UNIVERSAL MECHANISM 9

User`s manual

Simulation of Longitudinal Train Dynamics

2020

Contents

15. Simulation of longitudinal train dynamics

15.1. Introduction

Large longitudinal in-train forces are dangerous in a safety sense. They appear mainly by braking, and must be limited taking into account safety standards. Thus, the numeric evaluation of in-train forces is an important problem.

The train simulation module **(UM Train)** automates the process of creating and numeric analysis of railway trains including any number of units (railway cars and locomotives). Longitudinal dynamics of trains is computed in different types of running: braking, traction, etc. All variables necessary for the estimation of the train dynamics are computed at simulation such as in-train forces, braking forces, velocities, accelerations, inertial forces and so on.

UM Train includes a database of Russian cars, locomotives and wagon connections, which are used for creating train models. Tools allowing the user to develop railway units and couplings are available as well.

Each railway unit in a train model has only one or a few degrees of freedom. The advanced simulation of train dynamics is available with **UM Train3D** module, which allows including any number of 3D models of railway vehicles **(UM Loco)** in a train model along with simplified vehicle models.

15.2. Generalities

As a rule, simplified models of railway vehicles are used for train dynamics simulation in which vertical and lateral dynamics are neglected. All bodies of such railway vehicle model move translationally along one and the same line. A separate vehicle can consist of any number of bodies connected by force elements. For example, in the simplest case of the simulation of dynamics of a partially filled tank car, an additional mass is introduced which is connected to the carbody by an elastic-dissipative force element. The values of the additional mass, stiffness and dissipative coefficients can be determined experimentally or on the basis of simplified models of liquid sloshing.

The motion of a train in a curve is modeled by introduction of an additional resistance force which depends on vehicle mass, curve radius and in some models on vehicle speed. In transient curves, the resistance force increases from zero value to the value for a curve of constant radius (on entering a curve) and decreases to zero again (on exit).

When traveling on a tangent track with a grade (uphill and downhill), the additional longitudinal component of gravity force is introduced.

Separate vehicles of a train are connected by force elements which simulate wagon connections (cushioning devices with couplers). As a rule, bipolar forces are used for this.

When creating elements of a train model (cars, locomotives, coupling devices) the following conditions should be taken into account:

- about standard identifiers which parameterize some geometrical, force and inertial vehicle properties;
- about standard names of bipolar elements which simulate wagon connections;
- about standard comments which describe model elements;
- about standard connection points used for connection of force elements which model wagon connections.

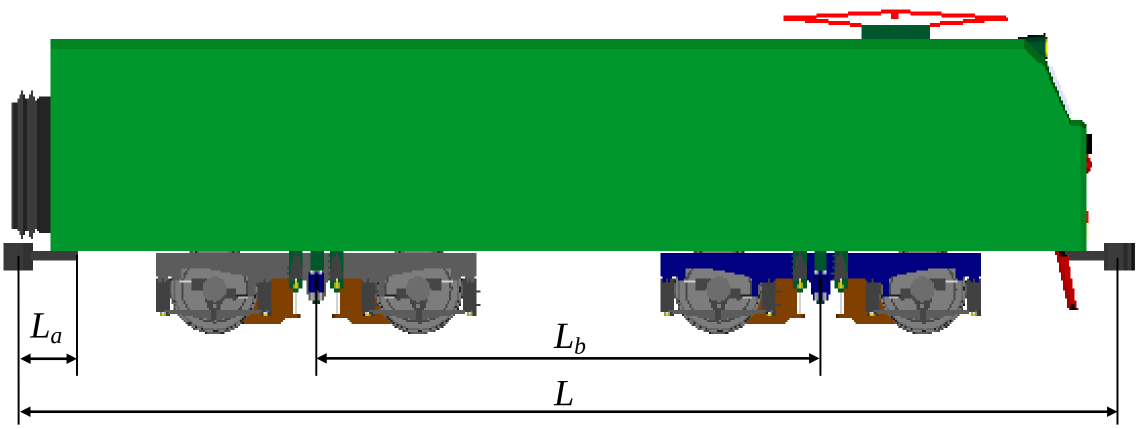


Figure 15.1. Standard geometrical vehicle parameters.

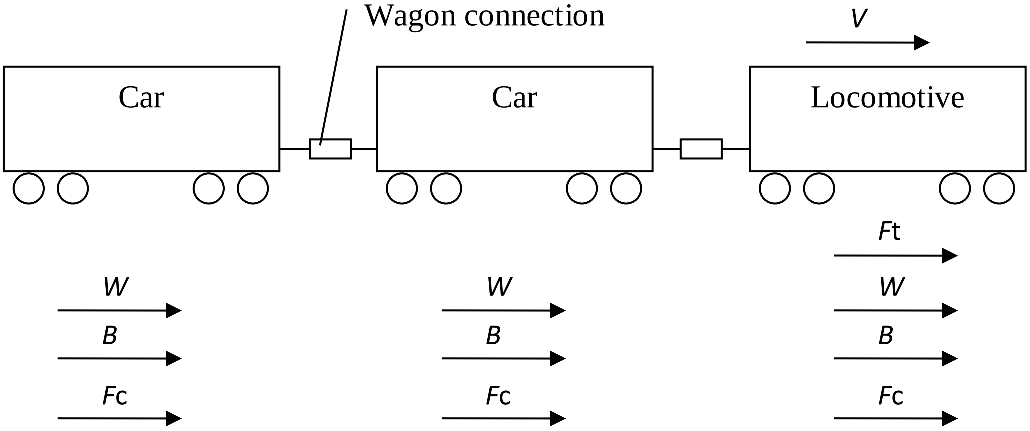
Geometrical parameters which must be set by standard identifiers are presented on Figure 15.1.

L is the vehicle length over couplings;

L_b is the bogie base; L_a is half the wagon connection.

15.3. Train model

Schematically, the train model used in module **UM Train** may be represented as follows



Forces on the scheme: F_t is traction or dynamic brake force, W is resistance force, B is pneumatic brake force, F_c is force in wagon connections.

The forces F_t and B are limited by the adhesion force, which is calculated by the formula:

$$F_{adh} = \eta \cdot \psi \cdot 9{,}81 \cdot M, \tag{15.1}$$

where η is adhesion weight usage factor (used in both traction and braking modes), ψ is adhesion coefficient between wheel and rail, M is vehicle mass, kg.

The adhesion weight usage factor shows what part of the theoretically possible traction force can realize the locomotive. For modern locomotives, this factor, as a rule, is higher than 0.92. The same factor is used for the limitation of the maximum braking force.

These parameters are defined as follows:

The adhesion weight usage factor is defined in a model by using identifier *adhesive_weight_factor*. If the identifier is not added to the model, the factor is equal to 1.

The adhesion coefficient is given by friction between wheel and rail when creating a railway track model, see Chapter 8, Sect. 8-5.1.3. *Creating of macro-geometry files*.

The mass of a vehicle is set by identifier *Mass*, see. Sect. 15.4.2. *"Required elements of vehicle model"*, p. 15-8.

15.4. Development of train model

The first stage of the train model creation is opening the **Train wizard** by using the **Tools | Train wizard** menu item, Figure 15.2.

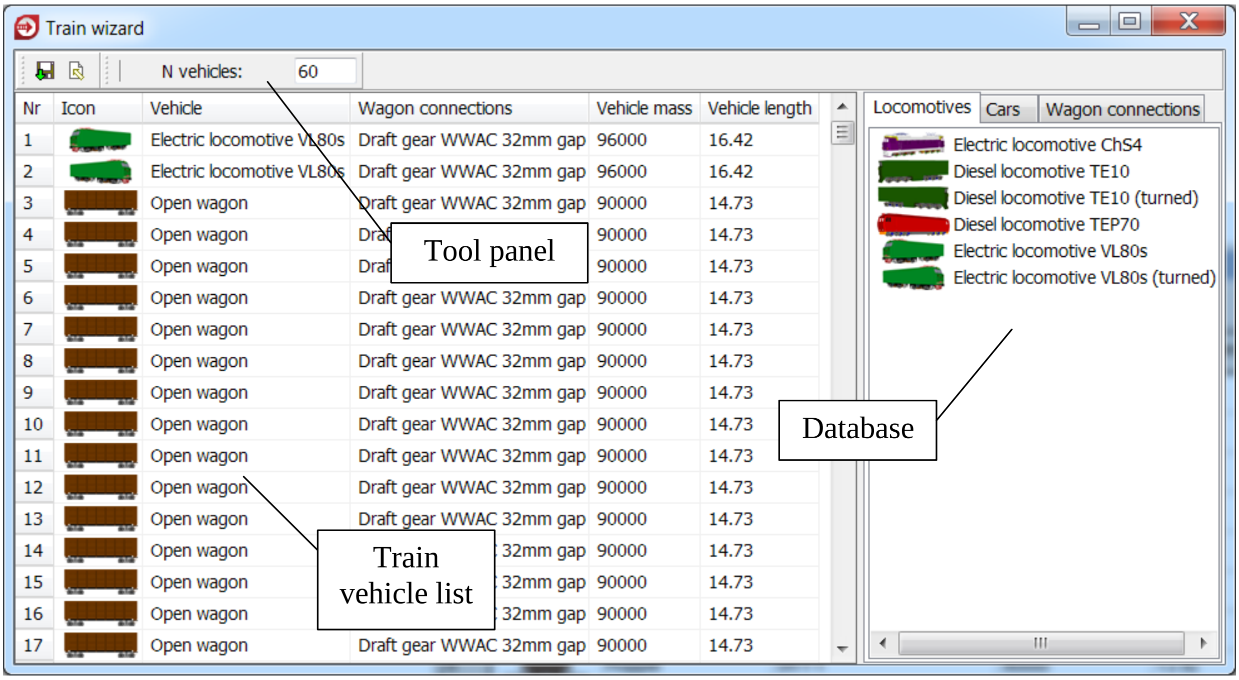
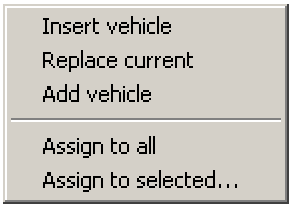


Figure 15.2. Train wizard.

When creating a train model the user points the number of vehicles in the model with the help of the **Wizard**. Necessary models of locomotives, cars and wagon connections for the designed train model are selected from the respective tabs of the database on the right side of the **Wizard**.

Let us describe the **Wizard** more detailed. To insert the selected vehicle from the database into the train vehicle list, double-click it or use the **Insert vehicle** command from the popup menu.



Database popup menu commands:

- **Insert vehicle** – insert the selected vehicle from the database into the train vehicle list,
- **Replace current** – replace the current vehicle in the train vehicle list by the selected one in the database,
- **Add vehicle** – add the selected vehicle to the end of a train model,
- **Assign to all** – assign the selected vehicle to all vehicles of a train model,

- **Assign to selected…** – assign the selected vehicle to the vehicles checked in the **Choice the element from list** form, Figure 15.3. Only “empty” vehicles are checked by default.

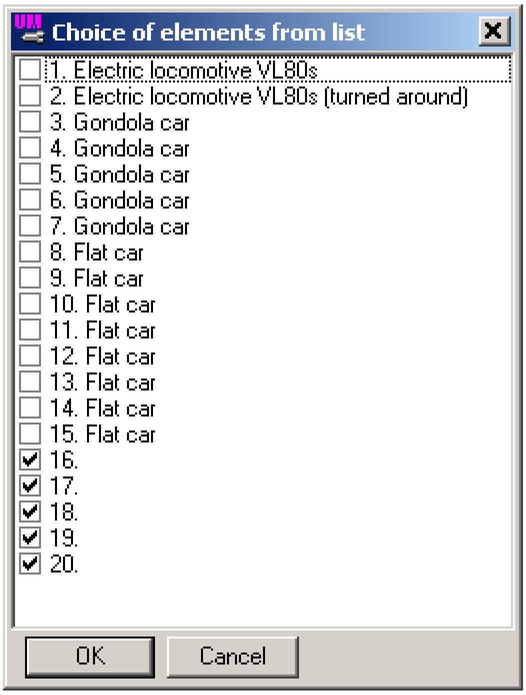


Figure 15.3. List of vehicles for popup menu item **Assign to selected…**

When a train model is ready, it is necessary to open it in new object or save. To open the model in new object, click the button on the tool panel.

To save it click the **Save as…** button. After the user should open the saved model in the **UM Input**, correct the model, if necessary, and compile it.

15.4.1. Data base

The database of railway vehicles can be added with any model of a vehicle. For this in the simplest case it is enough to create the graphical image of the vehicle, one body and one joint, assign the required identifiers (vehicle length over couplings, vehicle mass etc.) and tractive effort curves for locomotives. Every vehicle of a train in terms of “Universal Mechanism” is a subsystem which can be a model of any complexity. Though in most cases it is enough to create a single-mass model of a vehicle, more precise vehicle model can be included in a train model to make more detailed analysis of a separate vehicle.

Files of database are stored in the folder **{UM Data}\RW\Train**. This folder contains the following subfolders:

- ..*Absorbers* – the folder with wagon connection models;
- ..*Brakes* – the folder with brake system models;
- ..*Cars* – the folder with car models;
- ..*Liquid* – the folder with fluid dynamics models for tank cars;
- ..*Locomotives* – the folder with locomotive models;
- ..*Resistance* – the folder with resistance force models.

15.4.2. Required elements of vehicle model

The list of required elements of a vehicle model which will be added to the data base and used in the **Train wizard** to create a train model are shown in the Table 15.1. When creating new vehicle model a user should pay attention to the presence and correct usage of these elements.

Table 15.1

Required elements of vehicle model

Name	Type	Description
CouplingBase	*identifier*	Vehicle length over couplings, m.
VehicleBase	*identifier*	Vehicle base, m.
Mass	*identifier*	Vehicle mass, kg.
Throttle_Position	*identifier*	The number of throttle position (required for locomotive models).
FrontCouplingPoint	*connection point*	The connection point to the previous vehicle.
RearCouplingPoint	*connection point*	The connection point to the next vehicle (required for connection with 3D vehicles).
Vehicle	*body*	The body to which external forces are applied.
Liquid	*body*	The body to model liquid in a tank (required for tank car models).

The identifiers *CouplingBase* and Mass are used in the **Train wizard**, Figure 15.2: their values are set in the corresponding columns. Note, that the *Mass* identifier sets the full mass of whole vehicle, i.e. the sum of masses of all bodies including in the vehicle model. For example, the tank car model *Tank_liquid*, distributed with UM, contains two bodies: the first one *Liquid* with mass *MLiquid* and the second body named *Vehicle* with mass calculated as *Mass-MLiquid*.

Identifier *VehicleBase* sets vehicle base.

Identifier *Throttle_Position* sets the number of throttle position in a locomotive model. A vehicle will be identified as a locomotive (traction unit) only if it contains this identifier.

Any vehicle model should contain two connection points *FrontCouplingPoint* and *RearCouplingPoint*: the first one is used for connection with the previous vehicle and the second one for connection with 3D vehicle model added to a train model.

A vehicle model should contain a body with name *Vehicle* to which external forces are applied. If a model has only this body then its mass must be set by *Mass* identifier.

A body named *Liquid* must be present in a vehicle model if a tank car model, which will use liquid models included in UM software, Sect. 15.4.5. *"Wagon connection model"*, p. 15-13, is created. If a user realizes a liquid model by himself then this requirement is optional.

15.4.3. Additional elements of vehicle model

In addition to the required elements, which are necessary when creating a train model, the identifiers that define some vehicle parameters can be added to the vehicle model. The list of these identifiers are shown in Table 15.2.

Table 15.2

Additional elements of vehicle model

Name	Type	Description
N_throttle_positions	identifier	The number of throttle positions in traction mode.
Dynamic_brake_position	identifier	Throttle position in dynamic brake mode.
N_dynamic_brake_positions	identifier	The number of throttle positions in dynamic brake mode.
Adhesive_weight_factor	identifier	Adhesion weight usage factor, see Sect. 15.3. *"Train model"*, p. 15-5.

15.4.4. Vehicle model

Let us consider a railway vehicle model from the database by the example of the model of diesel-locomotive TE10, Figure 15.4, which is a single-mass system with one degree of freedom – the translation along the railway track.

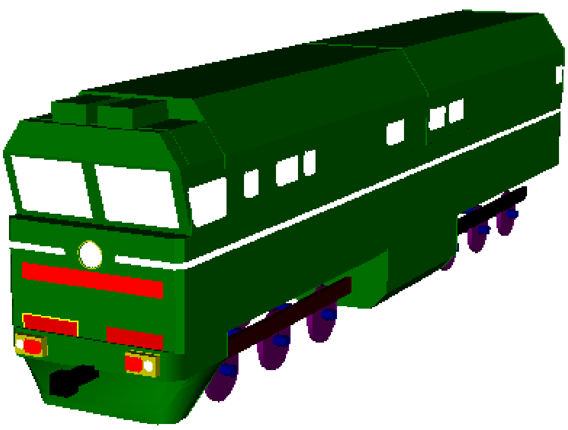


Figure 15.4. Model of TE10 diesel-locomotive.

The model consists of one body named *Vehicle*, one graphical image *Locomotive*, one translational joint *jVehicle*, and one bipolar force *RearCoupling*.

The *Vehicle* body represents the carbody of the vehicle model. Its parameters are presented in Figure 15.5. The body named *Vehicle* must always be in a vehicle model. In this example, only mass is set since the body has no rotational degrees of freedom. Mass value is set with the help of required identifier *Mass*, see Sect. 15.4.2. *"Required elements of vehicle model"*, p. 15-8.

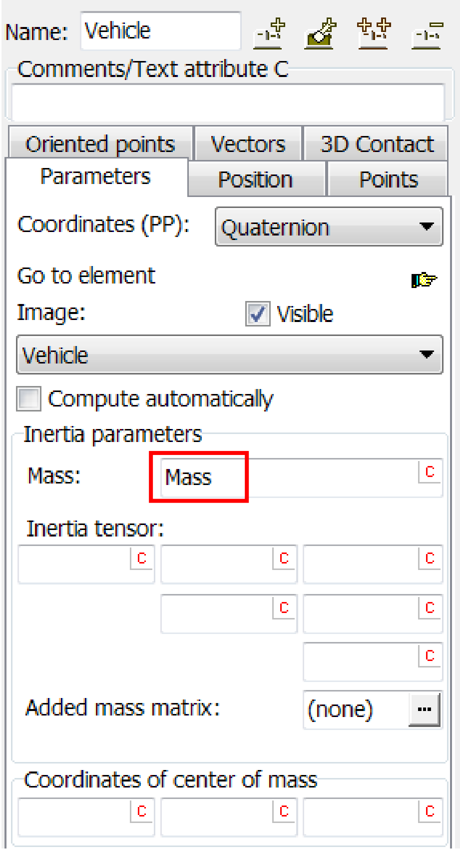


Figure 15.5. Parameters of Vehicle body.

Every vehicle model must have two connection points, at the least, Figure 15.6. They indicate attaching points of wagon connections (couplers).

The *FrontCouplingPoint* is used for connection of 1D models (simplified model). The wagon connection of the previous vehicle is connected to this point.

The *RearCouplingPoint* is used for connection of 1D model to 3D model (UM Loco models).

These connection points can belong to any body of a vehicle model. In this example, both these points belong to *Vehicle* body.

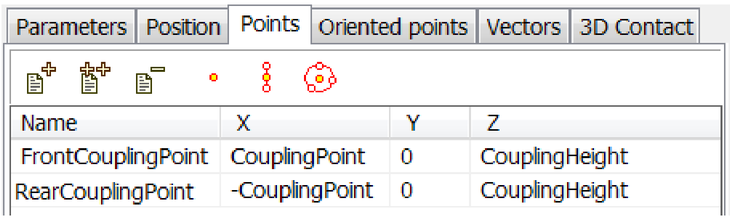


Figure 15.6. Connection points for *Vehicle* body.

Geometry parameters of the *jVehicle* joint are presented in Figure 15.7.

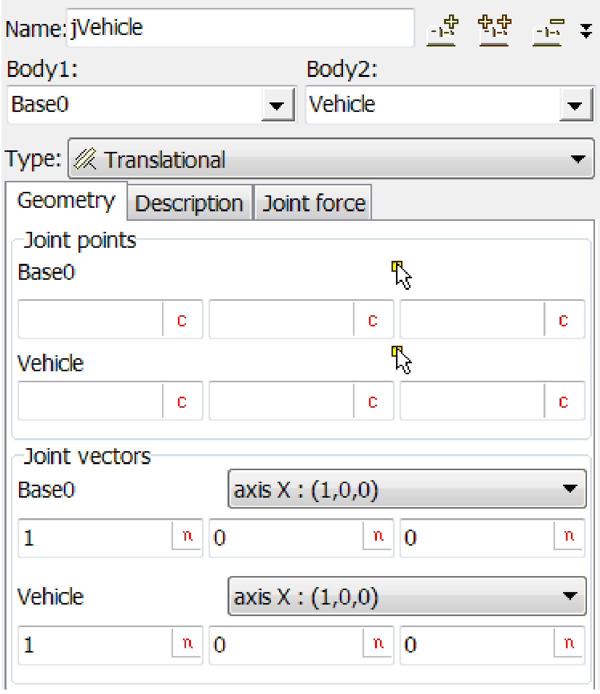


Figure 15.7. Parameters of jVehicle joint.

The locomotive model is fully parameterized. The list of identifiers, added to the model, is shown in Figure 15.8. The required identifiers for this model are *CouplingBase*, *VehicleBase* and *throttle_position*.

Whole list | Geometry | Coupling | Inertia

Name	Expression	Value	Comment
CouplingBase	16.969		Distance between coupling centres
WheelRadius	0.525		Wheel radius
Mass	1.2750000E+5		Vehicle mass
AxleOver	0.6		Wheel axle over
CouplingLength	2		Coupling length
BodyZ	1.5		Distance between rail head and car body bottom
VehicleBase	8.6		Distance between bogie centres
BogieBase	4.2		Bogie wheel base
WheelDistance	1.58		Distance between wheel treads
CouplingPoint	CouplingBase/2-CouplingLength/2	7.4845	Attachment point of coupling
CouplingHeight	1.05		Distance between rail head and coupling axis
CouplingOver	0.5		Coupling over
h	1.3+BodyZ	2.8	
throttle_position	0		Throttle position
n_throttle_positions	15		Count of throttle positions

Figure 15.8. Model identifiers.

Moreover the *sbTraction* joint force which models tractive effort is added to the model.

The type of this force must be set as **List of characteristics**. This type allows creating the dependence of force on coordinate, velocity or time by a set of curves. In this case the set of tractive effort curves of the described diesel locomotive was created with the help of this type of force, Figure 15.9. The **Curve identifier** edit box contains the name of the identifier which sets the throttle position (the number of the curve from the list): value *0* means zero force (free running), value *1* means the first curve (Curve 1, Figure 15.10), *2* means the second one etc. In the example in Figure 15.9, the *throttle_position* identifier sets the throttle position.

Note!	Creating of identifier *throttle_position* is a mandatory step for traction units. Without this identifier, the model will not be identified as a locomotive. If there is no need to model the traction force, but it is important that the model is identified as a locomotive, for example, for the speed profile traction mode, it is necessary to enter the *throttle_position* identifier fictitiously that is just add it to the list of identifiers.

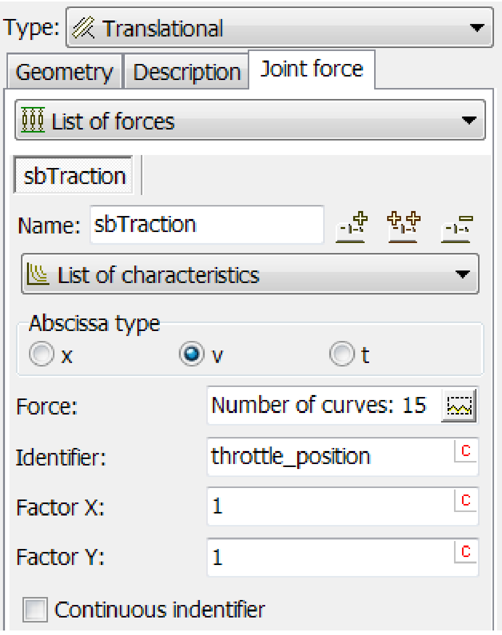


Figure 15.9. Setting tractive effort.

In Figure 15.10, the window for setting tractive effort curves is shown. The list of curves is situated on the lower right-hand side of the window; the list of points of the current curve is on the upper right-hand side (in this case for *Curve1*).

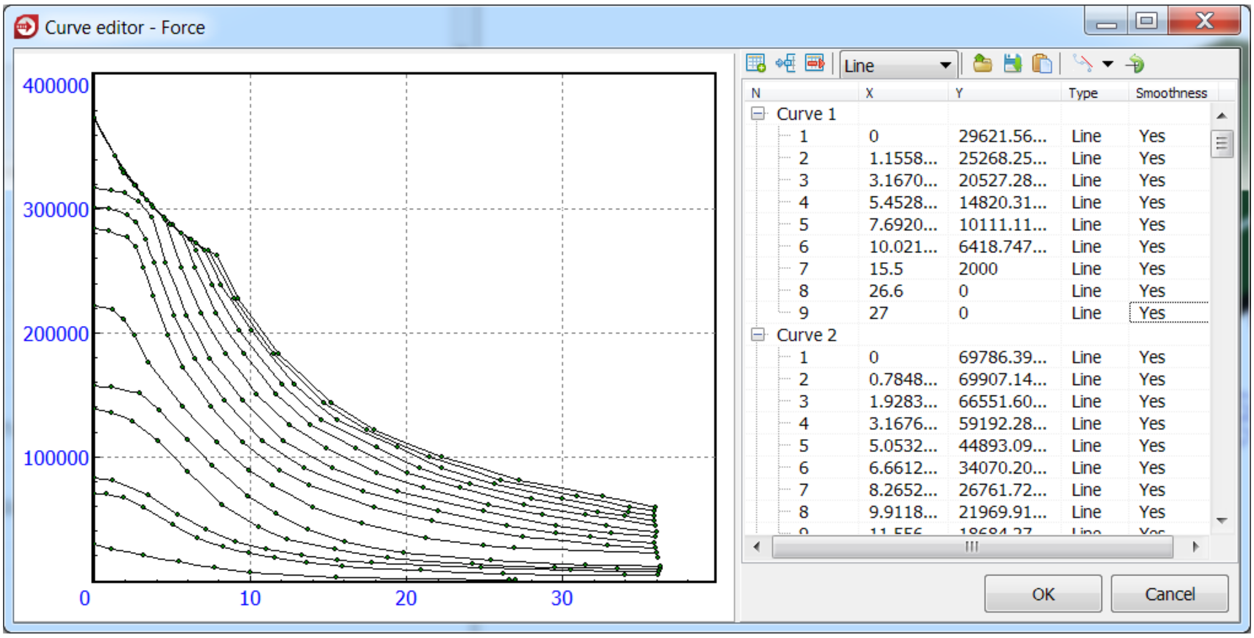


Figure 15.10. Tractive effort curves.

