver performance for different forms of generation of equations of motion and variants of use of JM is summarized in Table 1.5. Computations were made on the four-core processor (all cores are physical): Intel Core 2 Quad CPU Q6700 @ 2.67 GHz

<table>
<thead>
<tr>
<th>Solver</th>
<th>Number of threads</th>
<th>CPU time, s</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Without use of JM</td>
<td>With use of JM</td>
<td>Block-diagonal JM</td>
<td></td>
</tr>
<tr>
<td>Park method</td>
<td>1</td>
<td>40.7</td>
<td>16.1</td>
<td>15.4</td>
<td></td>
</tr>
<tr>
<td>Symbolic equation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Park method, numeric-</td>
<td>1</td>
<td>-</td>
<td>20.4</td>
<td>23.2</td>
<td></td>
</tr>
<tr>
<td>iterative equations</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The following conclusions can be drawn from these results.

1. The model is stiff because the use of JM makes the simulation much faster. This conclusion is quite evident; the model includes a lot of contacts with high stiffness.

2. If the Park method is used as a solver, generation of equations of motion in symbolic form is recommended. The user must set the corresponding option in Figure 8.270 and follow the instructions of Chapter 3, Sect. Compilation of equations of motion.

3. Sometimes use of block-diagonal JM is recommended.

4. The Park Parallel solver in this case is much faster than the Park method, even if the parallel computation are not used

5. Use of multithread computations improves the performance up to factor 2.3.

6. For the considered model, the use of block-diagonal JM (CG iterations is not active, Figure 8.267) in Park Parallel solver makes simulation slower. Other models of rail vehicles may show an opposite result.

7. The main conclusion is as follows. The combination of the new solver and a computer with a high performance leads to efficient simulation of the freight car, which is four times faster than real time!

Remark. In the case of scanning projects, the parallel computations are not used because a simultaneous run of several applications makes the total simulation faster (see the manual to UM Cluster, Chapter 6).
8.5. Scanning projects with models of rail vehicles

Here we suppose that the UM Experiments module is available in UM configuration, Figure 8.271.

8.5.1. List of internal identifiers parameterizing operation conditions of rail vehicles

Analysis of the rail vehicle dynamics with UM Experiments module has some features, that we discuss in these section. To improve the efficiency of scanning projects with rail vehicle, standard internal identifiers for operation conditions of a rail vehicle are introduced (macro-geometry, irregularities, profiles of wheels and rails end so on). These identifiers can be used for variation of the corresponding conditions in numeric experiments.

The list of internal identifiers is available on the Alternatives | Hierarchy of parameters tab, the List of parameters group, the RVParameters (Rail Vehicle Parameters) branch, Figure 8.272.
The full list of parameters is collected in Table 1.6.

Table 8.9

List of standard internal identifiers

<table>
<thead>
<tr>
<th>Branch of identifiers tree</th>
<th>Name of identifier</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>General</td>
<td>_irr_type</td>
<td>Type of irregularities. 0: no irregularities, 1: file, 2: deterministic, Sect. 8.4.2.4.3. &quot;Assignment of track irregularities&quot;, p. 8-159.</td>
</tr>
<tr>
<td></td>
<td>_irr_group</td>
<td>Number of irregularity group starting with 1, Sect. 8.4.2.4.3.1. &quot;Irregularities from file. Group of irregularities&quot;, p. 8-159.</td>
</tr>
<tr>
<td></td>
<td>_scr_scw_distance</td>
<td>(mm), distance between SC rail and SC wheel. The parameter specifies gauge, Sect. 8.2.1.1. &quot;Geometry of rails in an ideal track&quot;, p. 8-66.</td>
</tr>
<tr>
<td></td>
<td>_y_irr_factor</td>
<td>Scaling factor for lateral file irregularities, Sect. 8.4.2.4.3.1. &quot;Irregularities from file. Group of irregularities&quot;, p. 8-159.</td>
</tr>
<tr>
<td></td>
<td>_z_irr_factor</td>
<td>Scaling factor for vertical file irregularities, Sect. 8.4.2.4.3.1. &quot;Irregularities from file. Group of irregularities&quot;, p. 8-159.</td>
</tr>
</tbody>
</table>
Profiles | _i_wheel_profile | Number of wheel profile in the list starting with 1, Sect. 0.

**Gauge measuring interval** is a distance below a plane that rests across the top of the two rails which defines gauge measuring points taking the rail inclination into account (Figure 8.172). It is used to create *Gauge* variable, see. Sect. 8.4.3.1.2. "Variables related to the wheelset", p. 8-190.