In a vehicle model, a bipolar force named *RearCoupling* which models the wagon connection to the next vehicle. This force is used by default if it is not replaced by other model in the **Train wizard**.

Single-mass car models are created in the same way, saving that there is no the joint force for modeling tractive effort and the *throttle_position* identifier.

15.4.5. Wagon connection model

Wagon connection in a UM train model is a force element which models the behavior of the set of all devices connected two neighbor cars. For example for a freight car, a wagon connection model at least contains two mounted friction draft gears in tandem.

In terms of UM, wagon connections are modeled by bipolar elements. This force can be directly set in a vehicle model (with name *RearCoupling*). In this case, this element will be used by default, if it is not overlapped in the **Train wizard**.

The wagon connection data base, as well as the vehicle data base, can be filled by user.

15.4.6. Tank car model

The model of the tank car named *Tank_Liquid* is stored in the folder **{UM Data}\RW\Train\Cars**.

The tank car model is a two-mass system in which liquid is modeled by the reduced mass M_l connected with the tank body by using the elastic-dissipative force element with the following characteristics: k is the generalized stiffness coefficient; ν is the generalized damping coefficient, Figure 15.11. The damping coefficient is calculated as $\nu = 2\beta\sqrt{M_l k}$, where β is damping (0.05–0.2).

Tank body mass is calculated as $M_c = M - M_l$, where M is the total tank car mass.

Figure 15.11. Tank car model.

Dependences of reduced masses and stiffness coefficients on water surface are stored in the folder **{UM Data}\RW\Train\Liquid** in files with extensions *lqd*. The dependence shown in Figure 15.12.

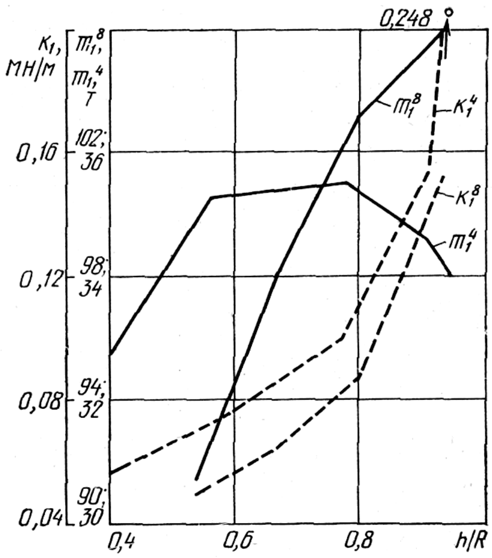


Figure 15.12. Dependences of reduced masses (m_1^4 and m_1^8) and stiffness coefficients (k_1^4 и k_1^8) on water surface for four-axle and eight-axle tank car respectively: *H* is the minimal distance from the water surface to the longitudinal symmetry axis of tank; *R* is radius of the cylindrical part of tank.

A body named *liquid* must be in a vehicle model in order to UM determines the vehicle as a tank car.

15.5. Simulation of longitudinal train dynamics

After a train model is created with the help of the **Train wizard** and compiled in **UM Input** program, it is possible to begin the next stage – train dynamics analysis in the **UM Simulation** program. For this run **UM Simulation** program and open the train model with the help of the **Open** menu item or button on the tool panel.

15.5.1. Train simulation inspector

One more tab **Train** is added in the **Object simulation inspector** for train model simulation, Figure 15.13. This tab contains several tabs too:

- **Options** – train model options,
- **Traction** – traction mode options,
- **Braking** – braking mode options,
- **Tools** – tools for data preparation of traction mode,
- **Masses** – settings of the table for vehicle mass changing.

The **Options** tab contains the following tabs, Figure 15.13:

- The **Track** tab allows setting railway track parameters, see Sect. 15.5.2. *"Railway track parameters"*, p. 15-16 for more details.
- On the **Resistance** tab, train driving resistance forces and curve resistance force are assigned, see Sect. 15.5.3. *"Propulsion resistance forces"*, p. 15-17, 15.5.4. *"Curve resistance force"*, p. 15-20.
- On the **Vehicle positions** tab the position of the first vehicle and positions of 3D vehicles are set, see Sect. 15.5.5. *"Vehicle positions"*, p. 15-21.
- The **Tank train** tab is enabled if tank cars are in a train model, see Sect. 15.4.5. *"Wagon connection model"*, p. 15-13.
- On the **Identification** tab, identifiers, which set control elements in driver's cab, are indicated, see Sect. 15.5.7.2. *"Identification of traction parameters"*, p. 15-32.

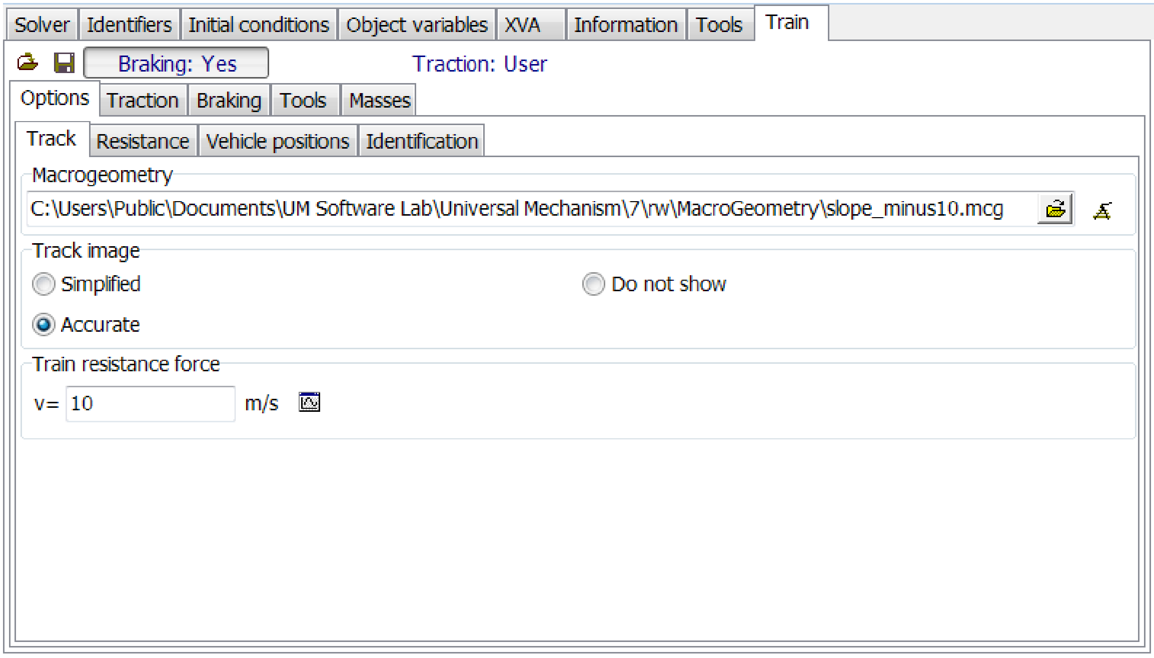


Figure 15.13. Object simulation inspector.

15.5.2. Railway track parameters

Railway track parameters are set on the **Track** tab, Figure 15.13. Let us describe this tab.

- **Macrogeometry** – loads a file with vertical and horizontal railway track profile. The detailed description of the tool for the creation of macrogeometry is in Chapter 8 Sect. 8.5.1.3 **Creation of macro-geometry files**.
- **Track image** – sets the simplified or accurate track image in an animation window.
- **Train resistance force** – allows obtaining the graph of total retardation forces for the current macrogeometry file and the given speed (m/s). The example for a train composed of 62 freight cars in a reverse curve (S-curve) at speed 10 m/s is shown in Figure 15.14.

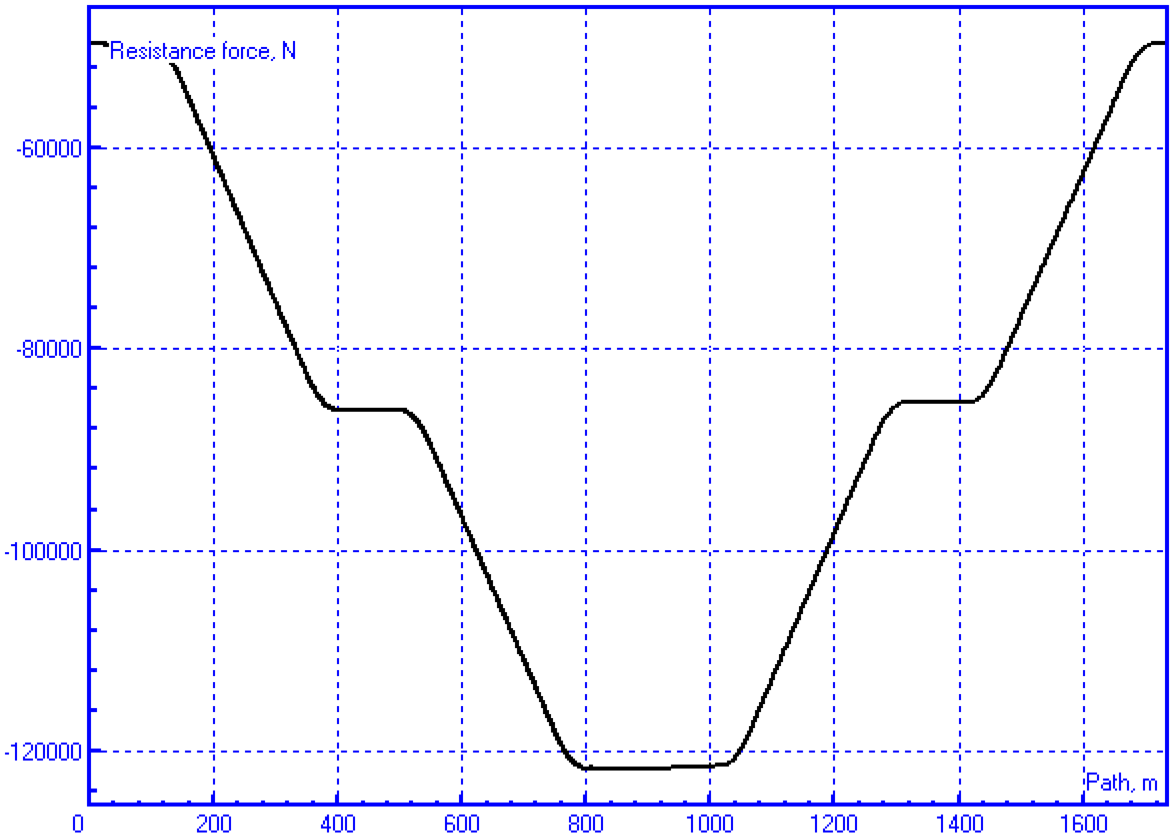


Figure 15.14. Graph of total resistance forces.

15.5.3. Propulsion resistance forces

In UM the total retardation force acting on every vehicle is the sum of propulsion resistance force, gravity force component and curve resistance force.

Gravity force component is calculated automatically by using vehicle mass value and current track slope value.

Propulsion resistance forces, which actually are the sum of rolling and air resistance forces, for every vehicle model are set on the **Resistance | Basic** tab, Figure 15.15.

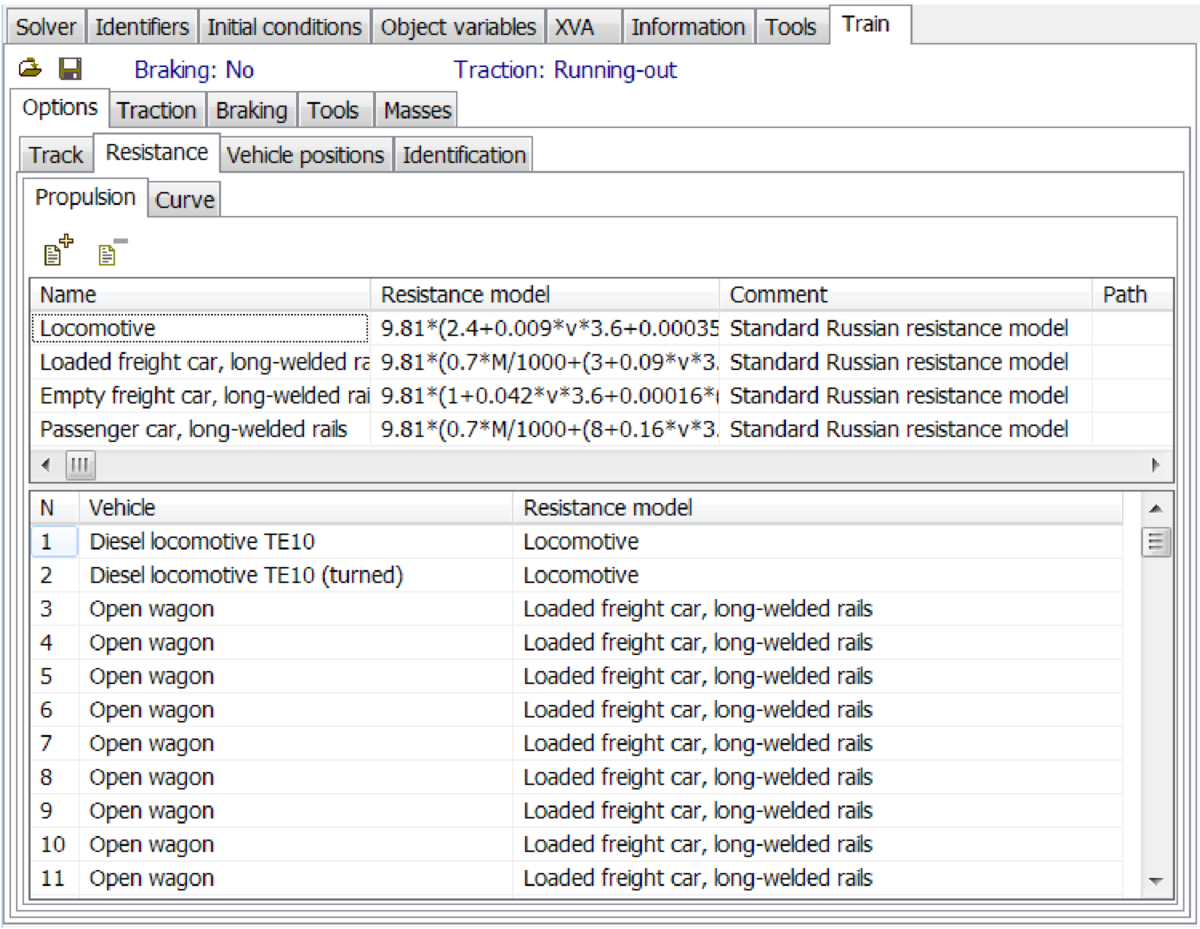


Figure 15.15. Setting train driving resistance forces.

Two lists are placed on this tab. The upper list (the list of loaded resistance force models) contains resistance force models loaded for the current train model. To add or delete resistance force models, use buttons and respectively. The lower list (the list of assigned models) contains the list of vehicles and resistance force models assigned to them from the upper list.

To assign a resistance force model from the list of loaded models (form the upper list) use mouse button double-clicking on the cell of the **Resistance model** column (the lower list) for the respective vehicle. Every double-click selects models from the list of loaded resistance force models. The **Assign to all** item of the popup menu of the list of loaded resistance force models assigns the current model to all vehicles.

There are four standard models of propulsion resistance forces for traveling on long-welded rails which always present in the list of loaded resistance force models and cannot be deleted from the list:

- **Locomotive** – train driving resistance force for diesel and electric locomotives:

$$W_0' = 9{,}81(2.4 + 0{,}009v \cdot 3.6 + 0{,}00035(v \cdot 3.6)^2)M/1000\,, N,$$

where v is the vehicle velocity, m/s,

M is the vehicle mass, kg.

- **Loaded car** – train driving resistance force for loaded four-axle cars with axle roller bearings:

$$W_O'' = 9.81(0.7M/1000 + (3 + 0.09v \cdot 3.6 + 0{,}002(v \cdot 3.6)^2) \cdot 4), N.$$

- **Empty car** – train driving resistance force for empty four- and six-axle cars with axle roller bearings:

$$W_O'' = 9.81(1 + 0{,}042v \cdot 3.6 + 0{,}00016(v \cdot 3{,}6)^2)M/1000, N.$$

- **Passenger car** – train driving resistance force for passenger cars with axle roller bearings (v ≤ 160 km/h)

$$W_O'' = 9.81(0.7M/1000 + (8 + 0{,}16v \cdot 3.6 + 0{,}0023(v \cdot 3.6)^2)4), N.$$

By default, the **Locomotive** model is assigned to hauling units and the **Loaded car** model to all cars.

Any user model of train driving resistance force can be created with the help of special tool. User resistance force model is given by the following function

$$W_O = W_O(m, x, v, t),$$

where W_O is resistance force, N;

m is the vehicle mass, kg;

x is the traveled path, m;

v is the vehicle velocity, m/s;

t is time, s.

To open the tool, choose the **Tools | Train | Resistance force…** menu item. In Figure 15.16, the view of the tool is presented where the resistance force model for a locomotive on jointed railway track is created as an example.

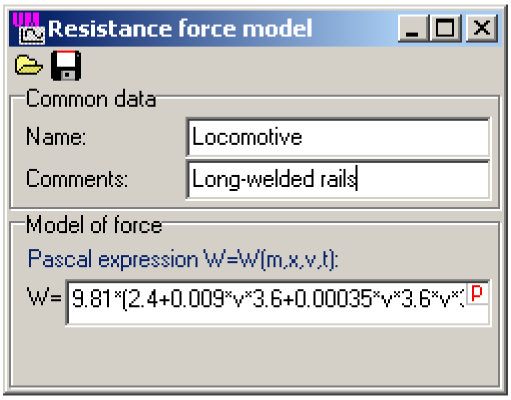


Figure 15.16. Example of train driving resistance force model creation.

15.5.4. Curve resistance force

Curve resistance forces are assigned on the **Options | Resistance | Curve** tab, Figure 15.17.

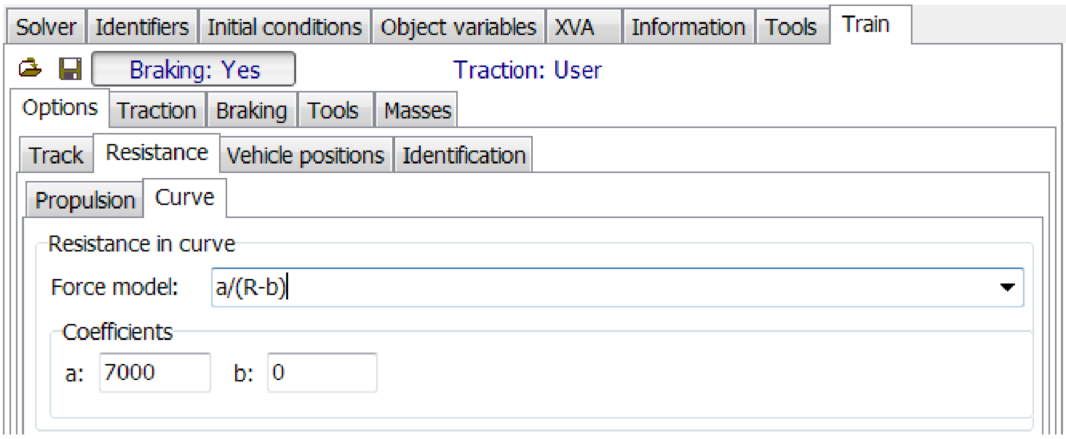


Figure 15.17. Curve resistance force setting.

The following curve resistance force models are available:

- **a/(R-b)** – the formula for specific curve resistance force (N/t), where *R* is curve radius, m; *a* and *b* are empirically determined coefficients (by default a = 7000, b = 0);
- **no lubrication, combined lubrication** – regressions obtained with the help of models of four-axle car with three-piece bogies created in Universal Mechanism.

15.5.5. Vehicle positions

On the **Vehicle positions** tab, the **Position of the first vehicle** is set, Figure 15.18. This parameter allows placing a train model in any position on the track. If a train model has 3D models, there exists the constraint: the position of the first vehicle must be such that all 3D vehicle models are situated on the straight section of the track.

Moreover on this tab, the position of 3D models in a train are set (**UM Train 3D** module). The **Subsystem name** column contains names of 3D vehicle models. In the **Position** column, the position of the model in a train model can be set.

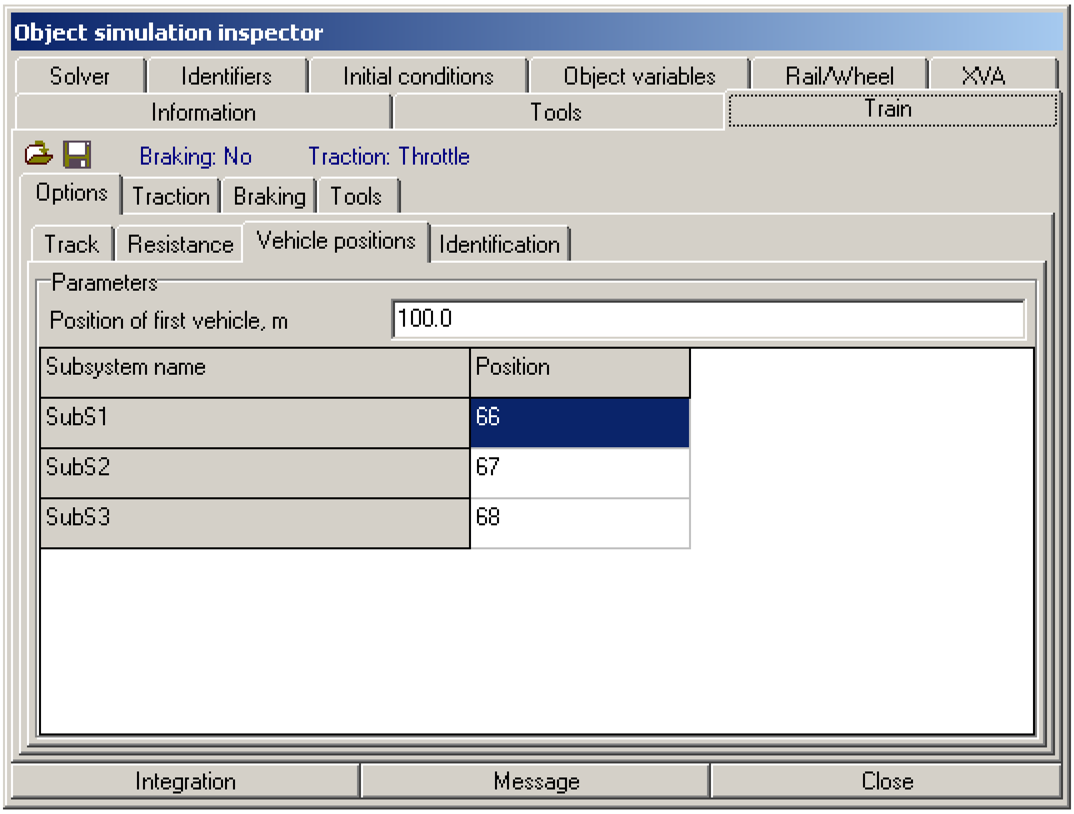


Figure 15.18. Vehicle positions.

15.5.6. Brake equipment

When creating the train brake system, it is necessary to set the following parameters: air pressure wave velocity for braking and release modes, the graph of brake cylinder pressure versus time, the number of brake cylinders, brake rigging system parameters, the number of brake shoes and friction coefficient between brake shoe and wheel.

The brake force is defined as

$$F_B = f \cdot F_N$$

where f is friction coefficient at the contact between wheel and brake shoe, F_N is normal (loading) force at the contact between wheel and brake shoe.

Loading force and friction coefficient are calculated separately for every vehicle taking into account the number of friction pairs “brake shoe – wheel” or “brake pad – disc”. For this, models of friction coefficients, brake rigging system models and graphs of pressure changing in brake cylinder (indicator diagram) are created and assigned to train vehicles.

15.5.6.1. Creation of friction coefficient model

To open the tool for creation of friction coefficient model, use the **Tools | Friction coefficient “brake block – wheel”…** menu item or the button on the panel tool, Figure 15.19.

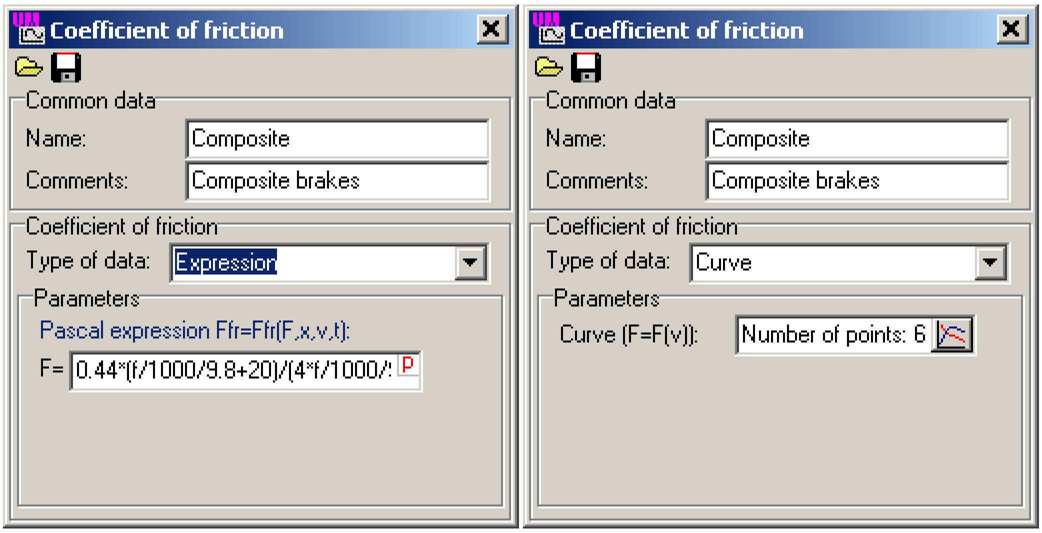


Figure 15.19. Tool for creation of friction coefficient models.

Friction coefficient models are stored in files with extensions *cf* in the folder **{UM Data}\RW\Train\Brakes\Coefs**.

Use buttons and to open and save models. The name and comments for friction coefficient model are assigned in edit boxes **Name** and **Comments**. The model can be defined in two ways by expression and by curve. It can be done by using the **Type of data** list items: **expression** – friction coefficient is a function of loading force (identifier *F*), traveled path (*x*), speed (*v*), and time (*t*); **curve** – friction coefficient is a friction coefficient-speed graph. SI units must be used for **expression** type: force in Newtons, path in meters, speed in meters per second, time in seconds.

Let us consider creation of friction coefficient model for a composite brake shoe as an example. The dependence of friction coefficient on loading force and speed is given as

$$f = 0{,}44 \frac{F_N + 20}{4F_N + 20} \frac{v + 150}{2v + 150},$$

where F_N is given in ton-forces, v in km/h.

To set this formula in the tool, choose **expression** from the **Type of data** list and input the formula taking into account SI units:

$$f = 0{,}44 * (f/1000/98 + 20)/(4 * f/1000/9.8 + 20) * (3.6 * v + 150)/(2 * 3.6 * v + 150).$$

Click the button to save the model. Now the created model can be loaded and assigned to any vehicle.

15.5.6.2. Load force calculation

Loading force is calculated as

$$F_N = n_{cyl} i \eta \left(pS\eta_{cyl} - F_{sp}\right)/m_p,$$

where n_{cyl} is the number of brake cylinders on a vehicle; i is brake rigging ratio; η is rigging efficiency; p is air pressure in brake cylinder, Pa; S is the square of brake cylinder piston, m^2; η_{cyl} is brake cylinder efficiency; F_{sp} is release spring force, N; m_p is the number of brake blocks (pads) on a vehicle (number of friction pairs “brake block – wheel”).

To calculate the loading force it is necessary to create the *brake rigging system model* and the graph of changing of *brake cylinder pressure (indicator diagram, ID curve)*. Different ID curves are created separately for service braking, emergency braking and release.

Brake rigging system

The tool for setting the brake rigging system parameters can be opened by the **Tools | Train | Rigging system** menu item or button on the tool panel.

All these parameters are assigned in the tool for creation of brake rigging system, Figure 15.20.

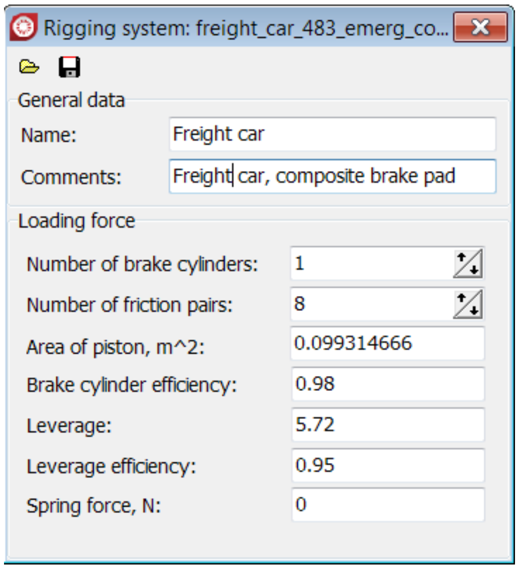


Figure 15.20. Creation of brake rigging system model.

The models made with the help of this tool must be added in the list on the **Train | Braking | Brake equipment | Rigging** tab to use them for the creation of train brake system.

<u>Indicator diagram (ID curve)</u>

The **ID curve** is the graph of brake cylinder air pressure versus time created by using a special tool opened by the **Tools | Train | Indicator diagram…** menu or button on the panel tool, Figure 15.21.

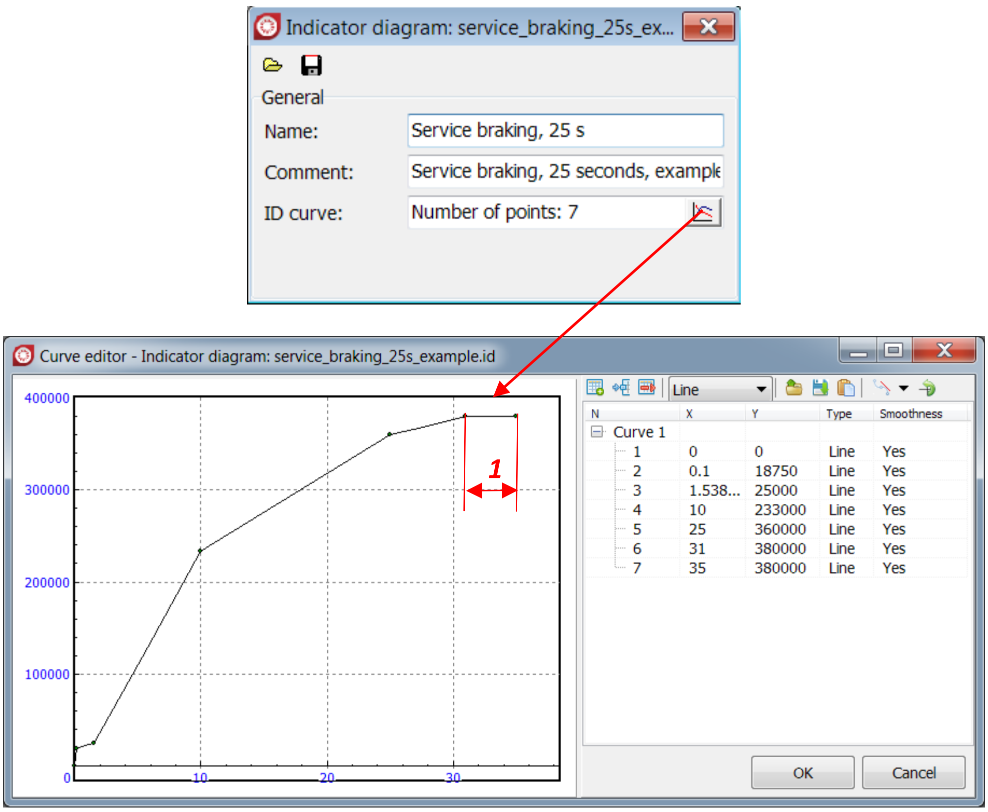


Figure 15.21. Brake indicator diagram setting.

User can create a graph of brake cylinder pressure change (Pascal, Pa) versus time (seconds, s) with the help of this tool for three brake modes:

- service brake,
- emergency brake,
- release.

ID curves for service and emergency brake should be stored in folder **{UM Data}\RW\Train\Brakes\BrakeID**. Release ID curves – in folder **{UM Data}\RW\Train\Brakes\ReleaseID**.

Note! Brake ID curves must be monotonically increasing functions, i.e. for $t1 < t2$, $p(t1) \le p(t2)$ – section 1 in Figure 15.21. The last section of ID curve, which sets the maximal pressure in brake cylinder, must be parallel to abscissa, i.e. for any *t*, $p(t) = p_{max}$ – section **1** in Figure 15.21.

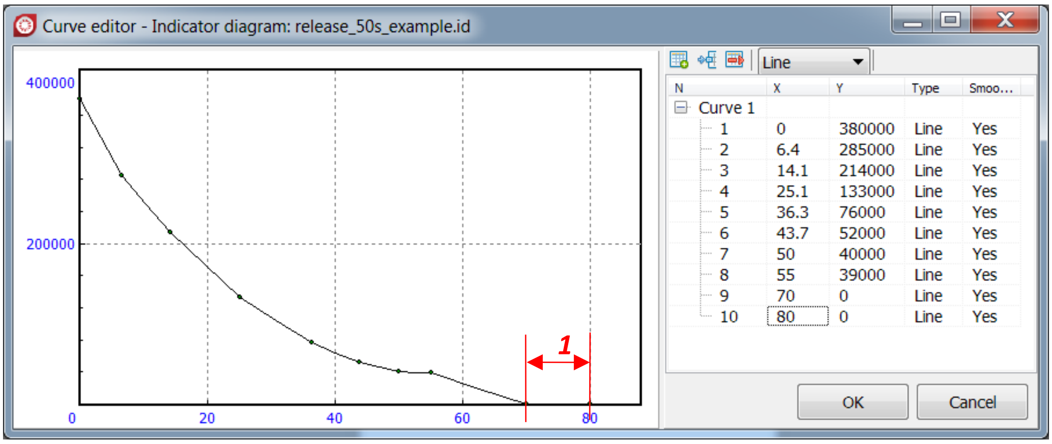


Figure 15.22. Release indicator diagram setting.

Note! Release ID curves must be monotonically decreasing functions, i.e. for $t_1 < t_2$, $p(t_1) \ge p(t_2)$ – section 1 in Figure 15.22. The last section of ID curve must be zero, i.e. for any *t*, $p(t) = 0$ – section **1** in Figure 15.22.

To use the created ID curves add them in the list on the **Train | Braking | Brake equipment | Brake ID** or **Train | Braking | Brake equipment | Release ID** tab and assign to necessary vehicles on the **Train | Braking | Brake equipment | Brake pipe** tab in the **Service braking, Emergency braking** or **Release** columns.

15.5.6.3. Creation of train brake system

Train brake system is formed in the Object simulation inspector on the **Train | Braking | Brake equipment tab**, Figure 15.23. Elements on the Braking panel are used to assign air pressure wave speed in service brake, emergency brake and release modes. The wave speed values are set in the corresponding edit boxes. If a brake wave speed is not constant, it can be taken into account by setting zero section at the beginning of the brake ID curves. In this case the corresponding flag should be turned off, Figure 15.23.

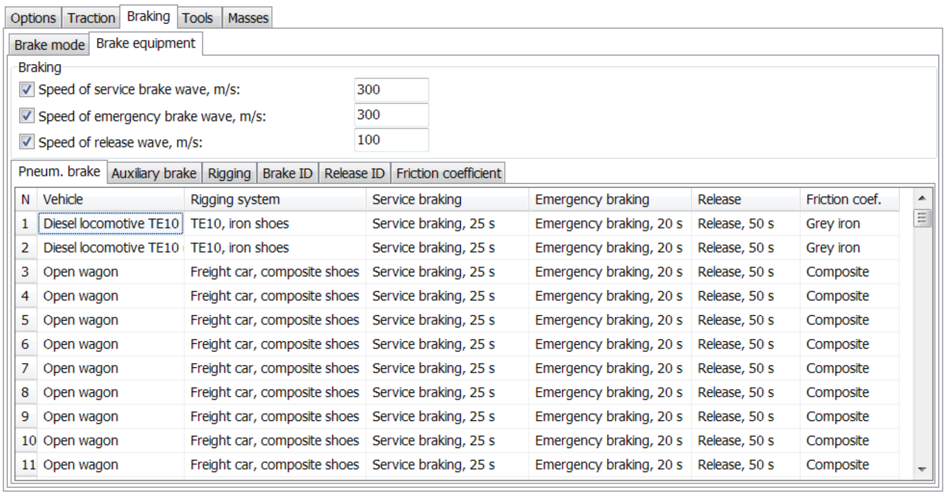


Figure 15.23. Brake equipment tab.

Pneum. brake – this tab is used for setting pneumatic brake parameters. On this tab, the created ID curves (for brake and release modes), rigging system models and friction coefficients are assigned to vehicles. Use double-clicking in the corresponding cell to change the model. Models are selected from list formed on the tabs **Rigging, Service brake, Emergency brake, Release** and **Friction coef**.

Auxiliary brake – on this tab, parameters of auxiliary brakes (used on locomotives) are set in the same way as on the **Pneum. brake** tab.

Rigging, Brake ID, Release ID and **Friction coefficient** – use these tabs to create the lists which items are used during the brake system creation process on the tabs **Pneum. brake** and **Auxiliary brake**.

Let us for example describe the **Brake ID** tab. In the list of loaded brake ID curves, there are built-in models **(none)** and **(interpolation)** which cannot be deleted. The result of the **(none)** model is always zero. It could be used if a vehicle cannot brake for some reasons (for example the brake cylinder is damaged). The **(interpolation)** model computes the ID value by linear interpolation using data from two nearest vehicles ahead and behind the current one which have assigned ID curves.

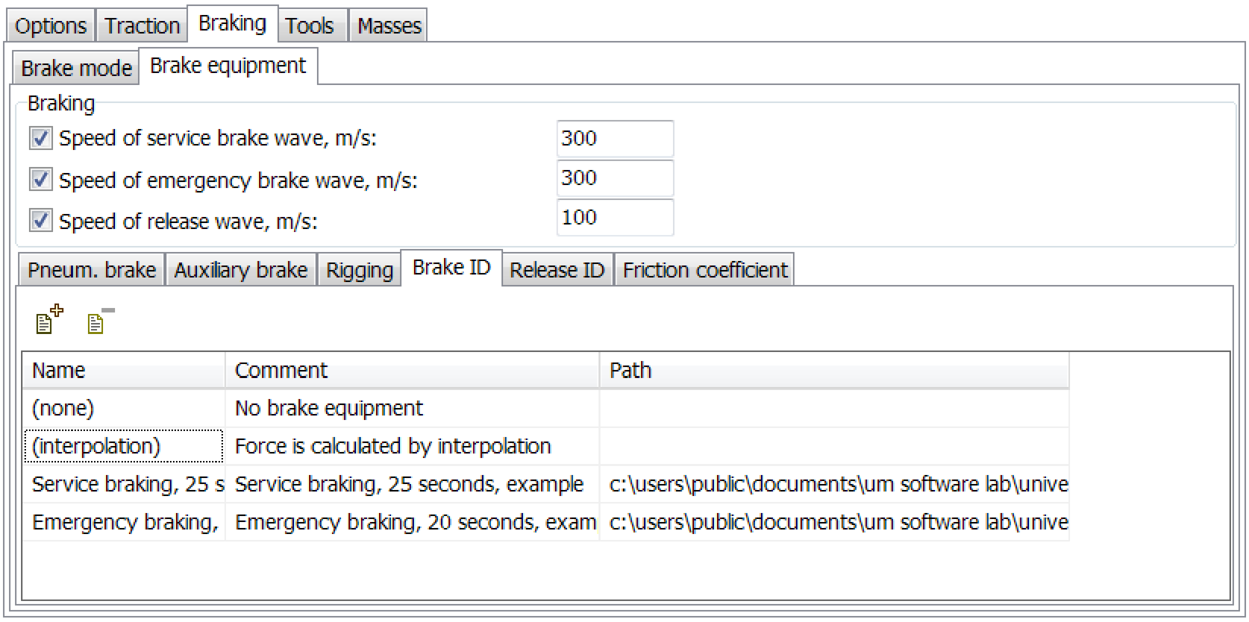


Figure 15.24. **Brake ID** tab.

With the help of popup menu, the selected ID curve can be assigned to all vehicles as service or emergency brake ID or can be deleted from the list.

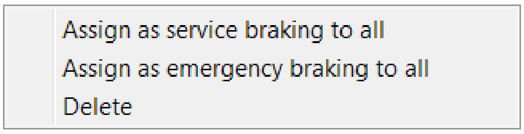


Figure 15.25. Popup menu for Brake ID tab.

15.5.6.4. Setting brake modes

Brake mode timetable is set on the **Train | Braking | Braking mode** tab, Figure 15.23.

The **Braking** check box turns on/off the braking system of the train model. This check box works together with the button **Braking: Yes (No)** located in the top left hand corner of the **Train** tab: the selected (down) button turns on the check box, the unselected (up) one turns off the check box and vice versa.

Use buttons  to add or delete tabs which used for setting the single brake mode. Set the time point (in seconds) or traveled path (in meters) from which the given mode begins to work in the **Time, s** or **Distance, m** edit box. Select the brake type from the **Brake type** list: **brake pipe** or **auxiliary brake**.

Choose the brake mode from the **Mode** tab. This list contains four items which values depend on the brake type. If the brake type is brake pipe (pneumatic brake) then the list contains the following modes:

- **release,**
- **lap,**
- **service braking,**
- **emergency braking.**

For the auxiliary brake:

- **release,**
- **running (repeater),**
- **lap,**
- **service braking.**

Let us describe the process of brake timetable making. The window with brake timetable settings is shown in Figure 15.26.

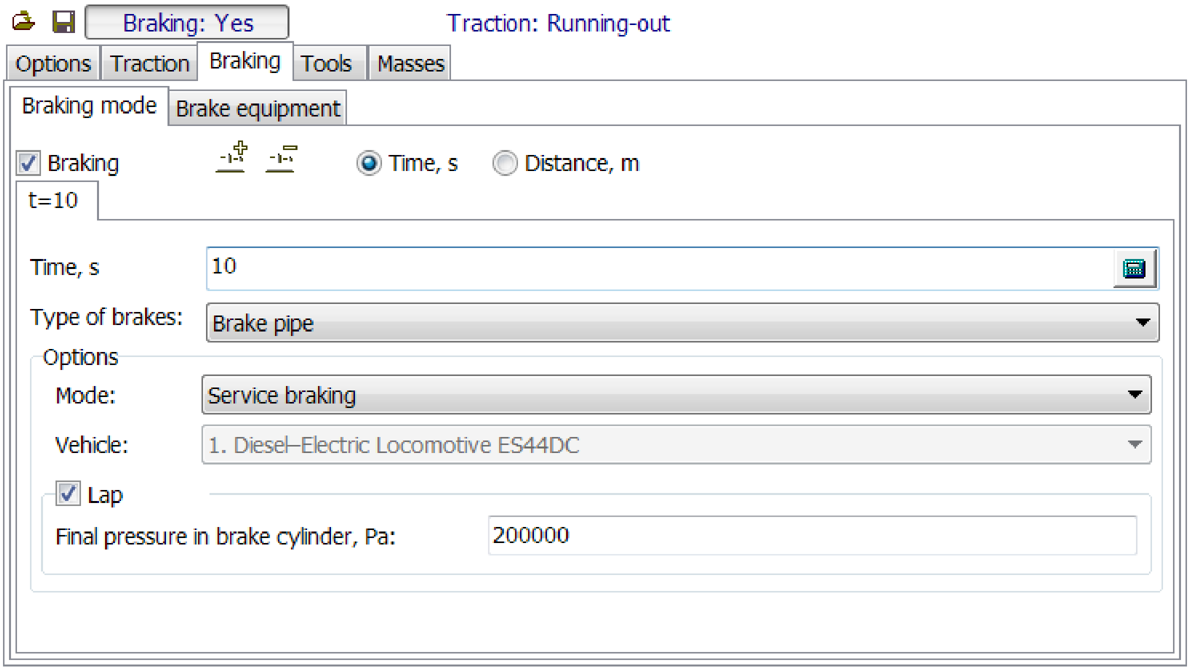


Figure 15.26. Brake mode setting.

Here the example of service braking mode setting is presented. The settings in this example are the followings: the time of braking start – **10 s**; brake type – **brake pipe** (pneumatic brake); brake mode – **service braking**; vehicle from which the current process (brake wave) starts – **first vehicle**. For service brake and release mode, it is possible to set the final pressure in brake cylinders, i.e. the subsequent mode automatically will be the lap mode. In this example, the braking process is going until the brake cylinder pressure in the first vehicle is 200 000 Pa (2 atm) after that the current mode becomes the lap mode. The obtained brake cylinder pressure on other vehicles will be the same as on the first one, if their ID curves have the same maximums as ID curves of the first vehicle or just the same curves are assigned to these vehicles. If the vehicles have ID curves with different maximums, for example a train contains empty and loaded cars, the pressure in brake cylinders of vehicles will be set in the same proportion to their maximal pressure value as on the first one.

Graph of braking forces for the first and last cars of a train are shown in Figure 15.27. In this example, the brake mode is set from the beginning of the simulation (t = 0 s).

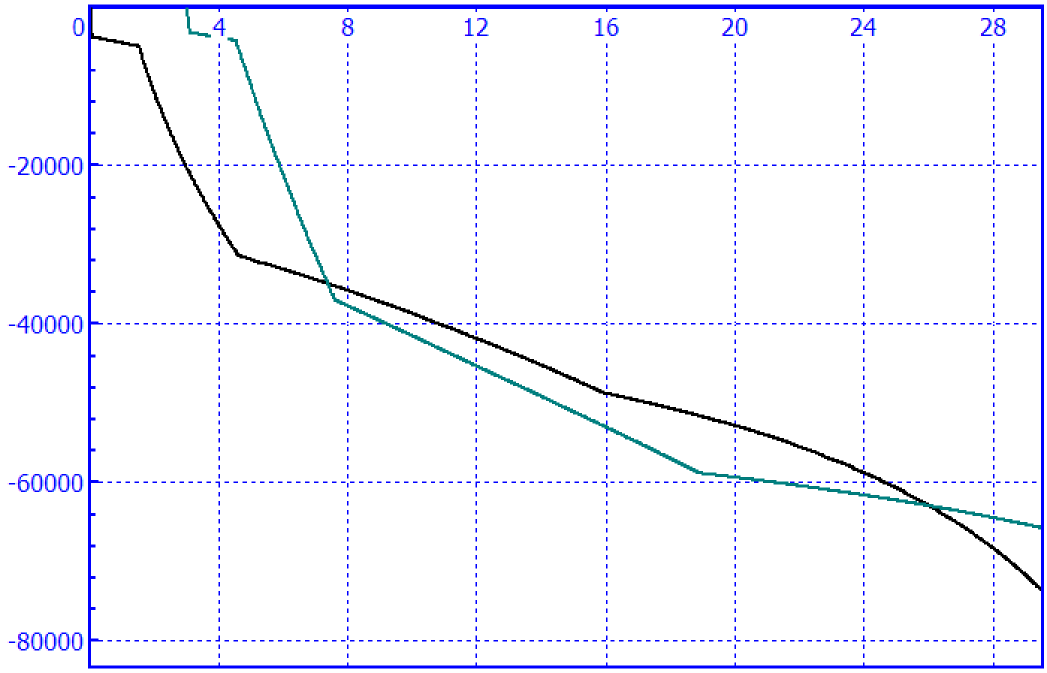


Figure 15.27. Braking forces.

15.5.7. Setting traction mode

There are several ways to set traction mode for a train model in UM: by using the throttle position profile, by using the speed profile, by using the traction force profile, quasi-static mode with constant forces applied to locomotives and the **x(t)=const** mode for keeping a vehicle in its given position, Figure 15.28. Let us describe these modes:

- **User** – in this mode, the tractive effort is not controlled by UM (but is limited by adhesion force) – user controls the tractive effort and dynamic brake force by himself. For example, user can change values of *throttle_position* and *dynamic_brake_position* identifiers during the simulation process by using the control panel.
- **Throttle** – setting the traction mode by using the throttle position profile. The profile can be loaded for any locomotive, see Sect. 15.5.7.1. *"Input of traction mode graphs"*, p. 15-31.
- **F=F(t)[F(s)]** – setting the traction mode by the traction force profile. The profile can be loaded for any locomotive, see Sect. 15.5.7.1.*"Input of traction mode graphs"*, p. 15-31.
- **v=v(t)[v(s)]** – setting the traction mode by using the speed profile. The profile is used for the vehicle selected in the **Vehicle** list.
- **Quasi-static** – in this mode, constant forces are applied to locomotive. This mode can be used for the calculation of initial conditions, for example to run simulation of a train model from stretched or compressed conditions.
- **x(t)=const** – in this mode, a specified vehicle is kept in the position set by initial condition by control force.

Note!	Traction force in any mode is limited by adhesion force that is calculated as a product of locomotive weight, adhesion coefficient and adhesion weight usage factor, see Sect. 15.3. *"Train model"*, p. 15-5.