---

<table>
<thead>
<tr>
<th>Track stiffness/damping</th>
<th>Sect. 8.4.2.4.1.1. &quot;Track stiffness and damping&quot;, p. 8-152.</th>
</tr>
</thead>
<tbody>
<tr>
<td>_z_rail_stiffness</td>
<td>(N/m) Vertical rail stiffness constant</td>
</tr>
<tr>
<td>_y_rail_stiffness</td>
<td>(N/m) Lateral rail stiffness constant</td>
</tr>
<tr>
<td>_z_rail_damping</td>
<td>(Ns/m) Vertical rail damping constant</td>
</tr>
<tr>
<td>_y_rail_damping</td>
<td>(Ns/m) Lateral rail damping constant</td>
</tr>
<tr>
<td>_torsional_rail_stiffness</td>
<td>(Nm/rad) Torsional rail stiffness constant</td>
</tr>
</tbody>
</table>

| Wheel radii difference, Sect. 8.4.2.7.2. "Wheel radii difference", p. 8-184. |
|-----------------------------|------------------------------------------------|
| _dr_wheel_\[n\]l           | (mm) Radius differences for left and right wheels, wheelset n |
| _dr_wheel_\[n\]r           |                                                 |

<table>
<thead>
<tr>
<th>Rail/wheel contact friction coefficient</th>
<th>_cfriction_left</th>
<th>Running surface of left rail</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>_cfriction_right</td>
<td>Running surface of right rail</td>
</tr>
<tr>
<td></td>
<td>_cfriction_left_s</td>
<td>Side face of left rail</td>
</tr>
<tr>
<td>Sect. 8.4.2.5</td>
<td>_cfraction_right_s</td>
<td>Side face of right rail</td>
</tr>
<tr>
<td>--------------</td>
<td>------------------</td>
<td>------------------------</td>
</tr>
<tr>
<td>Sect. 8.4.2.4</td>
<td>_type_z</td>
<td>Type of vertical irregularity. 0: h/2(1-cos x); 1: h</td>
</tr>
<tr>
<td>Sect. 8.4.2.5</td>
<td>_l_z</td>
<td>Wave length of vertical irregularity L</td>
</tr>
<tr>
<td></td>
<td>_h_z</td>
<td>Height of vertical irregularity H</td>
</tr>
<tr>
<td></td>
<td>_s0_z</td>
<td>Start of left vertical irregularity</td>
</tr>
<tr>
<td></td>
<td>_ds0_z</td>
<td>Shift of the right vertical irregularity</td>
</tr>
<tr>
<td></td>
<td>_count_z</td>
<td>Number of waves of vertical irregularity N</td>
</tr>
<tr>
<td>Rail/wheel contact,</td>
<td>_l_y</td>
<td>Wave length of lateral irregularity L</td>
</tr>
<tr>
<td>Sect. 8.4.2.5</td>
<td>_h_y</td>
<td>Height of lateral irregularity H</td>
</tr>
<tr>
<td></td>
<td>_s0_y</td>
<td>Start of left lateral irregularity</td>
</tr>
<tr>
<td></td>
<td>_count_y</td>
<td>Number of waves of lateral irregularity N</td>
</tr>
<tr>
<td>_contact_model</td>
<td>Model of creep forces. 0: simplified 1: Mueller, 2: FastSim, 3: FastSimA, 4: Minov</td>
<td></td>
</tr>
<tr>
<td>_sc_eq_conicity</td>
<td>Equivalent conicity λ</td>
<td></td>
</tr>
<tr>
<td>_sc_eq_cont_ang_par</td>
<td>(rad/m) Equivalent contact angle parameter</td>
<td></td>
</tr>
<tr>
<td>_sc_cont_ang0</td>
<td>(deg.) Nominal contact angle β0</td>
<td></td>
</tr>
<tr>
<td>_sc_dy2_max</td>
<td>(mm) Maximal lateral displacement y*</td>
<td></td>
</tr>
<tr>
<td>_sc_cont_ang2</td>
<td>(deg.) Flange contact angle β*</td>
<td></td>
</tr>
<tr>
<td>_sc_y2</td>
<td>(mm) Y coord. of flange contact y_r*</td>
<td></td>
</tr>
<tr>
<td>_sc_z2</td>
<td>(mm) Z coord. of flange contact z_r*</td>
<td></td>
</tr>
<tr>
<td>_fastsim_nstrips</td>
<td>FastSim : number of strips</td>
<td></td>
</tr>
<tr>
<td>_fastsim_nelem</td>
<td>FastSim : number of elements</td>
<td></td>
</tr>
<tr>
<td>Macro-geometry,</td>
<td>_mg_type</td>
<td>Type of macrogeometry 0: tangent, 1: curve, 2: S curve, 3: switch, 4: file</td>
</tr>
<tr>
<td>Sect. 8.4.2.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>.2. &quot;Track macrogeometry&quot;, p. 8-</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
8.5.2. Example: factorial experiment

An example of a factorial experiment is shown in Figure 8.273. In this experiments, influence of nine factors is estimated five of which are specified by internal identifiers.
Figure 8.273. Hierarchy of parameters in factorial experiment
8.6. Methods for evaluation of critical speed

It is recommended to use two methods for evaluation of the critical speed of rail vehicle. In both cases it is recommended to apply a short lateral irregularity, which initiates the perturbation of motion of a rail vehicle in lateral direction, as well as vertical irregularities along the full travel distance.