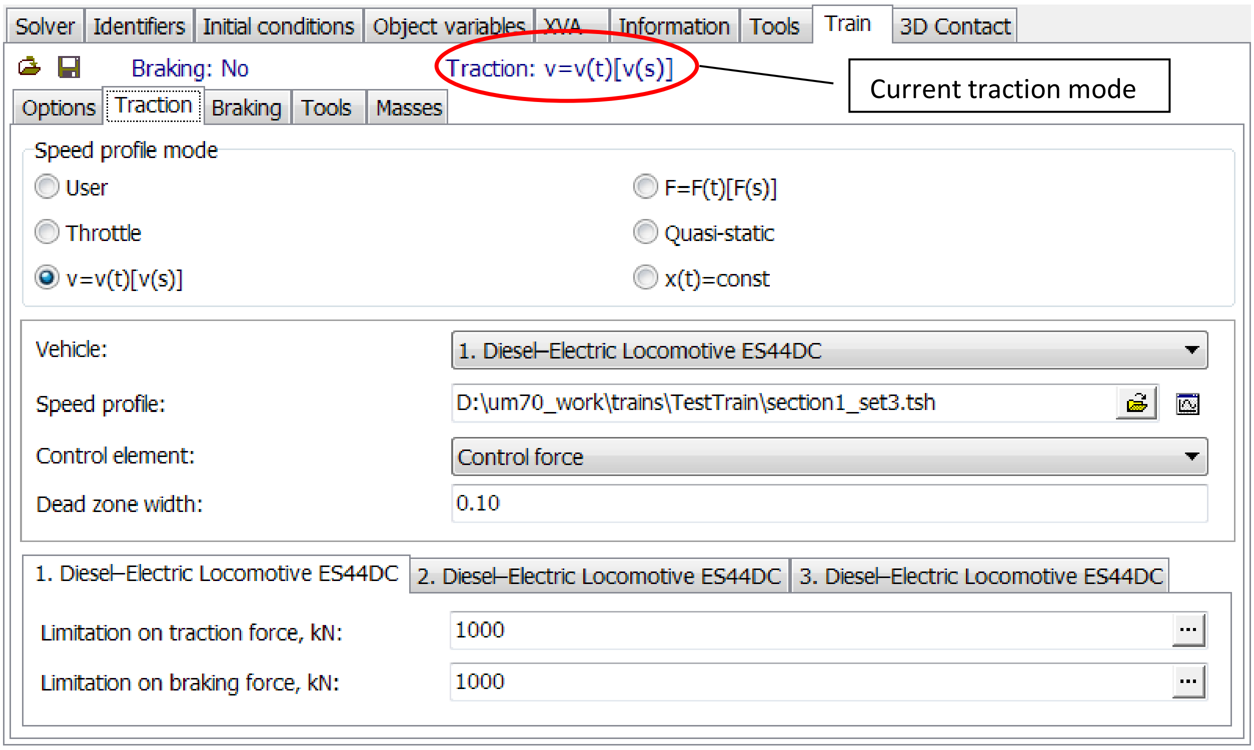


Figure 15.28. Traction mode setting.

15.5.7.1. Input of traction mode graphs

Tools required for input data for graphs of the throttle position profile, the speed and the traction force profiles are located on the **Train | Tools** tab, Figure 15.29. Select the type of created graph and input its name on the **Selection of a tool** panel. On the **Abscissa type** panel, select the type of abscissa: time (in seconds) or path (in meters). Use the button to input and edit the graph in the **Curve editor**.

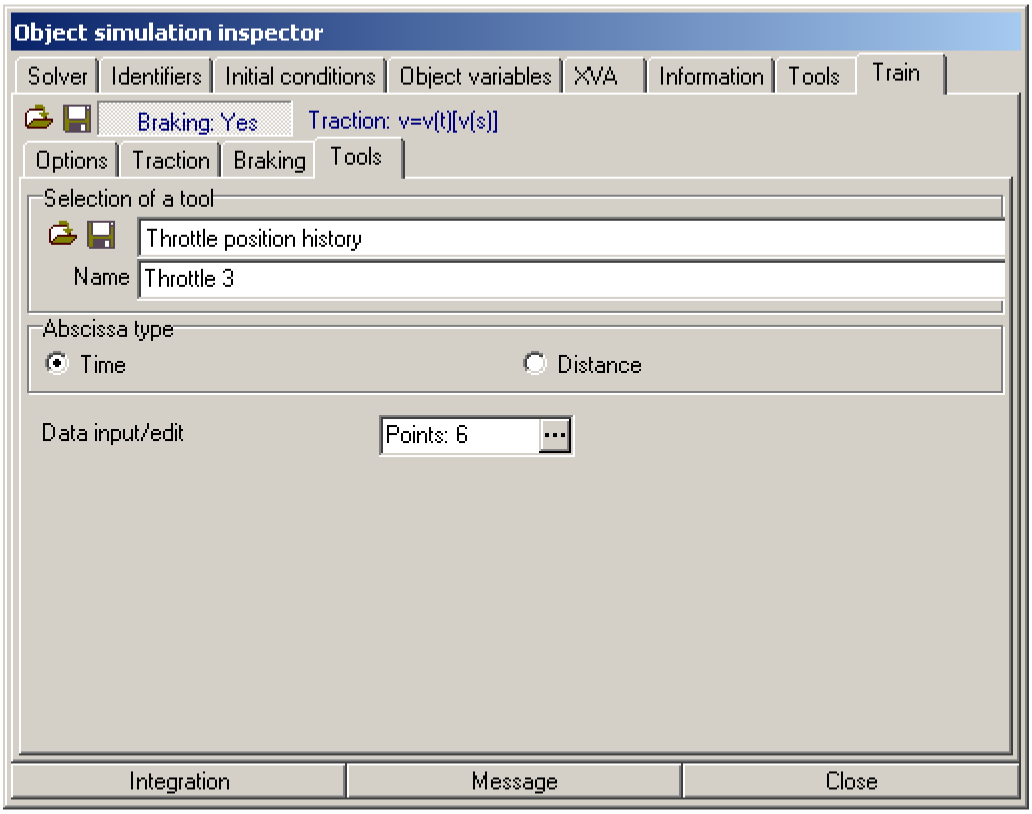


Figure 15.29. **Tools** tab.

15.5.7.2. Identification of traction parameters

To apply traction force, UM should identify which vehicles are locomotives. For simplified vehicles, it is done by adding the *throttle_position* identifier which parameterizes the number of throttle position, see Sect. 15.4.3. *"Additional elements of vehicle model"*, p. 15-9. For 3D vehicle models, it is necessary to add comment *locomotive* to the object, Figure 15.30.

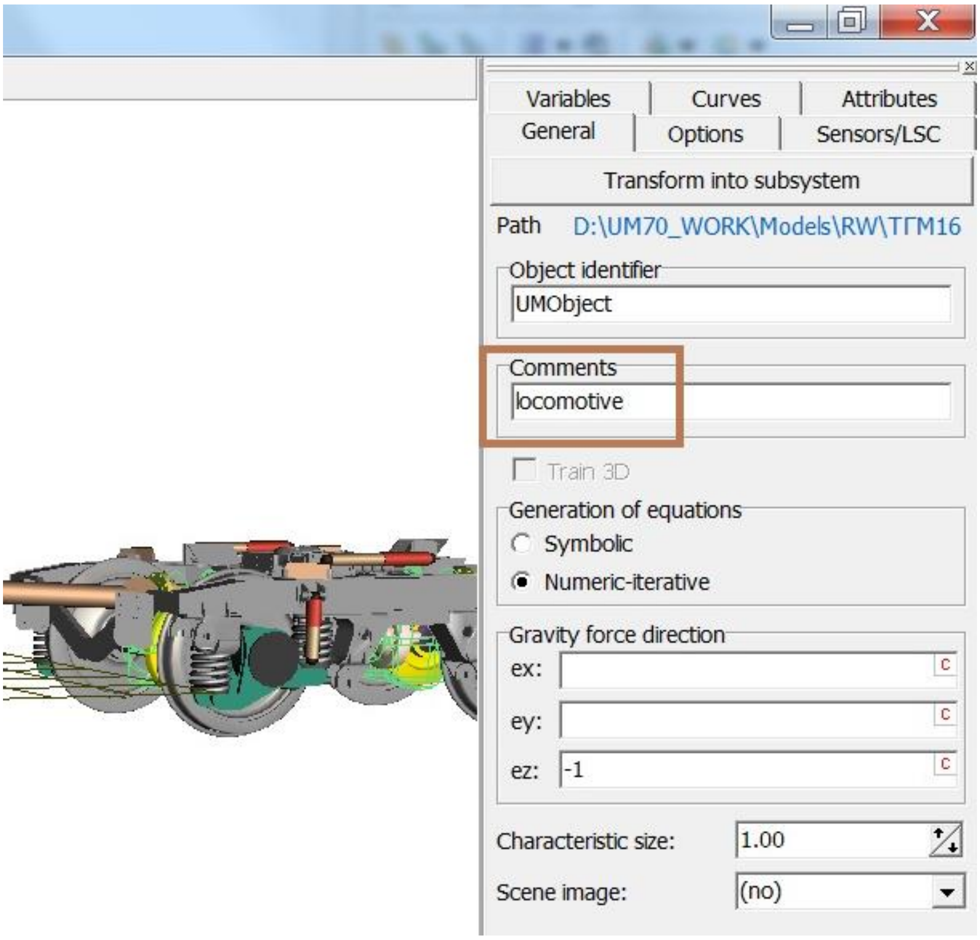


Figure 15.30. Identification of 3D locomotive model.

On the **Train | Options | Identification** tab, the identifiers which set the throttle position *(throttle_position)* and the dynamic brake position *(dynamic_brake_position)* are assigned for every locomotive, Figure 15.31. As a rule, these identifiers are curve identifiers in the joint force which has tractive effort and brake dynamic curves. The identifiers selected on this tab are used when a train travels in the throttle position profile mode as well as the speed profile mode, see Sect. 15.5.7. *"Setting traction mode"*, p. 15-29.

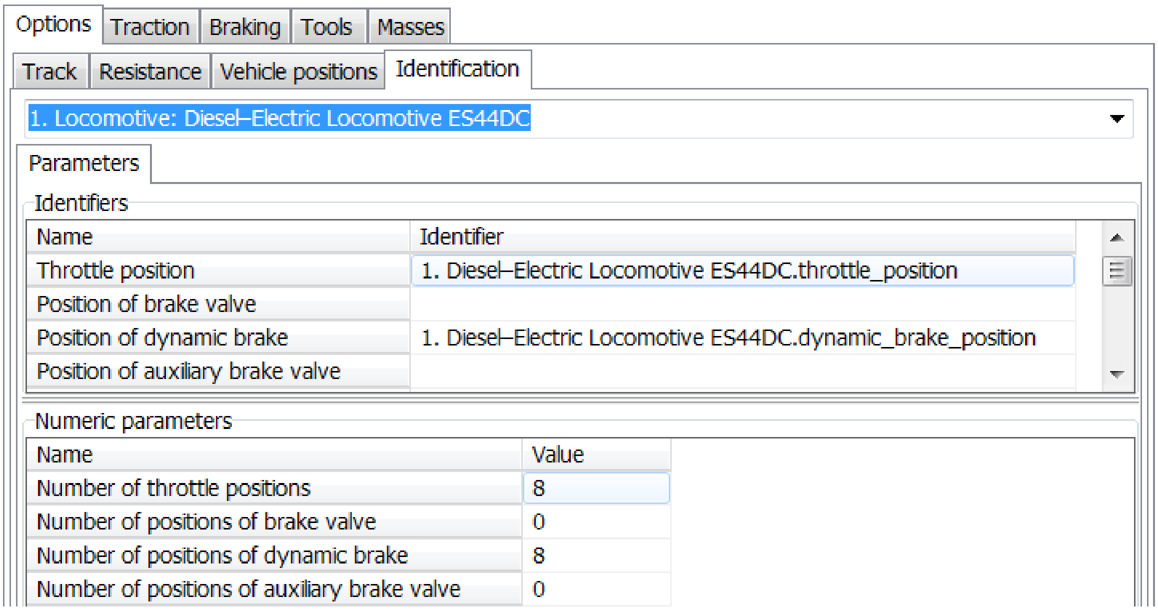


Figure 15.31. **Identification** tab.

15.5.8. Speed profile traction mode

In the speed profile mode **v=v(t)[v(s)]**, the user should set speed profile for the given vehicle from list **Vehicle** by using the **Speed profile** edit box, Figure 15.32. This speed is called the target speed and the vehicle is called the target vehicle. UM calculates the control force applied to a train to keep its velocity close to the target velocity. The calculated control force is divided into equal parts between all locomotives in the train model.

The algorithm of control force calculation is as follows. Let us describe a train as a material point with the mass of total train mass. In this case the equation of train motion can be written in the following form:

$$M\frac{dV}{dt} = F_{t/db} + F_b + F_{pr} + F_{cr} + F_g,$$

where M is train mass, V is train velocity, $F_{t/db}$ is traction and dynamic brake forces from locomotive units, F_{pr} is propulsion resistance, F_b is braking resistance due to pneumatic braking, F_{cr} is curving resistance, F_g is gravity force component. If it is supposed that on the selected section the pneumatic brake was not applied then the F_b term is zero. Obviously that $F_{t/db}$ is the force managed by a train driver to keep the required velocity. Let us call this force the control force F_c. By using the equation of train motion and taking into account that the train velocity is set by the target velocity V_t, the control force can be calculated as

$$F_c = M\frac{dV_t}{dt} - F_{pr} - F_{cr} - F_g$$

The control force mode **(control force** or **throttle)** can be selected by using the **Control element** combo-box, Figure 15.32. There are two modes for the application of the calculated control force:

- **Control force mode** – the calculated F_c force is applied to locomotives with taking into account limitations on traction and braking forces and adhesion force limitation.
- **Throttle mode** – the closest force value taken from tractive or dynamic brake effort curves for the current train velocity is applied. So in the throttle mode the identifiers for throttle position and dynamic brake position must be assigned, see Sect. 15.5.7.2. *"Identification of traction parameters"*, p. 15-32.

For the throttle mode, the **Dead zone width** parameter takes into account. This parameter can have a value from *zero* to *one*, where the *one* is equal to the width of the force difference between two adjacent positions of the throttle. The width of the dead zone shows at what relative value should change the control force after the transition to the adjacent position of the throttle, in order that the position of the throttle came back to the previous position. Increasing the width of the dead zone helps reduce "dancing" of throttle position, but shifts the points of the transition of throttle positions.

The calculated force can be limited by using edit boxes **Limitation on traction force, kN** and **Limitation on braking force, kN**, Figure 15.32.

Note! The control force, which actually is traction of braking force, is limited by adhesion force that is calculated as a product of locomotive weight, adhesion coefficient and adhesion weight usage factor, see Sect. 15.3. *"Train model"*, p. 15-5.

Plot of the calculated unlimited control force per one locomotive could be built by using variable **ControlForce**, see Sect. 15.5.9. *"Train variables"*, p. 15-36. The plot of the control force limited by traction and braking force is built with the help of variable **RestrictedControlForce**.

Variable **RealizedTractionForce** contains realized traction or braking force that is with taking into account the adhesion limit. This variable is calculated in any traction mode.

Note! If the brake cylinder pressure of any vehicle is not zero during the simulation process then the control force is assigned to zero.

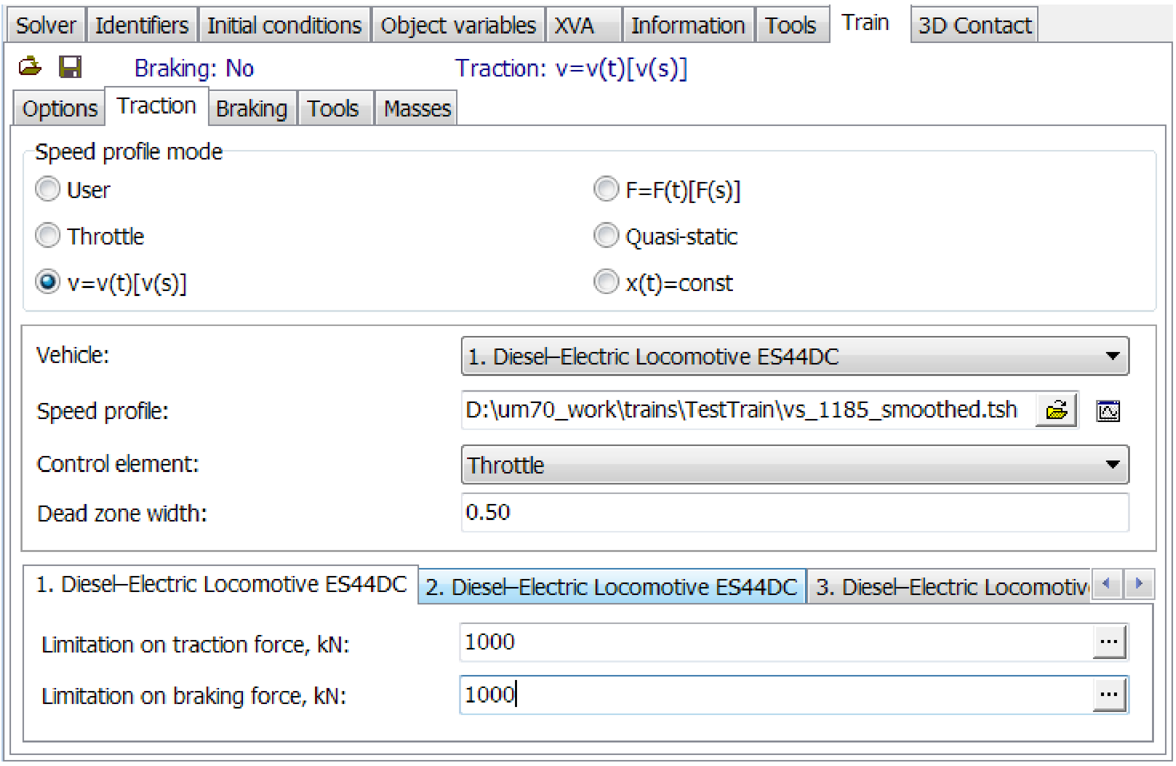


Figure 15.32. Speed profile mode settings.

15.5.9. Train variables

The variables calculated for train models are on the **Train** tab of the **Wizard of variables**, Figure 15.33.

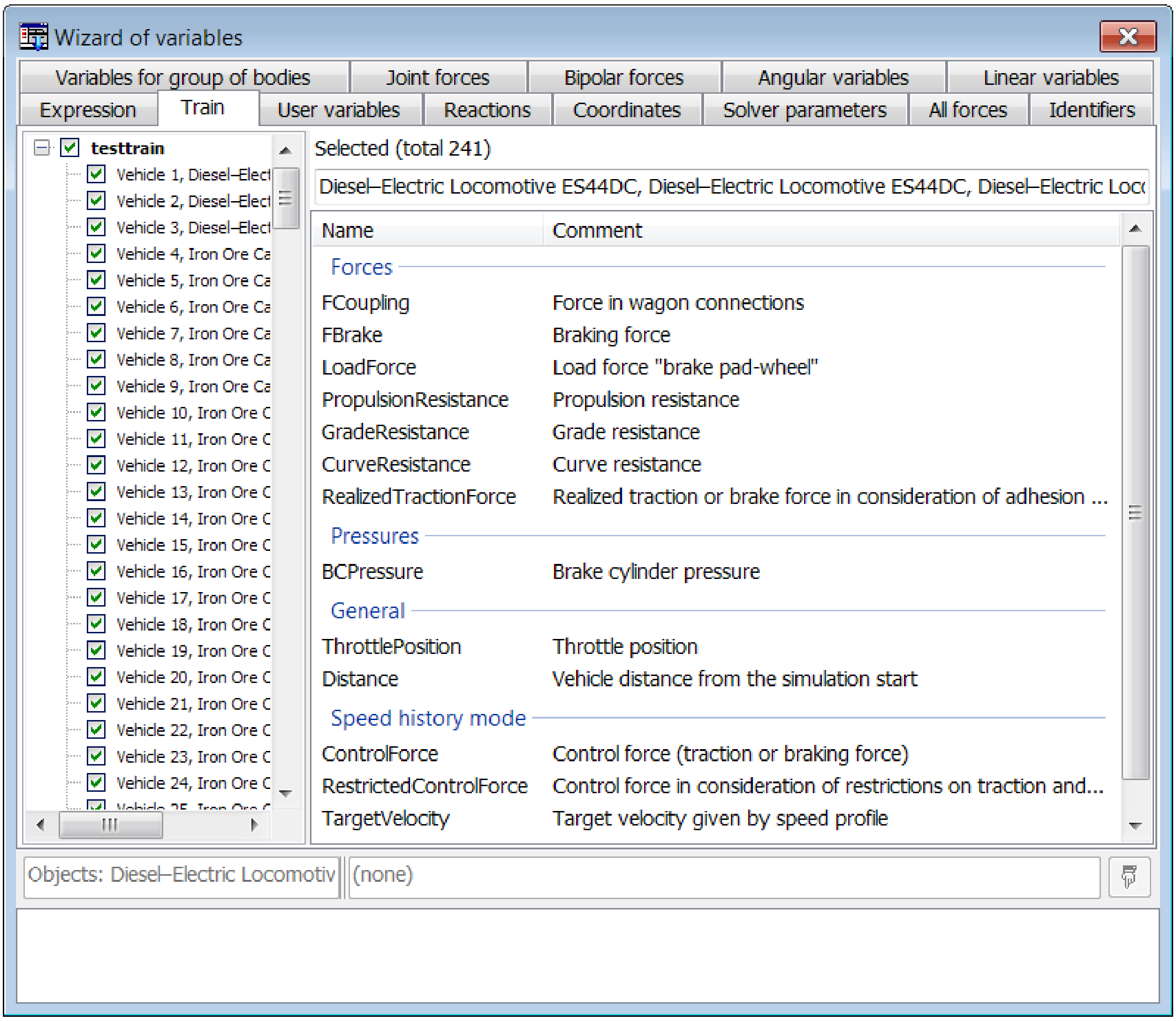


Figure 15.33. Train variables.

On the **Train** tab, the following variables are situated:

FCoupling – force in intercar coupling with the next car, N;

FBrake – full braking force of a vehicle, N;

LoadForce – load force in “brake pad-wheel” system, N;

PropulsionResistance – propulsion resistance force for a vehicle, N;

GradeResistance – grade force component, N;

CurveResistance – curving resistance, N;

RealizedTractionForce – realized traction or braking force with taking into account adhesion limit, N;

BCPressure – brake cylinder pressure of a vehicle, N;

ThrottlePosition – throttle position;

Distance – distance travelled by train from the simulation start, m;

ControlForce – control force calculated in speed profile mode without taking into account limitation on traction and braking force and adhesion limit, N;

RestrictedControlForce – control force calculated in speed profile mode with limitation on traction and braking force and without taking into account adhesion limit, N;

TargetVelocity – target velocity in speed profile mode (actually the velocity value from speed profile file), m/s.

15.6. Example of train model Train60

The example of a train model is included in the set of UM samples, Figure 15.34. The model from this example consists of Russian diesel locomotive 2TE10 and 58 freight cars.

Path to the model: {UM Data}\SAMPLES\Trains\Train60.

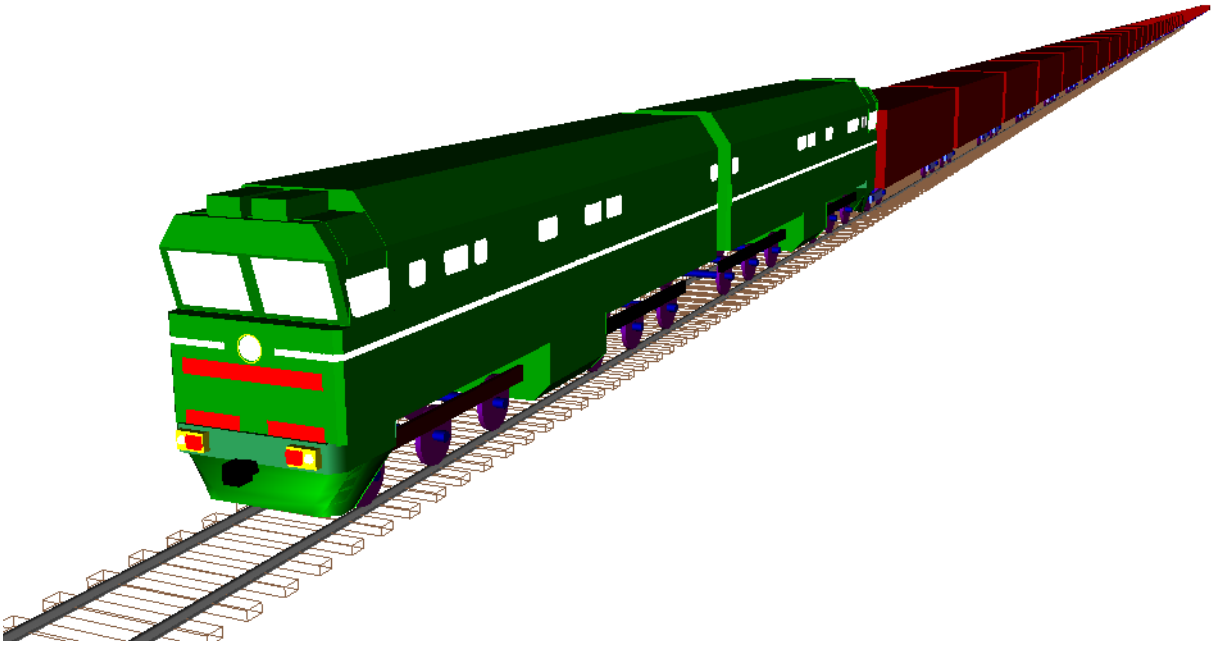


Figure 15.34. Train60 model.

15.7. Modeling of indexed car dumping

Rotary railcar dumpers and positioner systems are used for automated dumping of freight trains with bulk cargos in cargo railway stations and port facilities. A tandem rotary railcar dumper and a positioner – a device for precise locating of cars for dumper operation – are shown in Figure 15.35[1].

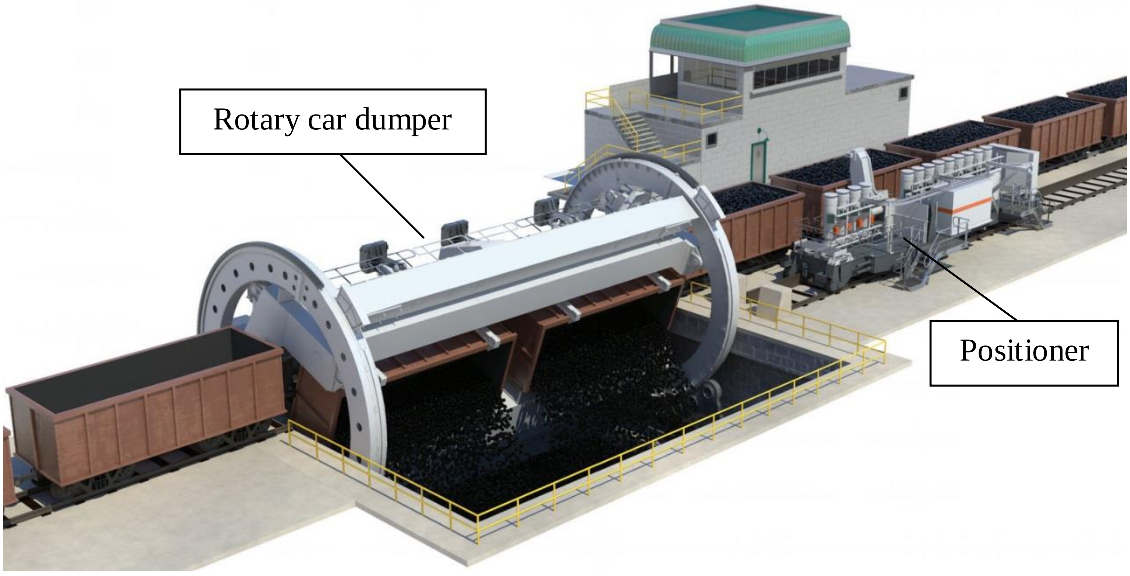


Figure 15.35. Rotary car dumper and positioner.

Field tests for some train configurations show high longitudinal forces (exceeding 1.2 MN) during the indexing operation. This can result in accelerated fatigue of wagon connection components, impact-related failures during the dumping operation and in some cases derailment of primarily empty cars because of high longitudinal forces. Therefore, it is necessary to reduce longitudinal in-train forces while keeping the dumping rate at an acceptable level.

The tandem rotary car dumper considered in this part of manual is designed for the simultaneous dumping of two cars (Figure 15.35). These cars are interconnected with the drawbar in order to reduce the free slacks between cars; this generally reduces longitudinal forces in the train. Pairs of cars are connected with rotary and fixed automatic couplers. This allows a pair of cars to rotate around the autocouplers axis relative to adjacent cars during dumping. Both drawbars and autocouplers are equipped with draft gears.

Let us briefly consider the process of a freight train dumping. A long freight train is delivered to the dumper by several locomotives located on the front of the train, so that the first two cars are placed in the car dumper. Two additional cars are attached to the rear of the train to hold the train brakes off while also providing optional drag braking and allowing correct indexing of the last loaded cars. Then the locomotive group is uncoupled and dumping commences. The positioner is used to index subsequent cars through the car dumper, two cars at a time. Longitudinal force from the positioner arm is applied to specially strengthened end walls of cars. The positioner runs parallel to the main railway track where the train is situated (Figure 15.35). In the process of dumping, the cars are not uncoupled and the positioner moves the entire train.

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[1] The picture is taken from a Metso Mineral Industries leaflet, www.metso.com

To prevent movement of the cars being dumped due to waves of longitudinal force, the cars each side of the car dumper are restrained by wheel clamps and wheel locks. After the placement of a pair of cars into the dumper the positioner returns to its initial position whilst the two cars are being dumped in the rotary car dumper. The dumping process is fully automated. Movements of the positioner arm, wheel locks and clamps and the rotary dumper itself are synchronized by a control system.

The methods and approaches for the simulation of longitudinal train dynamics during indexed car dumping for a long, heavy-haul train are described below. The models of all elements of the train and the dumper are explained. The developed train and car dumper model can be used to further investigate the effect of indexing and driving strategies on in-train forces. For instance, this model can be employed for optimization of production through dumpers; train configuration analysis; increased axle load studies; and derailment investigations.

The described below a train and car dumper model is included in the set of UM samples. Path to the model: {UM Data}\SAMPLES\Trains\Train and Car Dumper.

15.7.1. Model description

The car dumper model includes the positioning arm, wheel locks, clamps and the car dumper itself. Location of all main elements of the car dumper model is shown in Figure 15.36 and Figure 15.37.

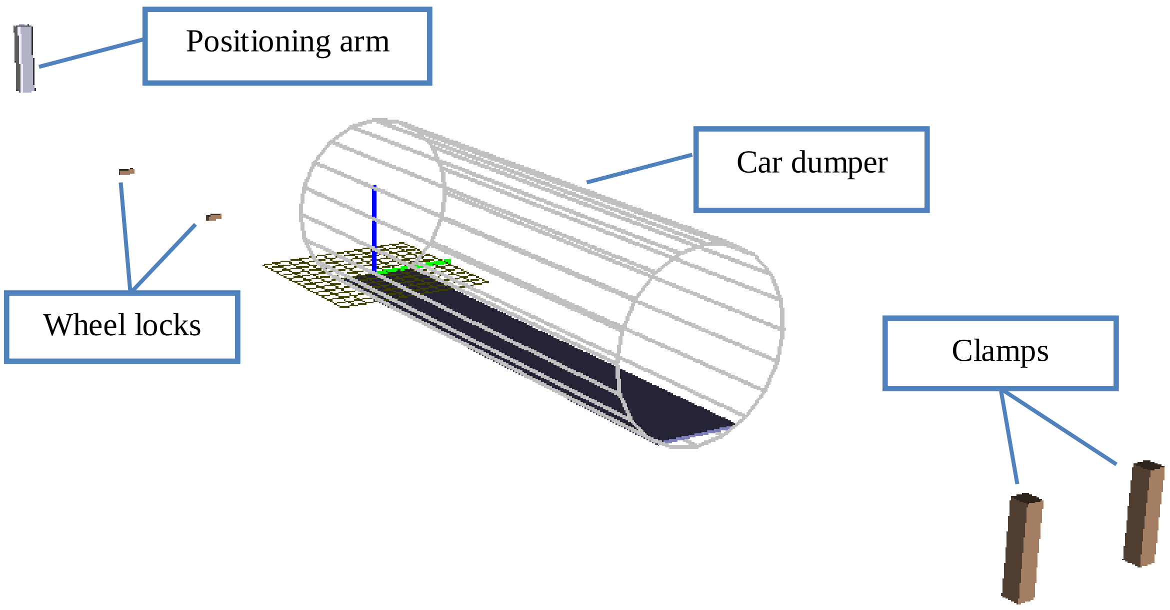


Figure 15.36. The model of rotary railcar dumper and positioner system.

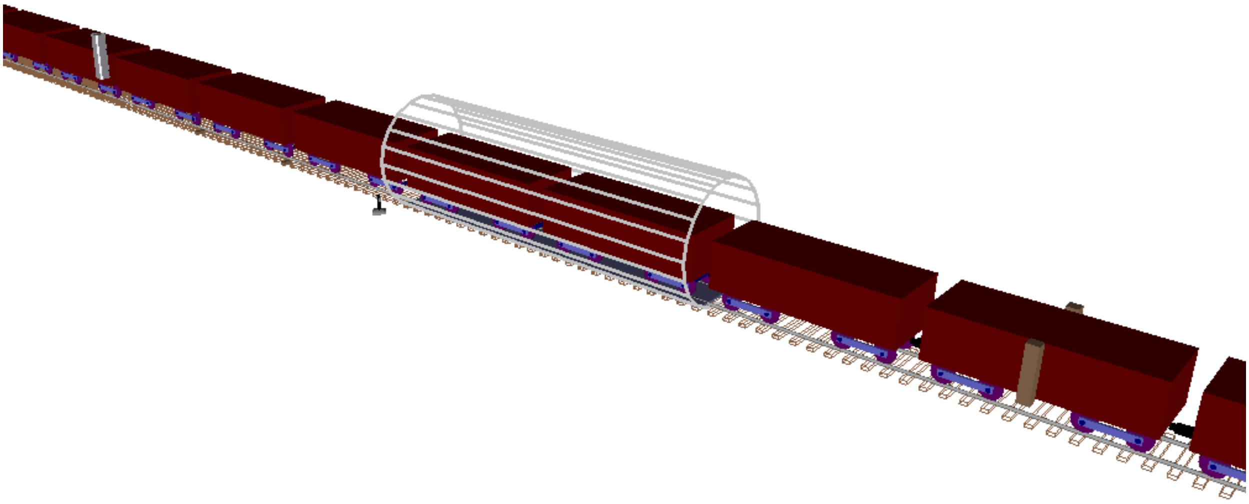


Figure 15.37. Train in the car dumper.

Interaction between positioning arm, wheel locks and clamps on the one hand and cars on the other hand is modelled as interaction between contact manifolds with the help of **UM 3D Contact** module (Chapter 2, Sect. 6.8). Contact manifolds are assigned with all cars and all elements of the car dumper.

Contact manifold that are assigned with dumper elements are given below in blue lines, Figure 15.38, Figure 15.39, Figure 15.40. Contact manifolds are not shown in the default mode of UM animation window.

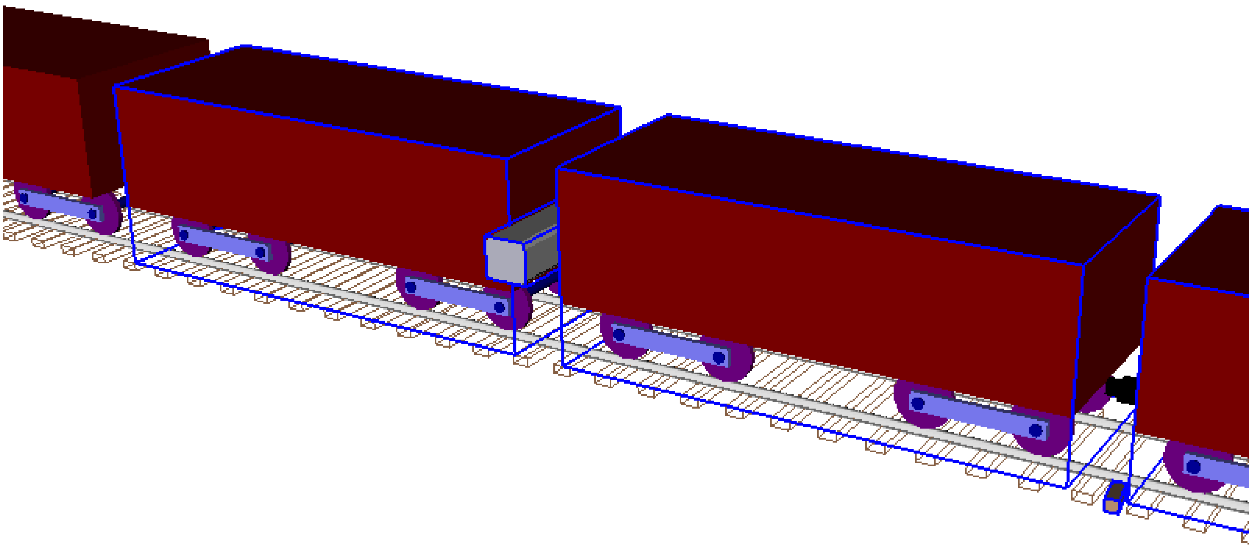


Figure 15.38. The positioning arm operation by used 3D Contact.

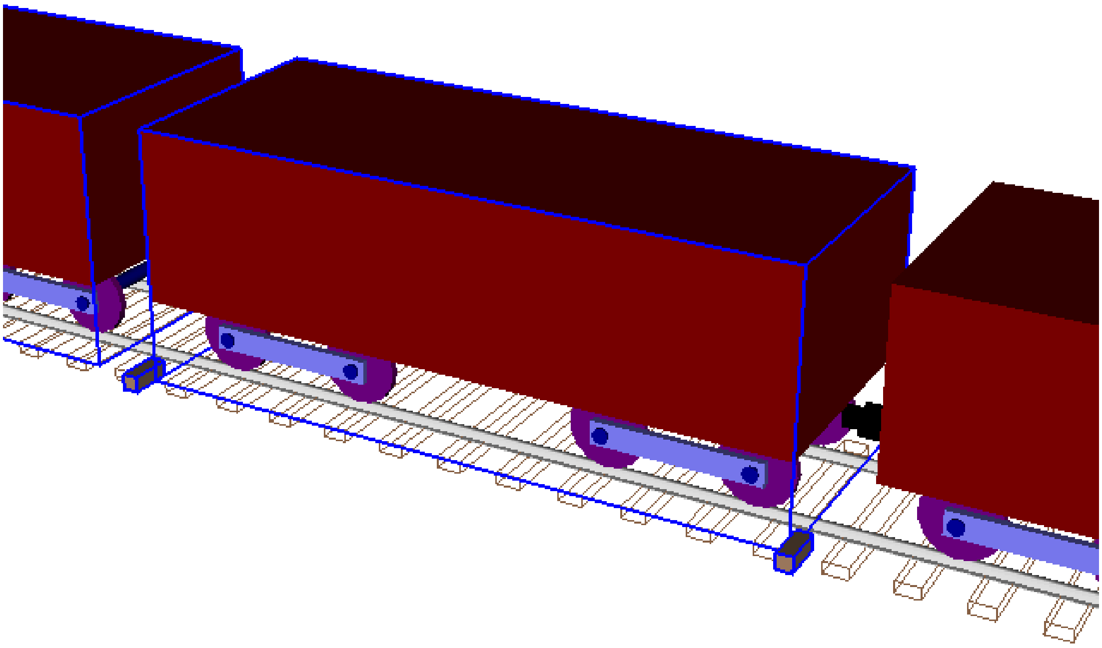


Figure 15.39. The wheel locks system operation by used 3D Contact.

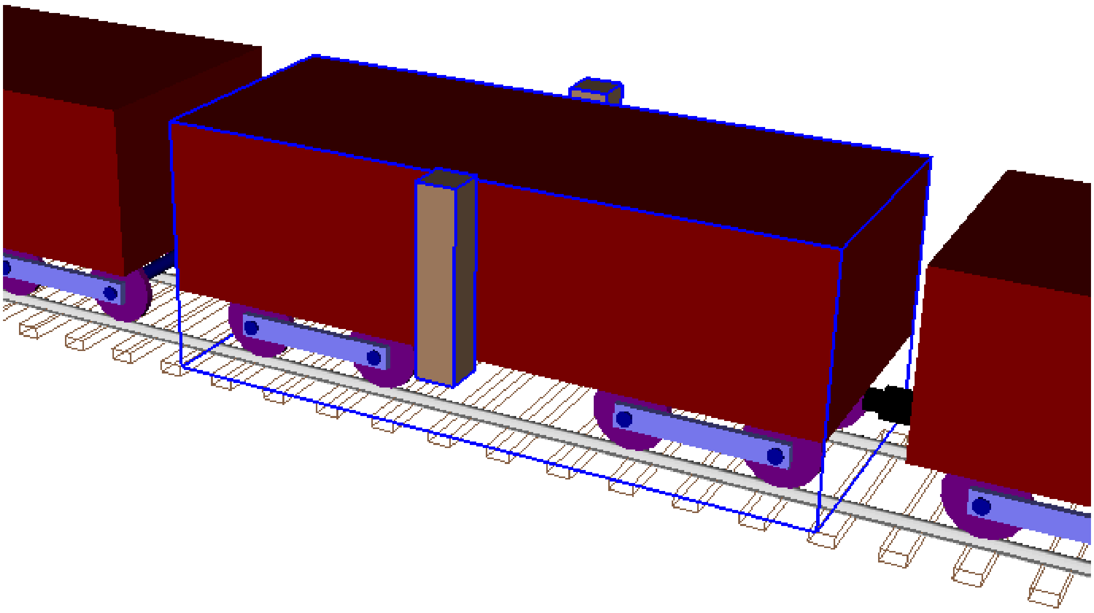


Figure 15.40. The clamps system operation by used 3D Contact.

15.7.1.1. Train model

In the one dimensional train model, each wagon is represented by a mass point with one degree of freedom and force elements between mass points to describe the draft gear characteristics. The train model is developed for car dumper which can unload two cars simultaneously. Therefore the types of connections drawbar and autocoupler are alternated through one car. For convenience the **slack_drawbar** and **slack_coupler** parameters are added in the whole list of train model. Example of train model is shown in Figure 15.41.

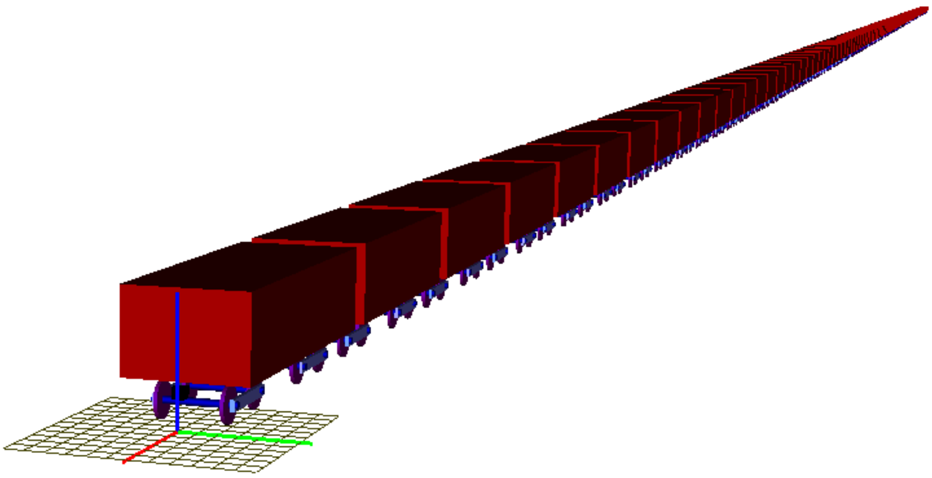


Figure 15.41. Train model.

15.7.1.2. Draft gear model

The bipolar force of hysteresis loop type is used for modeling draft gear. The performance curve of draft gear is represented in Figure 15.42.

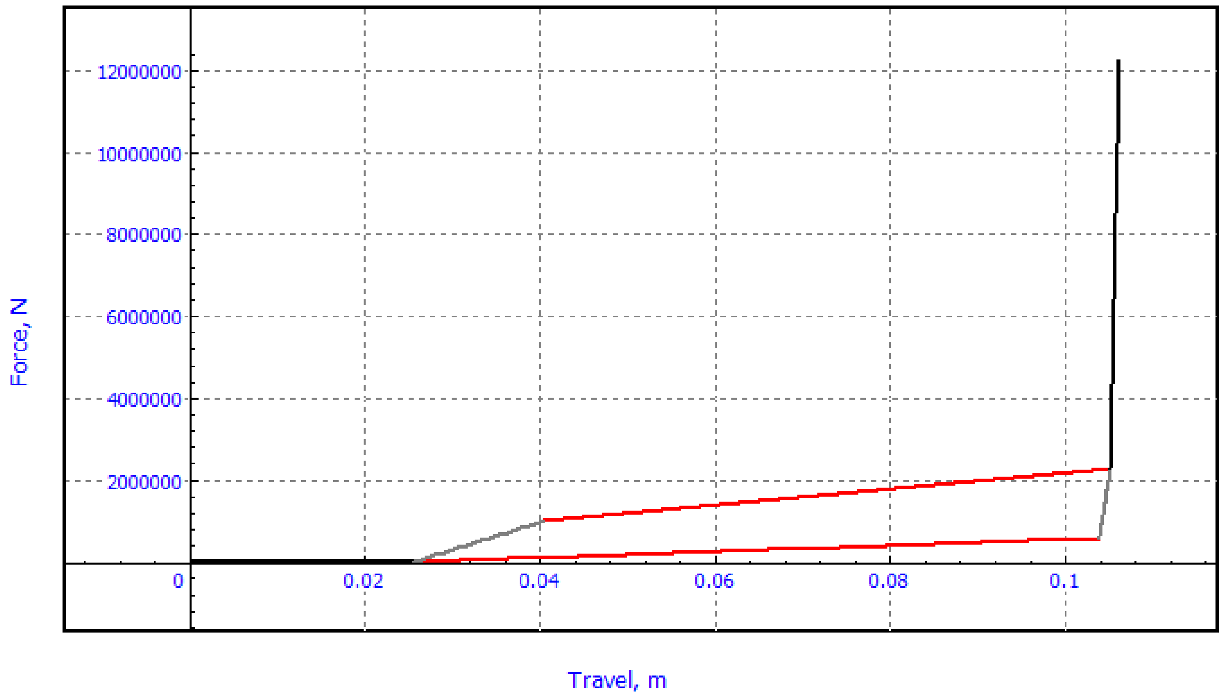


Figure 15.42. Bipolar force characteristic.

Every two cars have two draft gears and an autocoupler or drawbar in between. So the force element between every pair of cars should be equivalent to two connected in series draft gears described above. To provide equivalent dynamic behavior travel in the force characteristic should be increased twice. Moreover, the slacks are added to hysteresis loop. These slacks are parameterized. The resulting curve is presented in Figure 15.43.

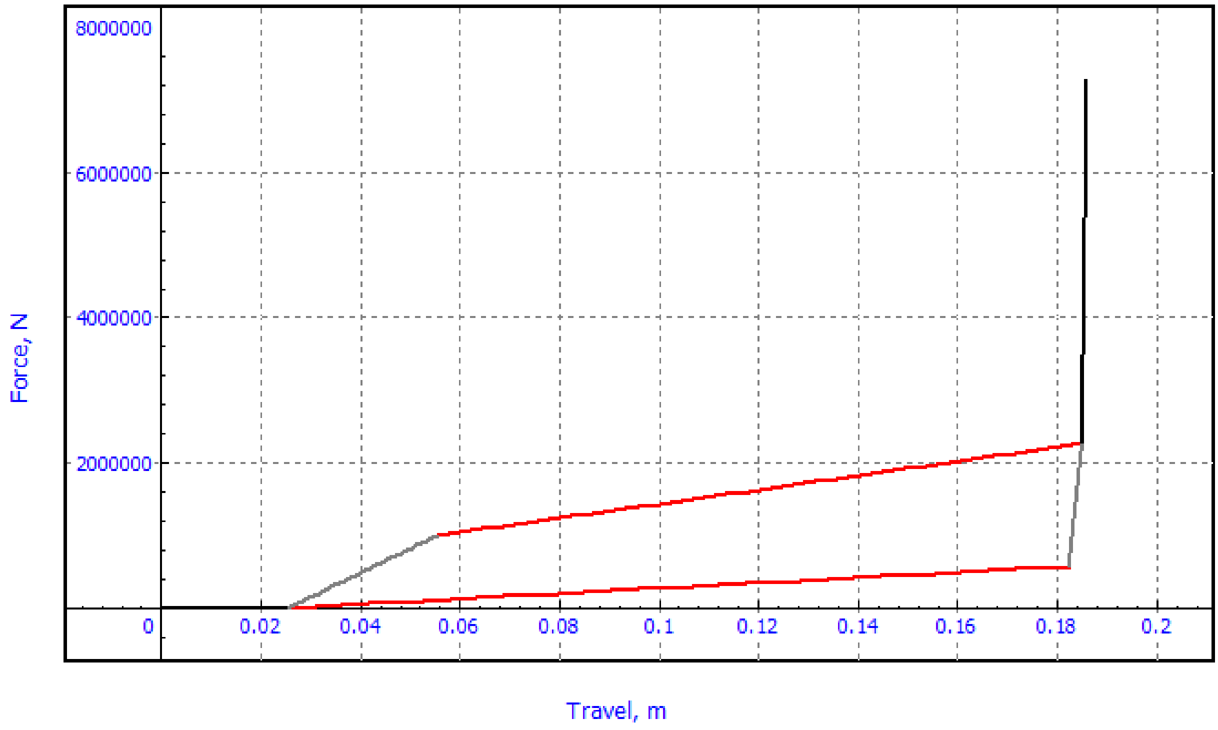


Figure 15.43. Bipolar force characteristic for double draft gear.

Since the bipolar force characteristic is symmetric only half the slacks is added in the hysteresis loop, Figure 15.44.

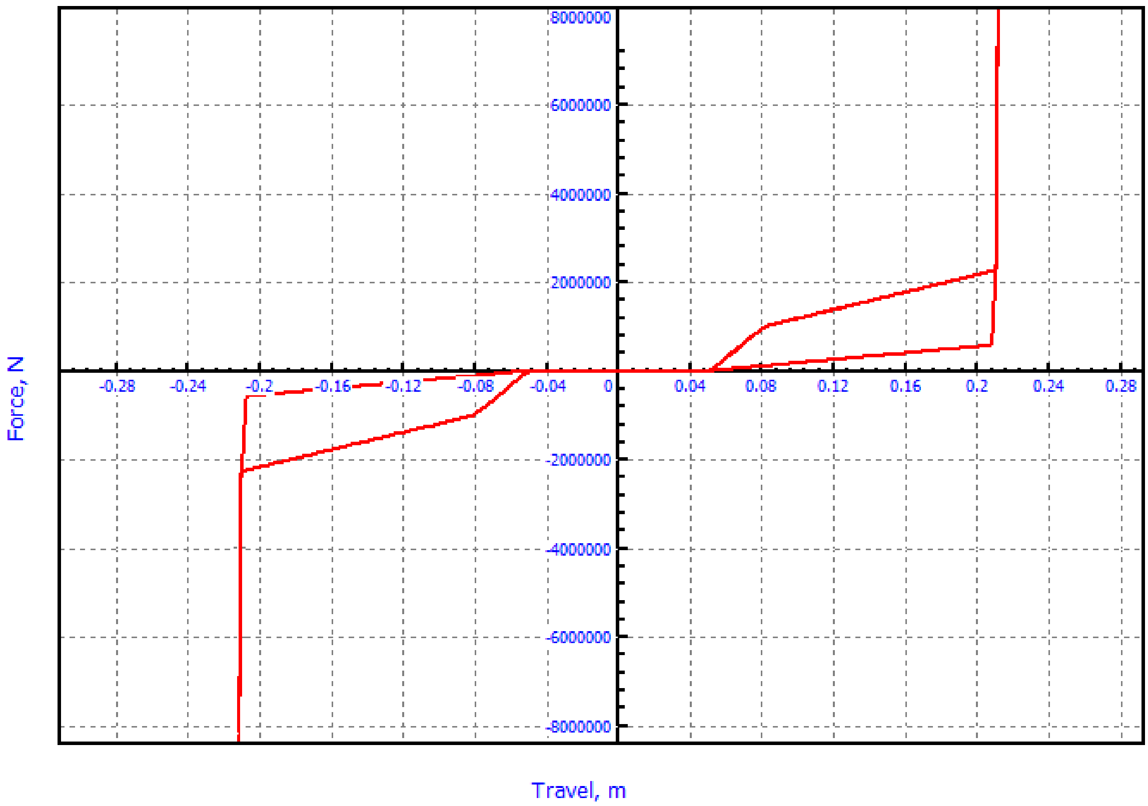


Figure 15.44. Testing of the draft gear model: symmetrical hysteresis loop.