Figure 8.274. Typical parameter values for deterministic irregularities in evaluation of critical speed

Deterministic irregularities are suitable for setting both lateral and vertical irregularities, Sect. 8.4.2.4.3.2. "Deterministic irregularities", p. 8-161. An example of such irregularities is shown in Figure 8.274. The following requirements should be met:
- vertical irregularities must be harmonic, equal for the left and right rail, and long enough due to large number of waves N;
- horizontal irregularity must be short; the recommended number of waves is 1.
8.6.1. Method of slow decrease of speed

The neutral mode of longitudinal motion should be set, Sect. 8.4.2.2.1. "Neutral", p. 8-140. Initial speed $v_0$ must be greater than the critical speed. It is to impart a small deceleration 0.1-0.2 m/s$^2$ to a rail vehicle. To do this, a constant force

$$F_x = -Ma$$

is to be applied to the car body of a rail vehicle, where $M$ is the mass of a rail vehicle, and $a$ is the desired value of the deceleration.

The force must be preliminary described in the UM Input program. Add a T-force and set its longitudinal component by an identifier with zero default value. The force vertical application point should be at the automatic coupler level, Figure 8.275.

To estimate the stability of a rail vehicle, a plot of lateral motion of the first wheelset versus speed is used. Two variables are created in the Wizard of variables and dragged into a graphic window, see Figure 8.276, Figure 8.277. The speed must be taken as abscissa: select the speed variable in the graphic window, call the popup menu by the right mouse button, and run the corresponding command, Figure 8.278.

Then set (Figure 8.279):

- a desired and negative (!) value for the identifier of the braking force,
- value of the initial speed $v_0$,
- big enough simulation time,
- neutral mode of longitudinal motion.
- track type: tangent.

It is recommended to deactivate drawing rails in animation window, because computation of a long track image requires a lot of time.

![Figure 8.275. Longitudinal force](image)
Figure 8.276. Creating variable: longitudinal speed of the vehicle

Figure 8.277. Creating variables: lateral displacement of the first wheelset
Figure 8.278. Variable $v_x$ is taken as abscissa

Figure 8.279. Preparing evaluation of critical speed
Critical speed can be estimated on the plot like in Figure 8.280. We have obtained this plot for the model of rail car AC4 (\texttt{UM Data\\SAMPLES\\Rail\_Vehicles\\AC4}). Critical speed is about 30 m/s as a boundary value between stable motion of the wheelset and its oscillations.

![Figure 8.280. Lateral oscillations of WS1 versus speed](image1)

Note that if we set zero value of vertical irregularities, the critical speed will be about 42 m/s according to the plot in Figure 8.281. This value of critical speed is wrong. The large difference in results appears because of inclined friction dampers in the model of the rail car. In the case of simulation without vertical irregularities, the friction dampers come to the sticking mode when the speed was big enough, and we have got quite different behavior of the vehicle.

![Figure 8.281. Lateral oscillations of WS 1 versus speed without vertical irregularities](image2)
8.6.2. Evaluation of critical speed by multivariant calculations

We suppose in this section that the UM Experiments is available, see Figure 8.271.

The following steps are required for evaluation of critical speed by a scanning project.

1. Create a new scanning project by the Scanning | New project… menu command.
2. Load the rail vehicle model by the button, Figure 8.282.

![Figure 8.282. List of speed values for evaluation of critical speed](image)

3. Create a list of speeds; the lowest speed must correspond to the stable region, the highest one must be greater than the critical speed.
   - click on the speed identifier \( v_0 \) in the identifier list, Figure 8.282;
   - create a list of speeds with some step size, e.g. in 1 m/s.
Figure 8.283. List of speeds

4. Set deterministic irregularities in the Alternatives | Rail/Wheel | Track | Irregularities tab, Figure 8.274. Assign wheel and rail profiles, set other parameters and options. If necessary, assign identifier values.

Figure 8.284. Processing results

5. Use the Wizard of variables to create a variable corresponding to lateral motion of the leading wheelset. Drag the variable in the Alternative | Variables tab.

7. After end of the computations, open the Results | Wizard of graphs tab and create a plot of RMS of the lateral WS motion vs. speed, Figure 8.284:

- select **Group1** in the list **Parameter**;
- set **Units** to **Milli**;
- double click on the variable **ry**;
- analyze the results; the critical speed lies in the region of growth of the RMS value.

In our case the critical speed lies in the interval from 30 to 31 m/s, which is close to the result obtained by the slow decrease of the speed.
References


[16] Электроподвижной состав с асинхронными тяговыми двигателями /Н.А. Ротанов,
Chapter 8. Railway Vehicle Dynamics