For more detailed information about bipolar force of hysteresis loop type see Chapter 2, Sect. 2-6.5.12. *Hysteresis*.

Two models of draft gears were prepared for the train model:

- Doubled Draft Gear drawbar.bfc;
- Doubled Draft Gear autocoupler.bfc.

Mentioned above bipolar force files are completely the same besides the slack definitions. Parameter **slack_drawbar** introduces the slack in **Doubled Draft Gear drawbar.bfc** model (total free slack between two adjacent cars with a drawbar in the middle). Default value of **slack_drawbar** is 50,8 mm. Parameter **slack_coupler** introduces the slack in **Doubled Draft Gear autocoupler.bfc** model. Default value is 101,6 mm.

15.7.1.3. Positioning arm model

Positioning arm is considered as a rigid body with the contact manifold (**UM 3D Contact**) that allows it to interact with cars, see Figure 15.38. The graphical image of positioning arm is shown in Figure 15.45.

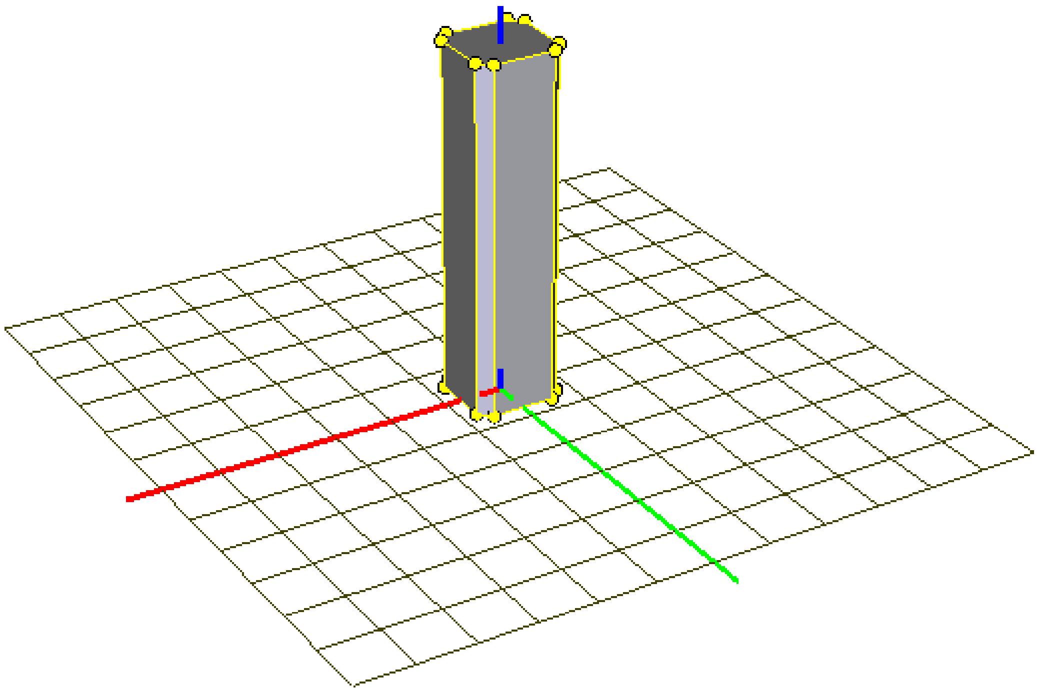


Figure 15.45. Graphical image of positioning arm.

It is convenient to set a speed as function of time – speed profile – for mode of longitudinal motion of the positioning arm. An example of speed profile is presented in Figure 15.46

For describing of speed profile in the model four specific points are used. These point set by parameters *Arm_t1*, *Arm_t2*, *Arm_t3*, *Arm_t4* and *Arm_v1*, *Arm_v2*, *Arm_v3*, *Arm_v4*, see Table 15.3. The trapezoidal speed profile including one or two plateau can be drawn via mentioned points. The main condition of construction of speed profile is trapezium area must be equal to double coupling base. Just such working travel the positioning arm makes during one dumping cycle.

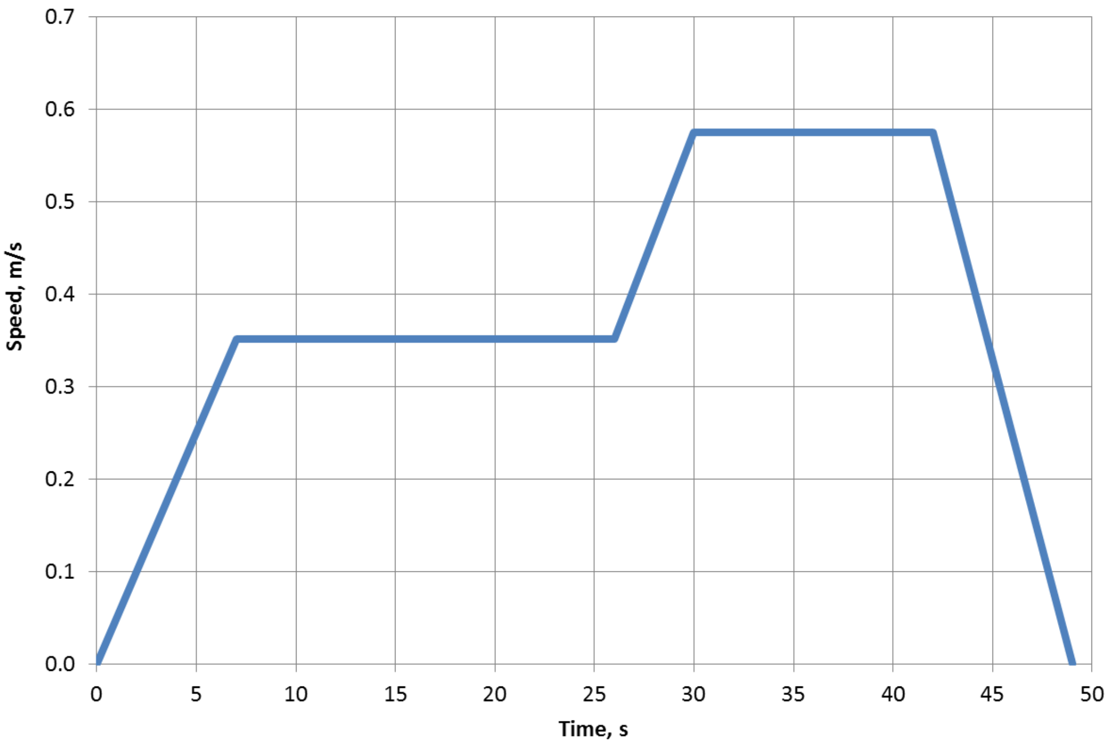


Figure 15.46. Speed profile of positioning arm.

Table 15.3

The parameters of the positioning arm model

Name	Expression	Value	Comment
Arm_Width		0.74	X dimension of the positioning arm (m)
Arm_Thickness		0.7	Y dimension of the positioning arm (m)
Arm_Length		3	Z dimension of the positioning arm (m)
Arm_Upward_Shift		2	A distance between the rail head and bottom of the positioning arm (m)
Arm_Sideward_Shift		2.5	Positioning arm offset relative to the centre of the car body width (m)
Arm_Displacement	3*Car_Coupling_Base	28.002	Starting position of the positioning arm along the X axle (m)
Cycle_time		80	The time of the full cycle of unloading (s)
Start_time		5	The time of the movement start (s)

Stop_time		2	Operating time of the stoppers (s)
Arm_Push_time		49	The time of pushing of the positioning arm (s)
Arm_Return_time	Cycle_time-2*Start_time-Arm_Push_time-Stop_time	19	The time of return of the positioning arm (s)
Arm_t1		7	The time #1 for the speed profile of the positioning arm (s)
Arm_t2		26	The time #2 for the speed profile of the positioning arm (s)
Arm_t3		30	The time #3 for the speed profile of the positioning arm (s)
Arm_t4		42	The time #4 for the speed profile of the positioning arm (s)
Arm_v1		0.351245	The speed according to time #1 (m/s)
Arm_v2		0.351245	The speed according to time #2 (m/s)
Arm_v3		0.575	The speed according to time #3 (m/s)
Arm_v4		0.575	The speed according to time #4 (m/s)
Arm_angle		1.5708	The angle of rotation of positioning arm (rad)

Joint '*jBase0_Positioning Arm*' of generalized type describes the motion of the positioning arm as a preset time function, see Figure 15.47. In Figure 15.48 an exemplary speed profile throughout unloading cycle is given. An angle as function of time is used for rotation mode of positioning arm. It is required in order to put the positioning arm in or away between cars at the start and finish of dumping cycle. An exemplary of the rotation diagram of positioning arm is shown in Figure 15.49.

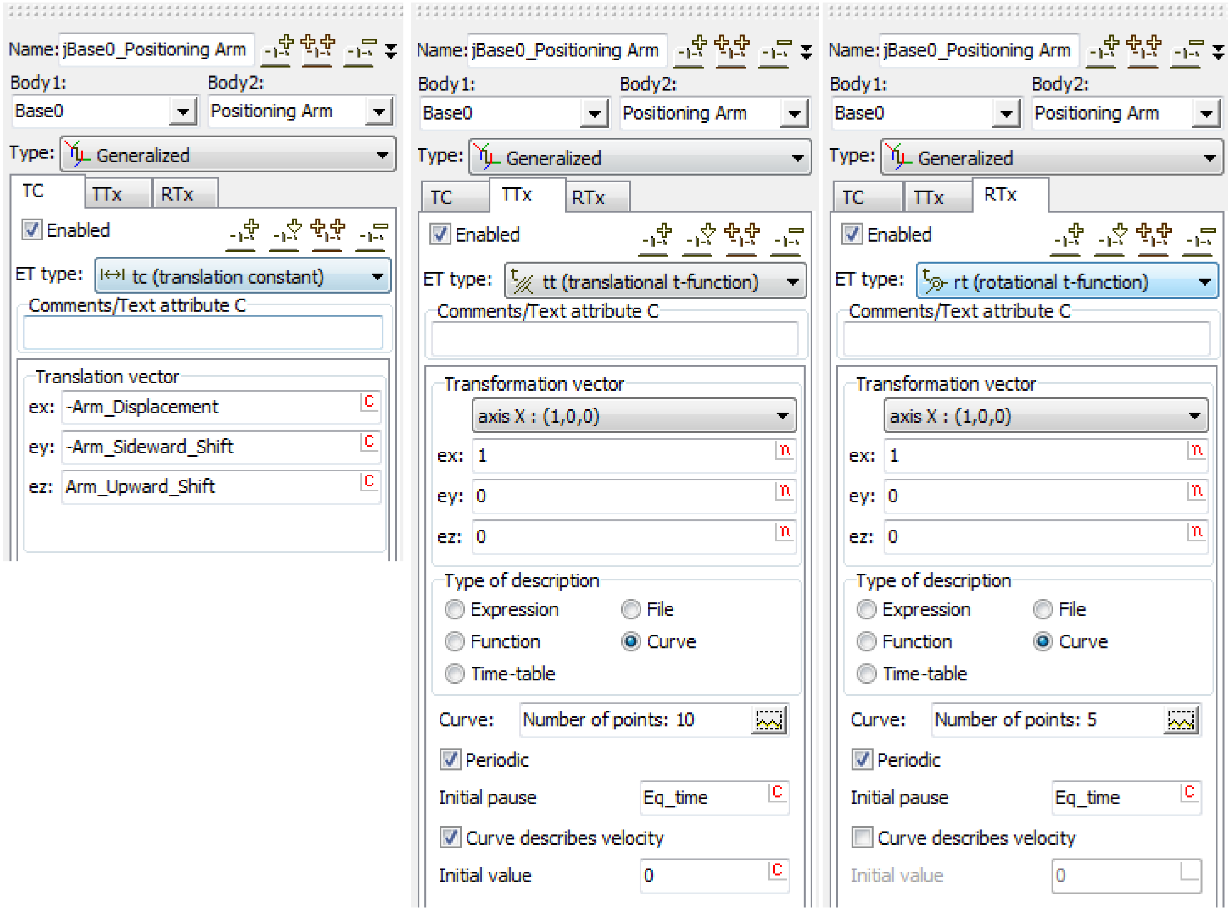


Figure 15.47. Settings of the movement mode of positioning arm.

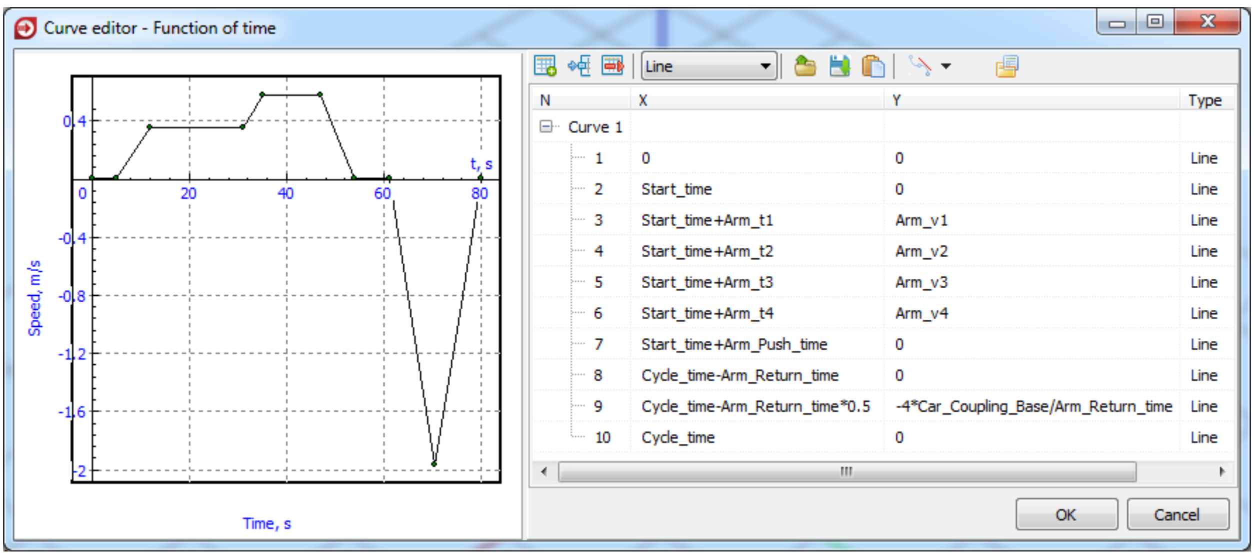


Figure 15.48. Speed profile of positioning arm throughout dumping cycle.

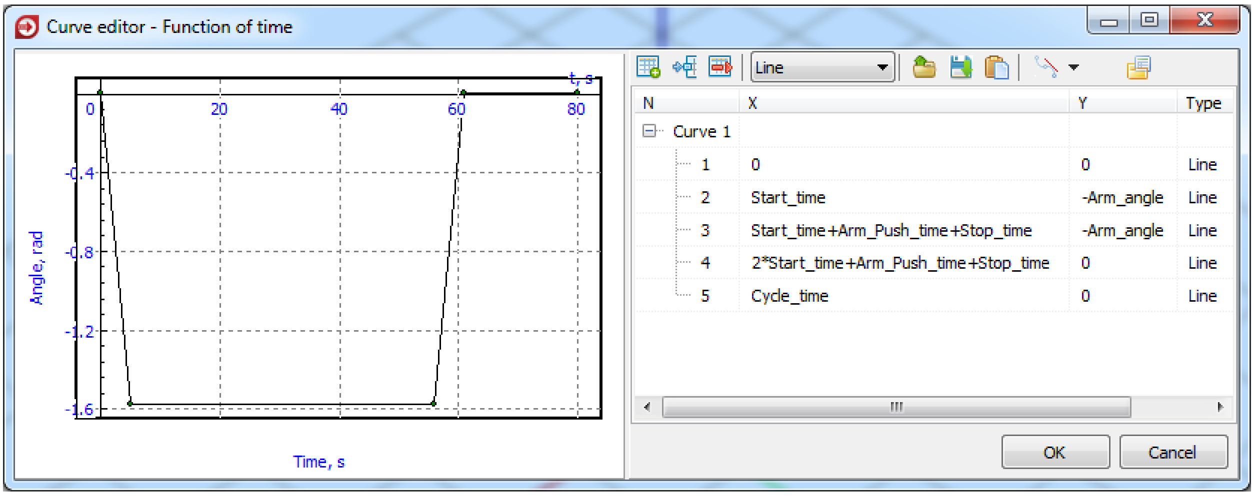


Figure 15.49. Rotation diagram of positioning arm.

15.7.1.4. Car dumper model

Rotary railcar dumper and positioner system is subsystem of whole model as well as each freight car. The dumper itself interacts with nothing. It is introduced into the model as pure illustrative element that gives the researches a possibility to better imagine the whole process. The graphic model of car dumper is presented in Figure 15.50. The dumper rotates according to the function of time given below; see Figure 15.51, Figure 15.52.

The *Displacement* parameter allows to locate the dumper at the any part of track. The '*Dumper*' subsystem gets this displacement along the track as is shown in Figure 15.53.

The process of dumping itself was not simulated because it does not influence longitudinal forces in inter-car couplings. So car dumper rotates only visually.

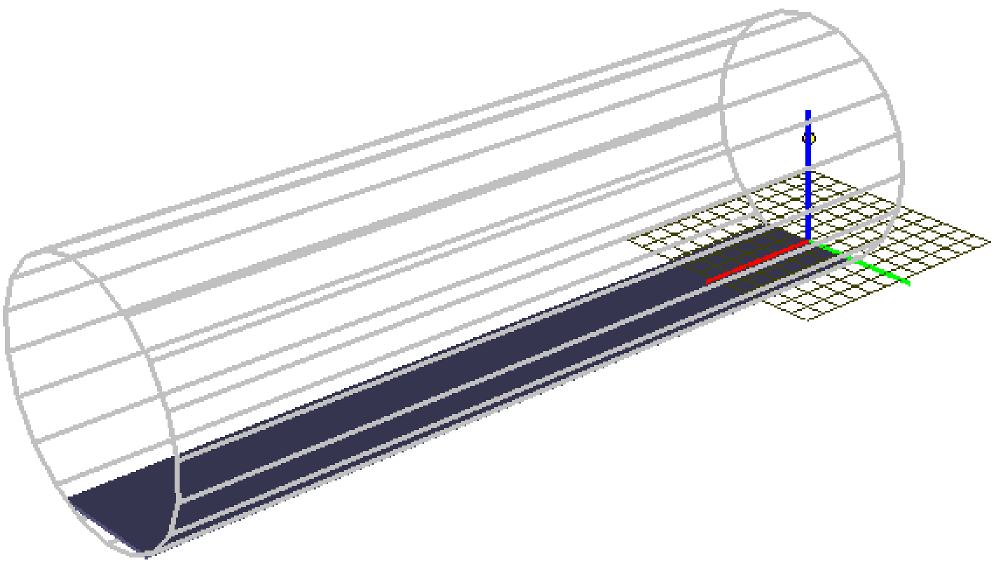


Figure 15.50. Car dumper model.

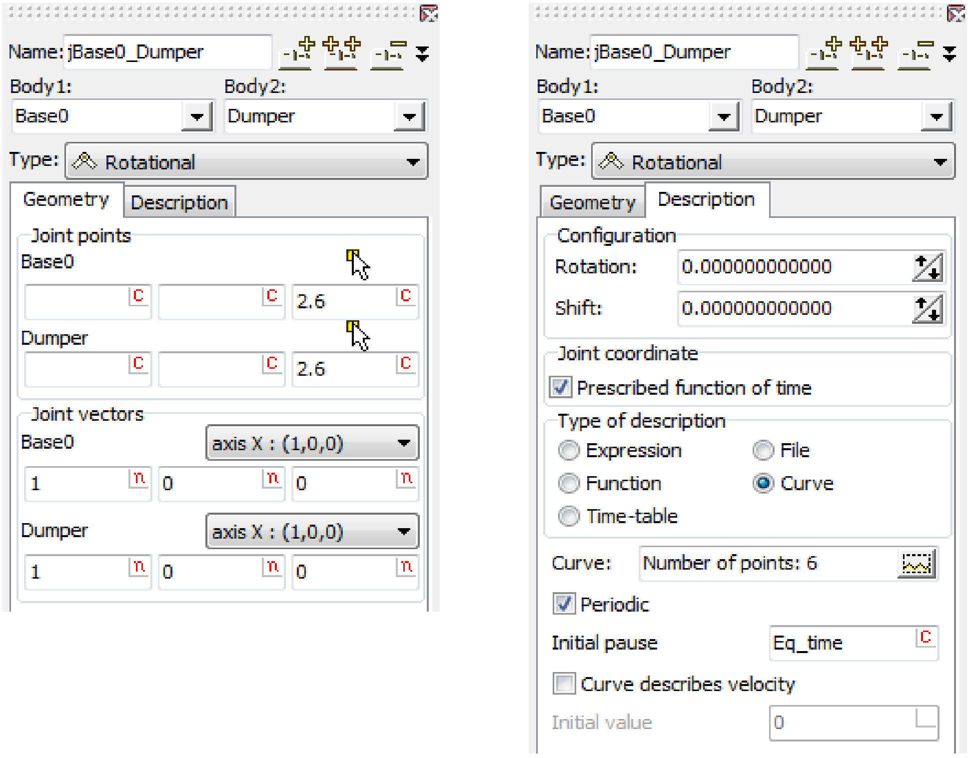


Figure 15.51. Settings of the rotation mode of dumper.

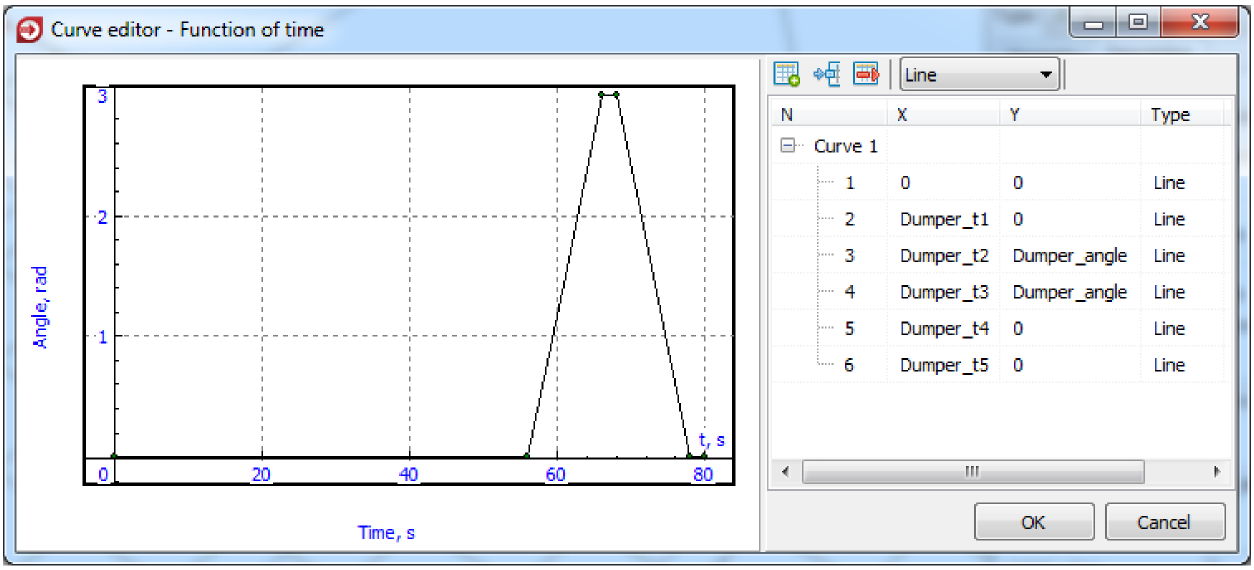


Figure 15.52. Rotation diagram of dumper.

Note! Railway track is modeled by using horizontal and vertical profiles thus it is three-dimensional curved line, see Sect 15.7.1.9. *"Track macrogeometry"*, p. 15-60. Displacement of dumper is set by natural coordinate but not by cartesian coordinates. So the coordinate in the '*x*' string in Figure 15.53 is the natural coordinate which to set the displacement of dumper along three-dimensional curved line but not along *x* axle.

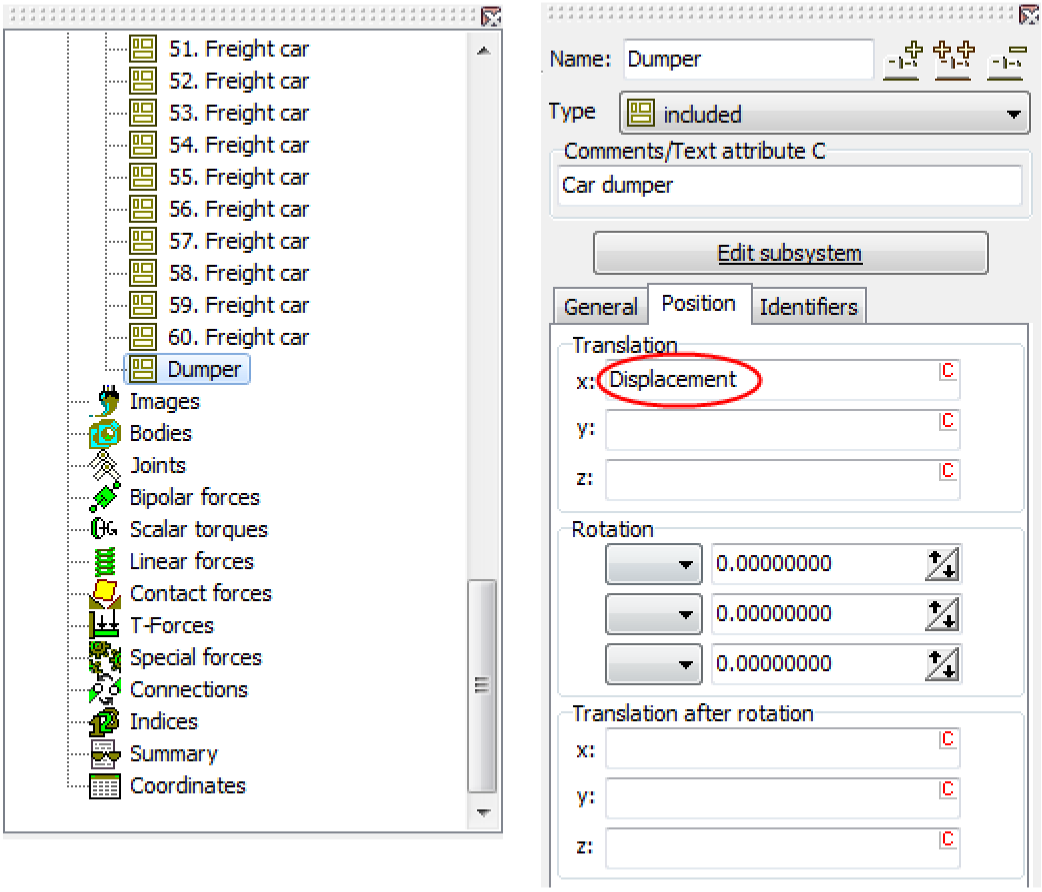


Figure 15.53. Displacement of dumper along the track.

15.7.1.5. Wheel locks model

Interaction between wheel locks and cars is modelled as interaction between contact manifolds with the help of **UM 3D Contact**, see Figure 15.39. The front lock operates in the linear displacement mode. The rear lock operates in the rotation mode. Travel and rotation angle of wheel locks are given as prescribed functions of time. The modes of operation of the wheel locks are presented in Figure 15.54.

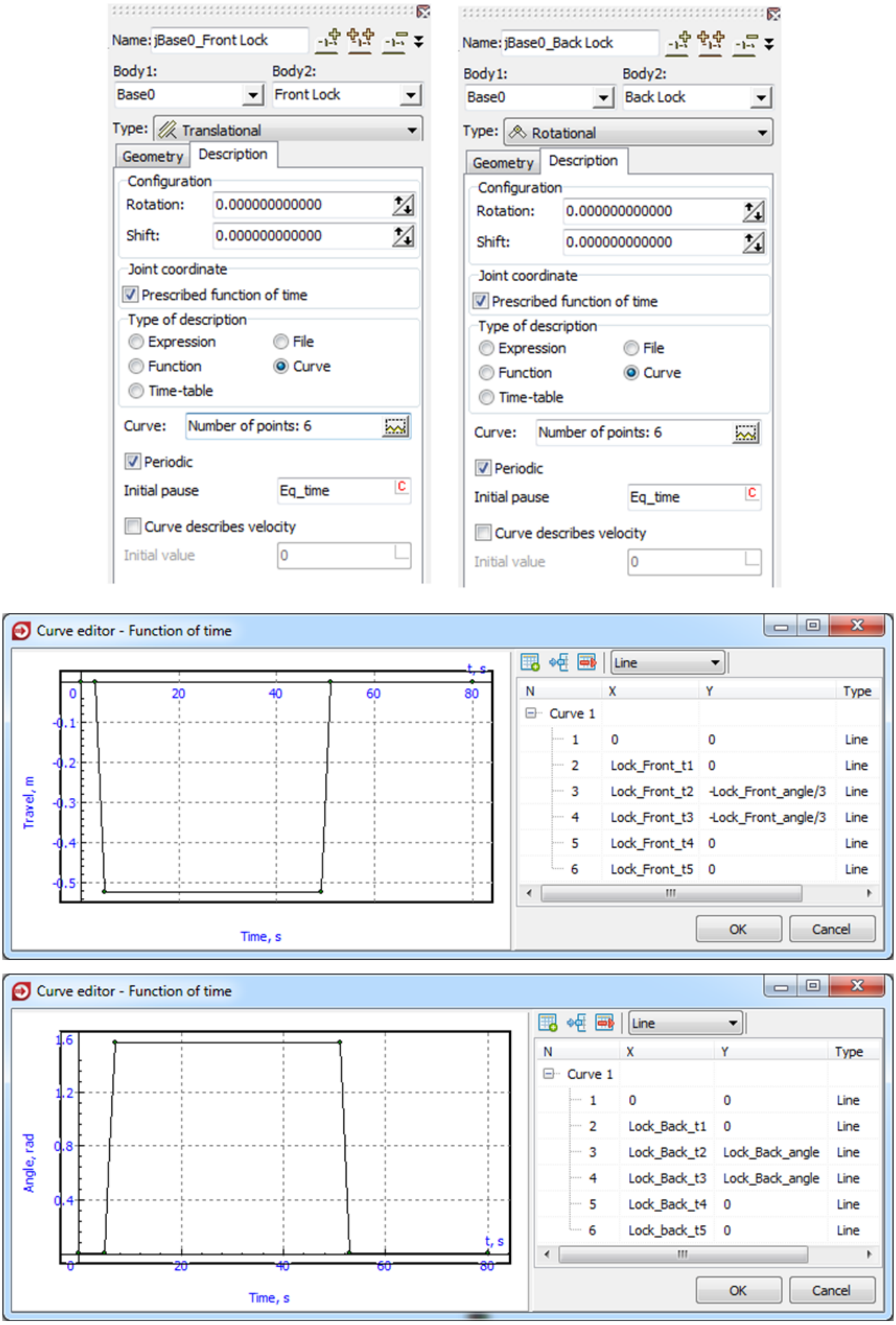


Figure 15.54. Operation modes of wheel locks.

15.7.1.6. Clamps model

Clamp is considered as a rigid body with the contact manifold (**UM 3D Contact**) that allows it to interact with cars, see Figure 15.40. The graphical image of clamp is shown in Figure 15.55

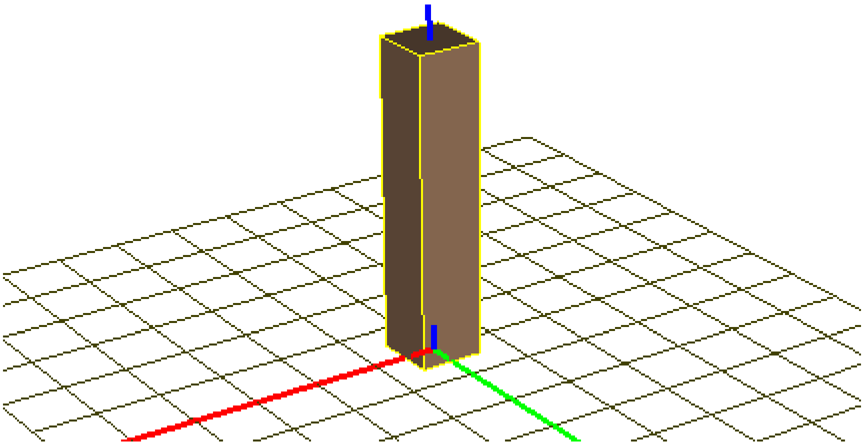


Figure 15.55. Graphical image of clamp.

The clamps press the car both sides by using two forces. The lateral force produces friction force big enough to stop and hold the train, see Table 15.4.

Table 15.4

The parameters of the clamps model

Name	Expression	Value	Comment
Clamp_pressing_force		2E+6	Pressing force of clamp (N)
Clamp_stiff_stopper	Clamp_pressing_force/0.1	2E+7	Coefficient of stiffness of the stopper
Clamp_damp_stopper	2*sqrt(4680* Clamp_stiff_stopper)	6E+5	Damping coefficient of the stopper, where 4680 is mass of the clamp (kg)
Clamp_t1	Start_time	5	The first interval of the movement profile of clamps (s)
Clamp_t2	Start_time+ Arm_Push_time	54	The second interval of the movement profile of clamps (s)
Clamp_t3	Clamp_t2+Stop_time	56	The third interval of the movement profile of clamps (s)
Clamp_t4	Cycle_time	80	The fourth interval of the movement profile of clamps (s)
Clamp_offset		0.1	Offset of the clamp (m)

Joints '*jBase0_Right Clamp*' and '*jBase0_Left Clamp*' of translational type describe the motion of the clamps as a preset time function, see Figure 15.56 and

Figure 15.57.

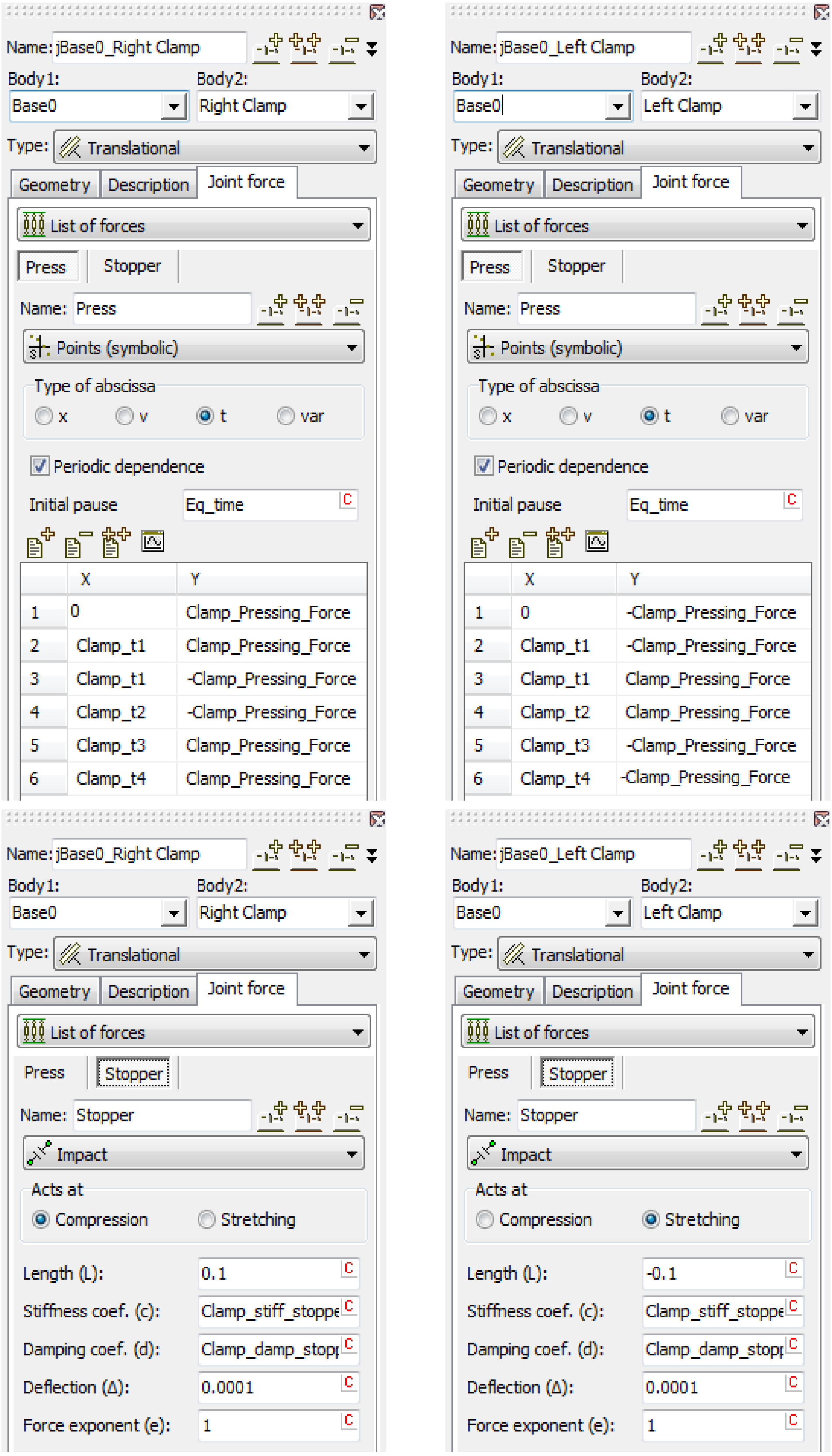


Figure 15.56. Settings of pressing forces.

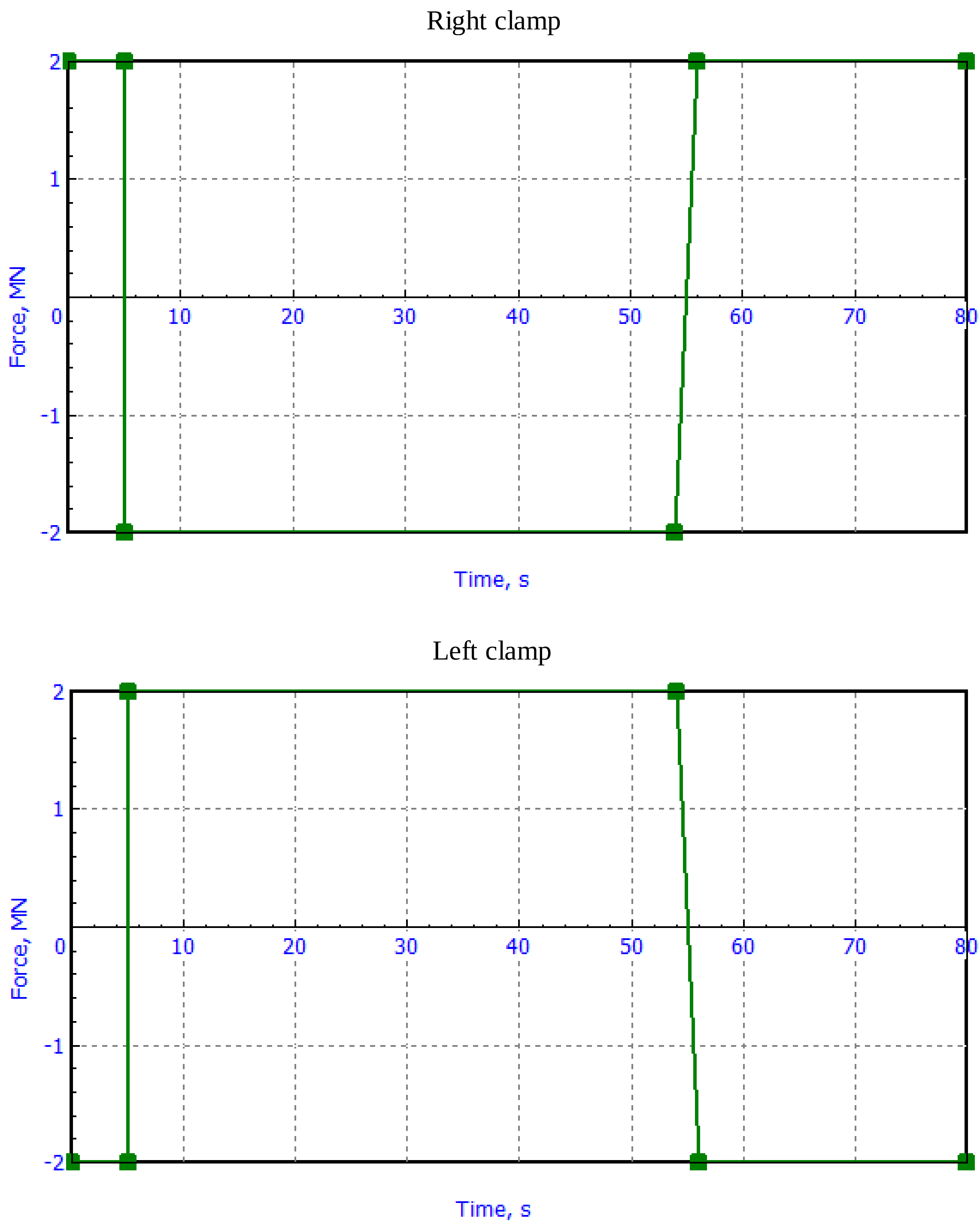
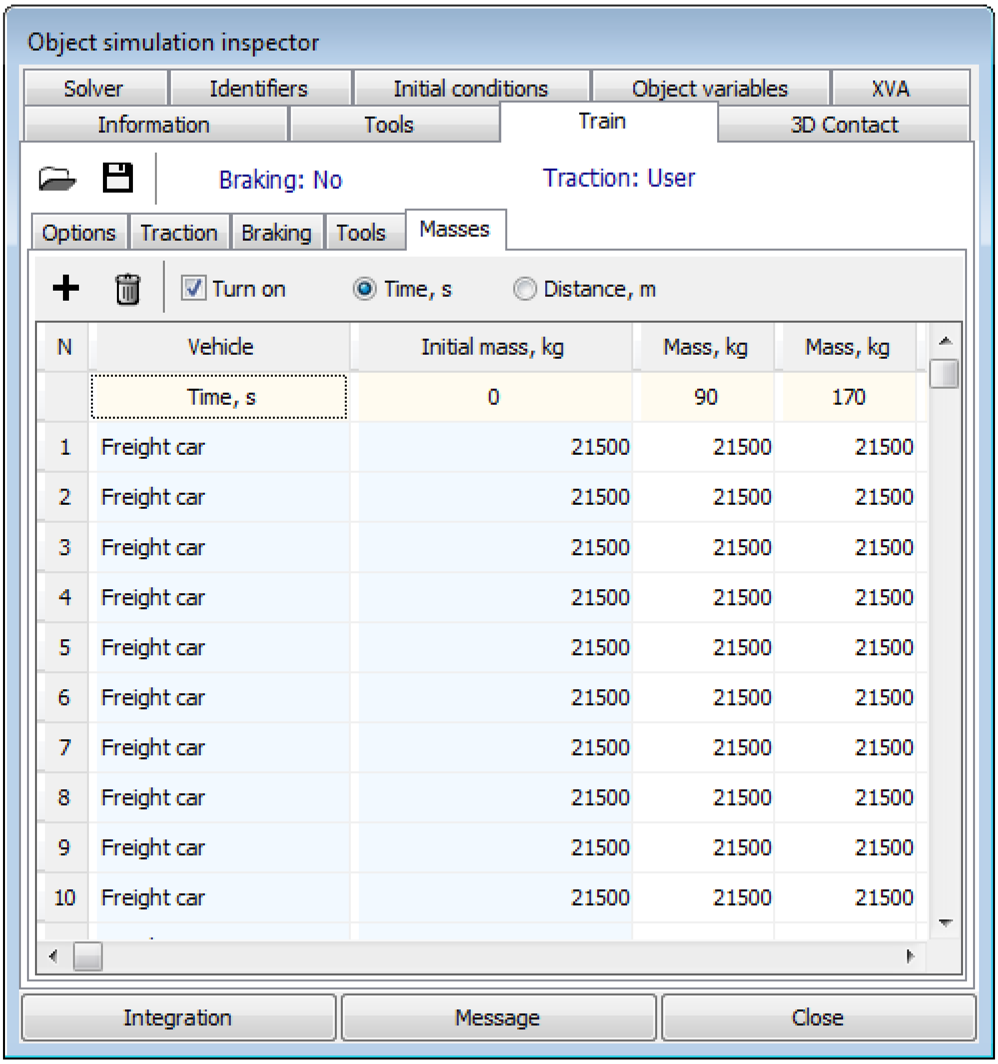


Figure 15.57. Operation modes of clamps.

15.7.1.7. Table of masses

UM software allows changing the mass of bodies during computer simulation. This makes it possible to change the mass of each car after dumping. In the computer simulation the mass of dumped cars is changed instantly at the end of a dumping cycle.

The mass of car can be changed depending on time or distance with help table of masses. It is possible to set the table of masses at **Train | Masses** tab of **Object simulation inspector**, see Figure 15.58.



N	Vehicle	Initial mass, kg	Mass, kg	Mass, kg
	Time, s	0	90	170
1	Freight car	21500	21500	21500
2	Freight car	21500	21500	21500
3	Freight car	21500	21500	21500
4	Freight car	21500	21500	21500
5	Freight car	21500	21500	21500
6	Freight car	21500	21500	21500
7	Freight car	21500	21500	21500
8	Freight car	21500	21500	21500
9	Freight car	21500	21500	21500
10	Freight car	21500	21500	21500

Figure 15.58. Example of table of masses.

As a rule the long heavy-haul trains contain a lot of cars, their number could reach several hundred. For this reason adding the columns in the table manually is very long and uncomfortable procedure. This table can be created via master of creation of table of masses. Master runs by right button of mouse click on table field. The **Specify dumping parameters** item of popup menu is needed to choose as shown in Figure 15.59.

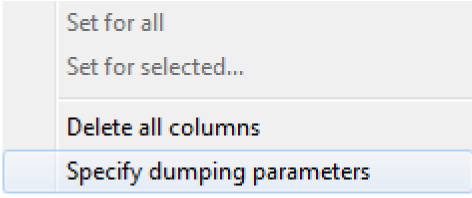


Figure 15.59. Popup menu of table of masses.

The parameters of dumping can be set in the appeared window, see Figure 15.60.

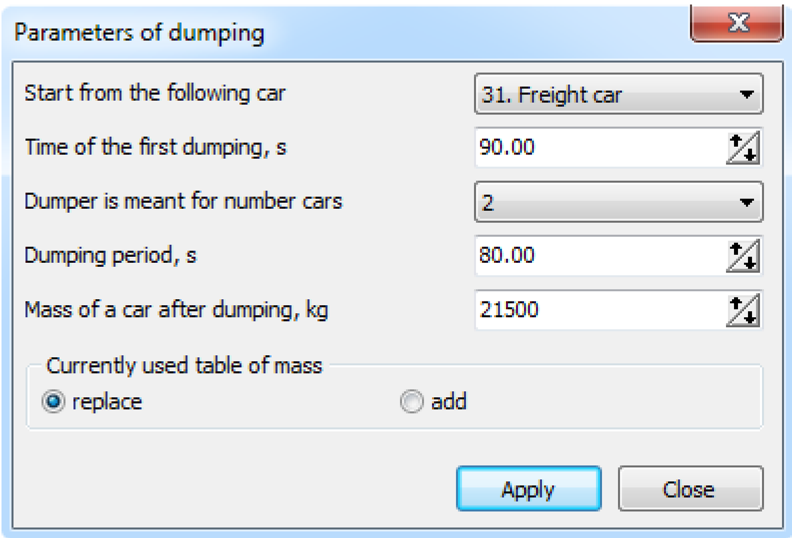


Figure 15.60. Master of creation of table of masses.

15.7.1.8. Synchronization of operations

The operations of all mechanisms such as positioning arm, dumper, clamps, and wheel locks are synchronized each other. The values of parameters of model are presented in Table 15.5.

Combination of the work modes of mechanisms in the time scale are shown in Figure 15.61.

The procedure of step-by-step execution of operations during one cycle is described in Table 15.6.

Table 15.5

The model parameters defining the modes of mechanisms operations

Name	Expression	Value
Eq_time		10
Cycle_time		80
Start_time		5
Stop_time		2
Arm_Push_time		49
Arm_Return_time	Cycle_time-2*Start_time-Arm_Push_time-Stop_time	19
Arm_t1		7
Arm_t2		26
Arm_t3		30
Arm_t4		42
Arm_v1		0.351245
Arm_v2		0.351245
Arm_v3		0.575
Arm_v4		0.575
Arm_angle		1.5708
Clamp_t1	Start_time	5
Clamp_t2	Start_time+Arm_Push_time	54
Clamp_t3	Clamp_t2+Stop_time	56
Clamp_t4	Cycle_time	80
Dumper_t1	Start_time+Arm_Push_time+Stop_time	56
Dumper_t4	Cycle_time-Stop_time	78
Dumper_t2	(Dumper_t1+Dumper_t4)*0.5-1	66
Dumper_t3	(Dumper_t1+Dumper_t4)*0.5+1	68
Dumper_t5	Cycle_time	80
Dumper_angle		3
Lock_Front_t1	Start_time-Stop_time	3
Lock_Front_t2	Start_time	5
Lock_Front_t3	Start_time+Arm_Push_time-5	49
Lock_Front_t4	Lock_Front_t3+Stop_time	51
Lock_Front_t5	Cycle_time	80
Lock_Front_angle		1.5708
Lock_Back_t1	Start_time	5
Lock_Back_t2	Lock_Back_t1+Stop_time	7
Lock_Back_t3	Lock_Front_t3+Stop_time	51
Lock_Back_t4	Lock_Back_t3+Stop_time	53
Lock_Back_t5	Cycle_time	80
Lock_Back_angle		1.5708

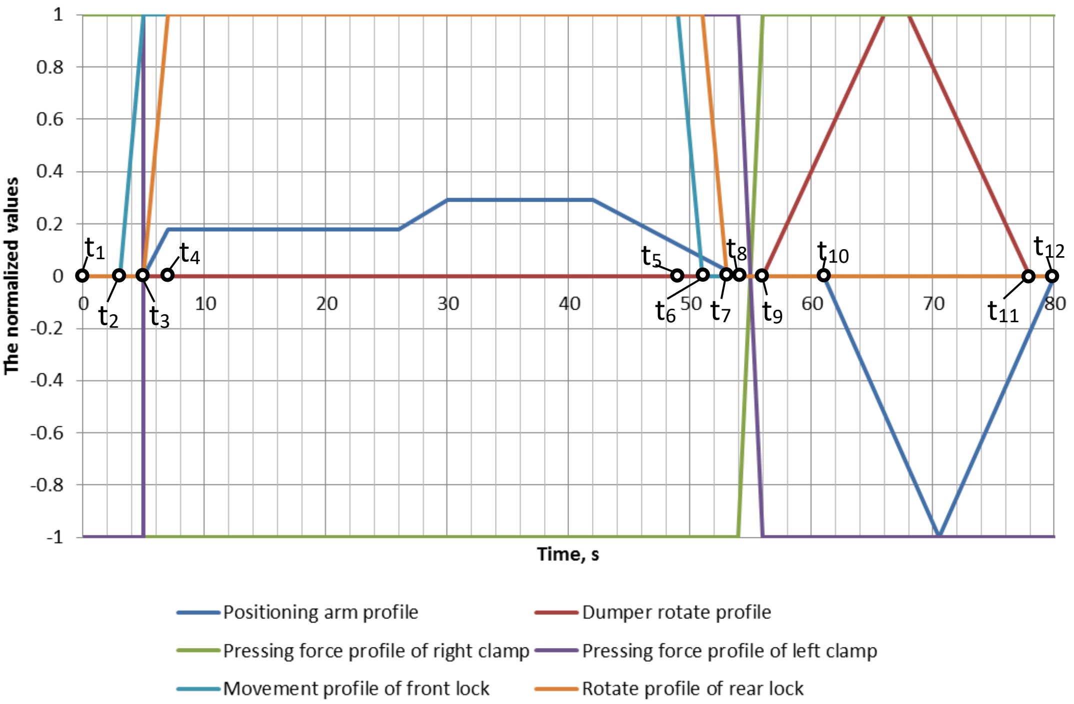


Figure 15.61. Combination of the profiles of different mechanisms in the time scale.

Table 15.6

Timetable of operations during one cycle

Point	Time, s	Event
t_1	0	The positioning arm starts to rotate until setting between cars
t_2	3	The front lock starts to open
t_3	5	1) The front lock finishes to open 2) The rear lock starts to open 3) The clamps get opened 4) The positioning arm starts to push car
t_4	7	The rear lock finishes to open
t_5	49	The front lock starts to close
t_6	51	1) The front lock finishes to close 2) The rear lock starts to close
t_7	53	The rear lock finishes to close
t_8	54	1) The positioning arm is stopped 2) The clamps start to close
t_9	56	1) The clamps finish to close 2) The positioning arm starts to rotate getting out between cars 3) The dumper starts to rotate
t_{10}	61	The positioning arm starts to move to home position
t_{11}	78	The dumper finishes to rotate
t_{12}	80	The positioning arm comes to home position

15.7.1.9. Track macrogeometry

Macrogeometry includes horizontal and vertical profile of the railway track, see Figure 15.62 and Figure 15.63.

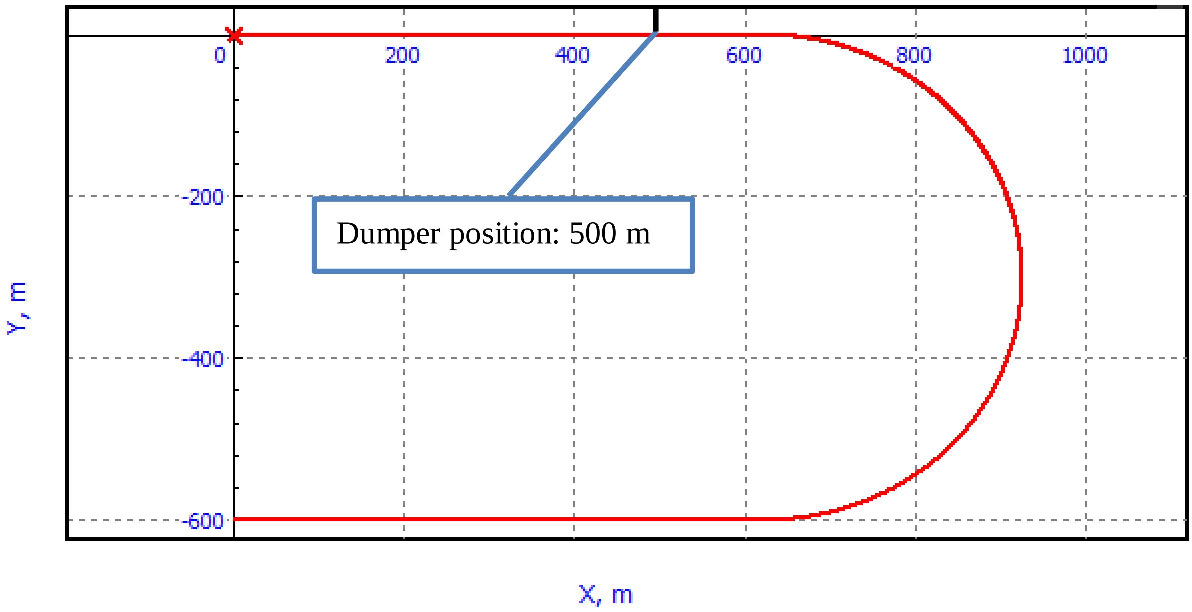


Figure 15.62. Horizontal macrogeometry.

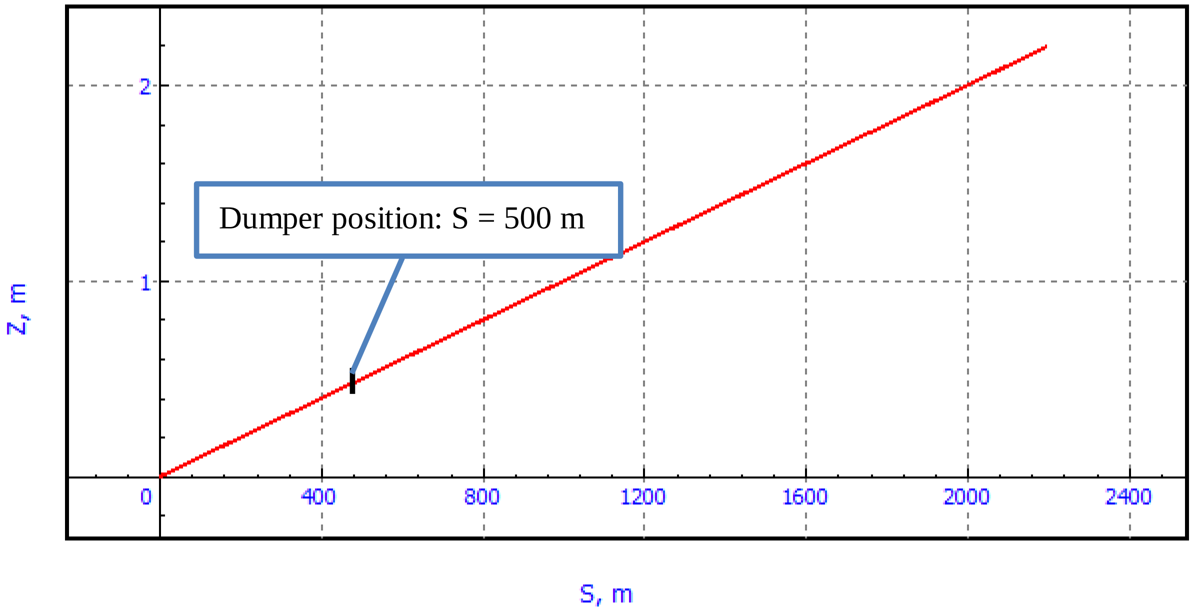


Figure 15.63. Vertical macrogeometry.

15.7.2. How to use the model

Please note before first use model is needed to copy the files listed below to the mentioned folders, see Table 15.7.

Table 15.7

The files list which is needed to copy in UM library

Source	Destination
"Iron Ore Car" folder	*{UM Data}\rw\Train\Cars*
Doubled Draft Gear autocoupler.bfc	*{UM Data}\rw\Train\Absorbers*
Doubled Draft Gear drawbar.bfc	*{UM Data}\rw\Train\Absorbers*
Car dumper macrogeometry.mcg	*{UM Data}\rw\MacroGeometry*
Australian Mineral Railways.rf	*{UM Data}\rw\Train\Resistance*

Iron Ore Car model and Draft Gear models are needed for creating Train model by using **Train wizard** in **UM Input** program. For example see Figure 15.64.

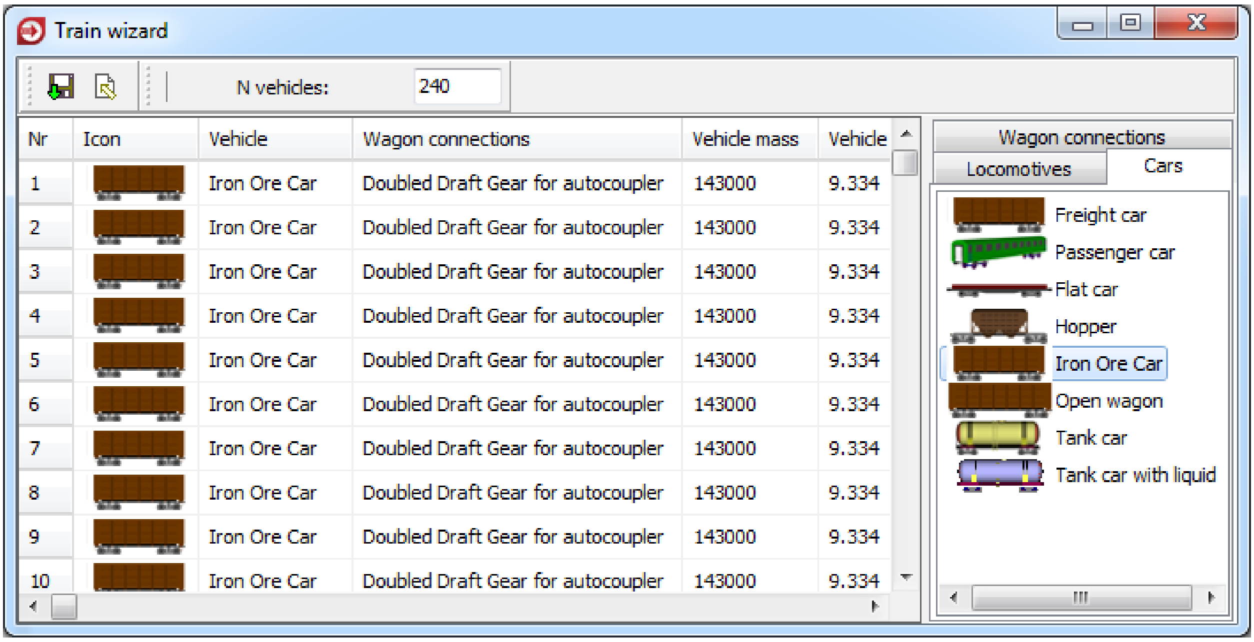


Figure 15.64. Creating Train model by Train wizard in **UM Input**.

"Car dumper macrogeometry.mcg" file should be added in **Train | Options | Track** tab sheet of **Object simulation inspector**, see Figure 15.65.

Default propulsion resistance model is suitable for both empty and loaded cars and corresponds to Australian Mineral Railway. "*Australian Mineral Railways.rf*" file should be added to the list on **Train | Options | Resistance | Propulsion** tab of **Object simulation inspector**. Set this resistance model for all vehicles of train by right-clicking mouse and selecting **Assign to all** menu command, see Figure 15.66.

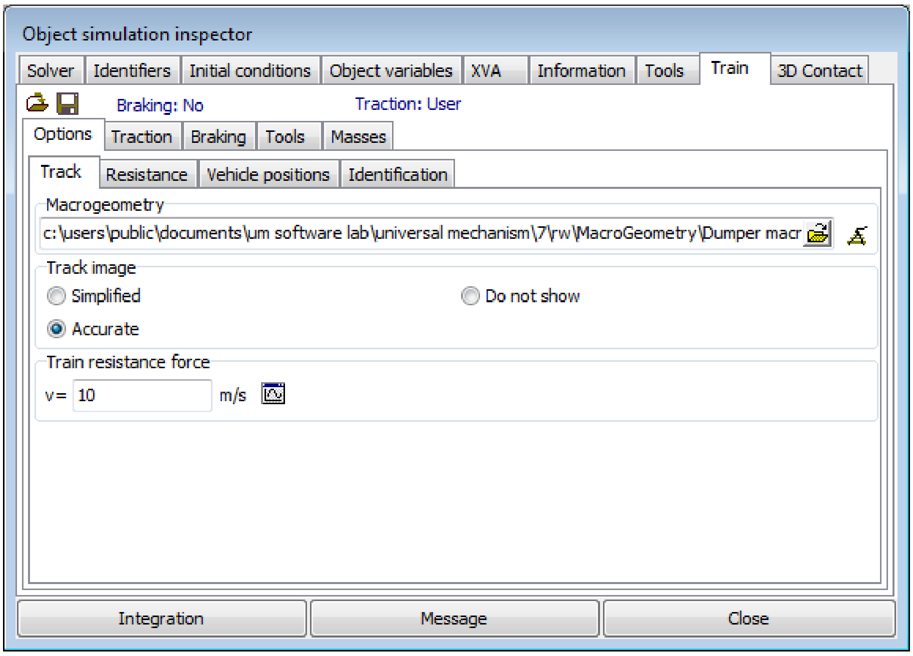


Figure 15.65. The adding of Track model to the Train model.

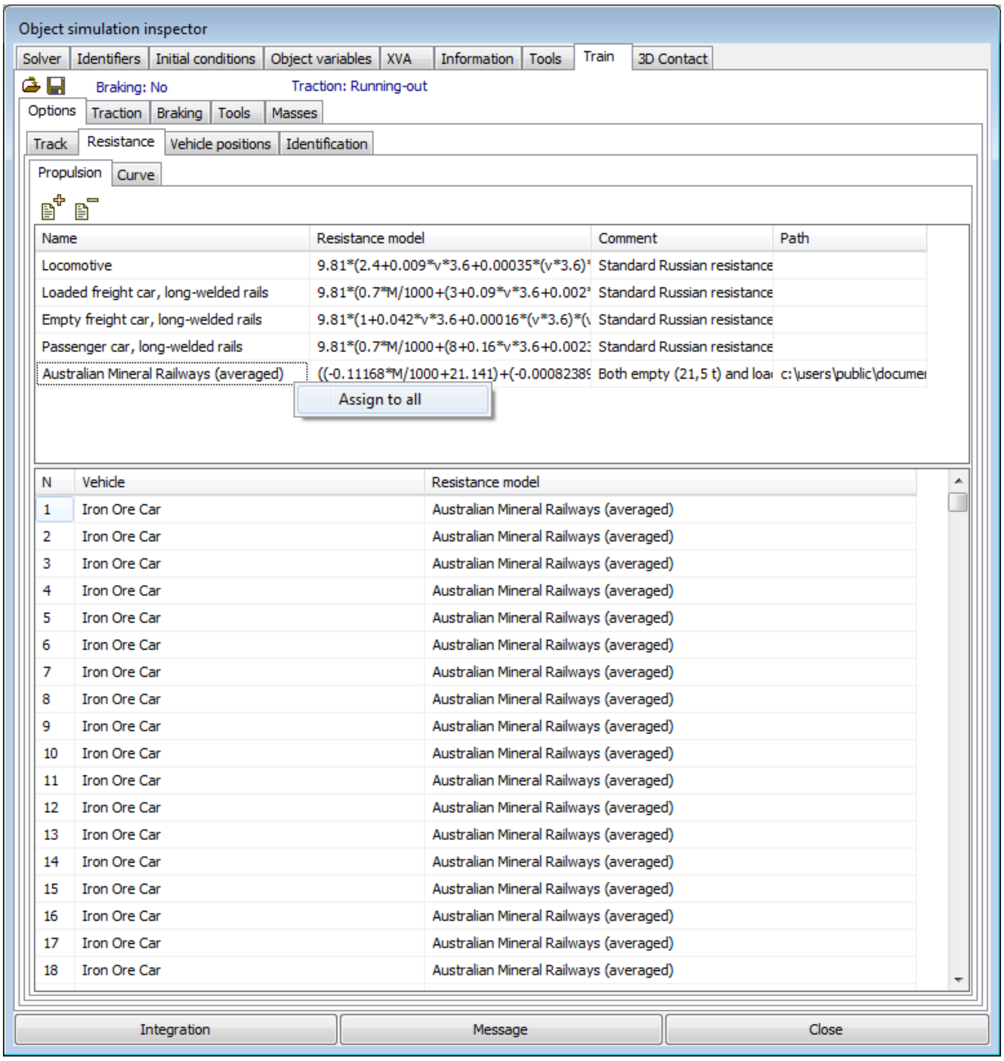


Figure 15.66. How to set propulsion resistance force model.

15.7.2.1. Predefined configurations

Train&Dumper model includes two predefined configurations: *Case 1* and *Case 2*. In test *Case 1* the positioning arm pushes the car number 3, position of the first vehicle is 500 m. In test *Case 2* the positioning arm pushes the car number 31, position of the first vehicle is 761.352 m. Every test case includes at least 5 full dumping cycles.

Use **File | Load configuration** menu command to load predefined configurations. After loading any of these configurations is not needed to execute equilibrium test, see Sect. 15.7.2.2. *"Initial conditions"*, p. 15-63.

15.7.2.2. Initial conditions

Equilibrium test should be done prior to simulation if at least one of the following model parameters were changed: the position of the car dumper along the track, the position of the first car of train, free slacks, a propulsion or curving resistance parameters, energy consumption of draft gears, the geometric parameters of cars.

To calculate initial condition load the model in **UM Simulation** program and run **Object simulation inspector**, then select **Train | Traction** tab and set **Speed profile mode** to **User**, see Figure 15.67. Then select **Identifiers** tab and set *Eq_time* parameter to 200 (seconds).

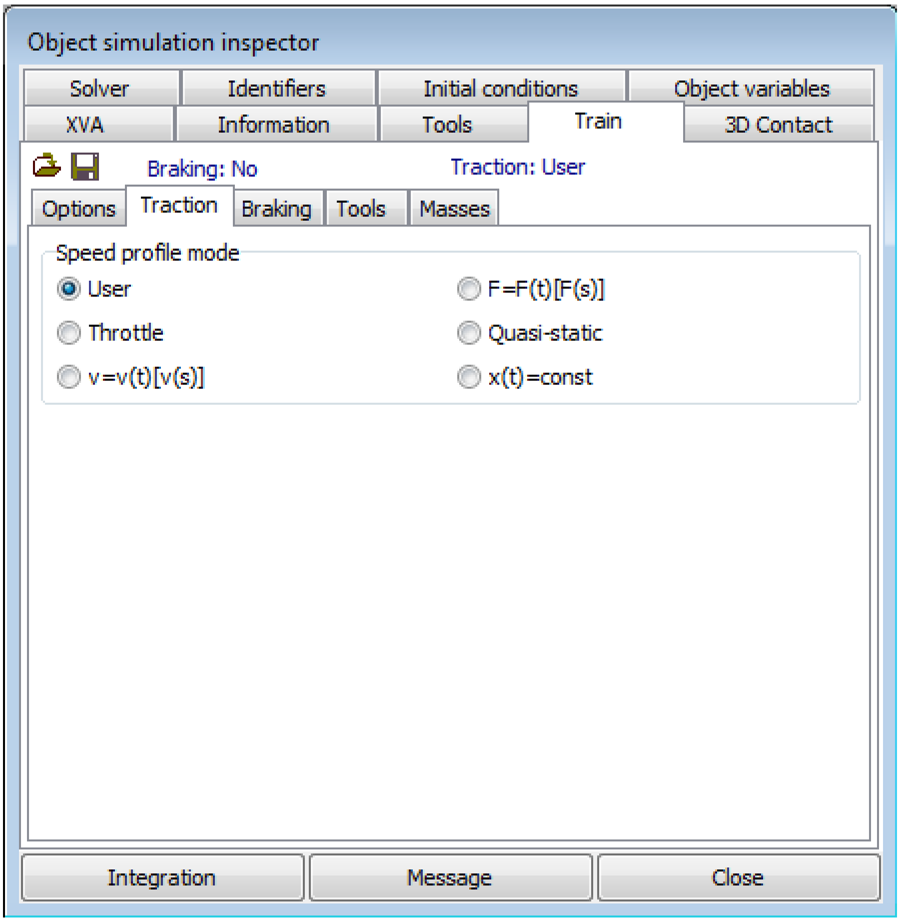


Figure 15.67. Speed profile mode choice.

To place the train in the proper position use **Position of the first car** edit box in **Train | Options | Vehicle positions** tab. For instance, position of the train that corresponds the position of 31rd car right after the positioning arm is 761.352 m as it is shown in Figure 15.68. The car that is placed into locking mechanism will be fixed during the *Eq_time* time slot. So the position of the locked car will keep nearly constant during the equilibrium test.

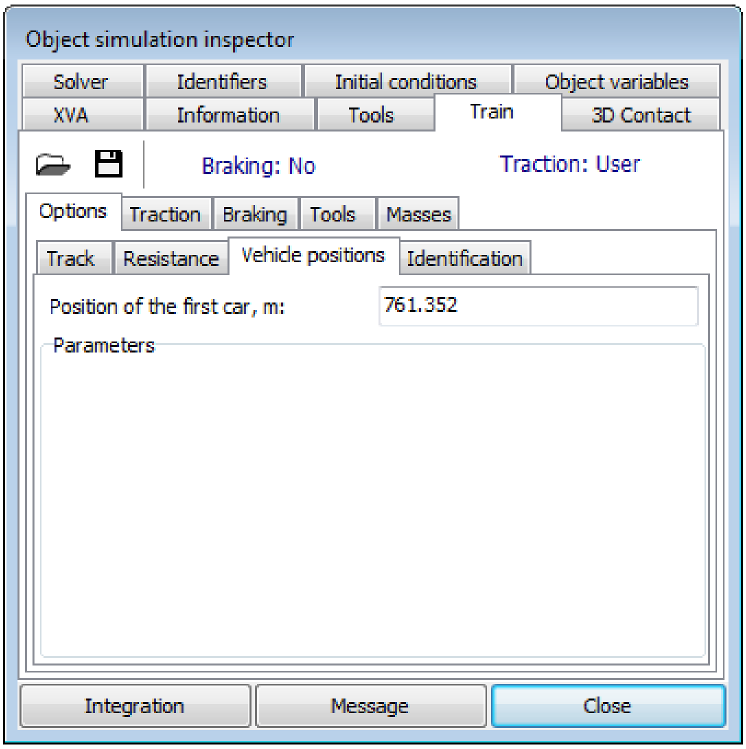


Figure 15.68. Setting the train position.

Please also note it is needed to switch table of mass off before running the equilibrium test. For that select **Train | Masses** tab and remove check mark in **Turn on** switch, see Figure 15.69.

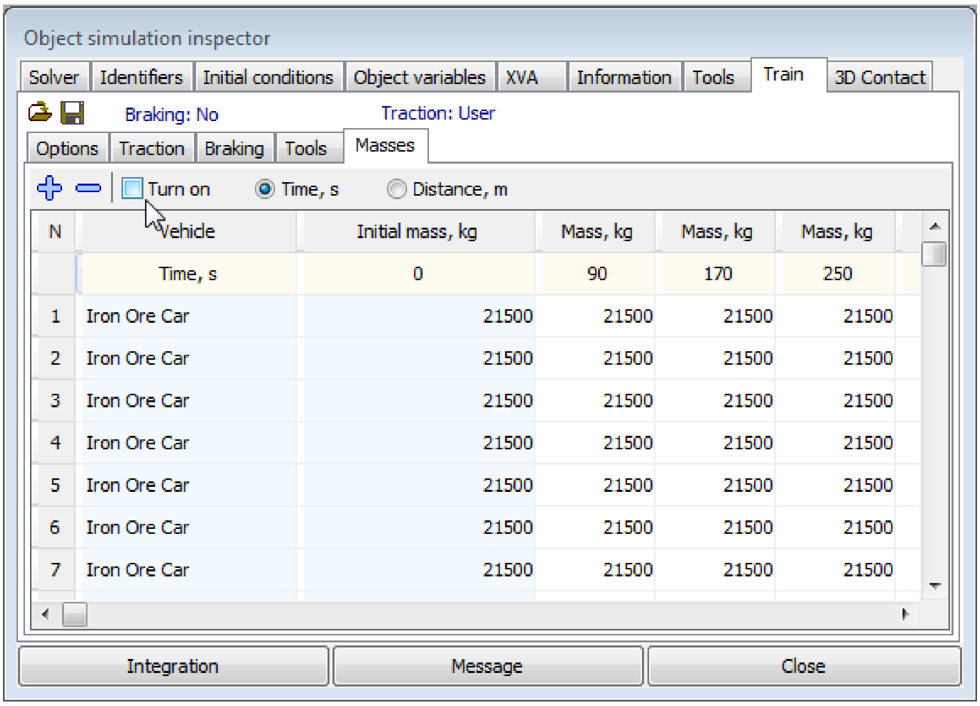


Figure 15.69. The switching off of table of masses.

Please also note that the simulation time should not exceed the given *Eq_time* time, see Figure 15.70. Otherwise positioning arm will start moving and equilibrium position will be lost.

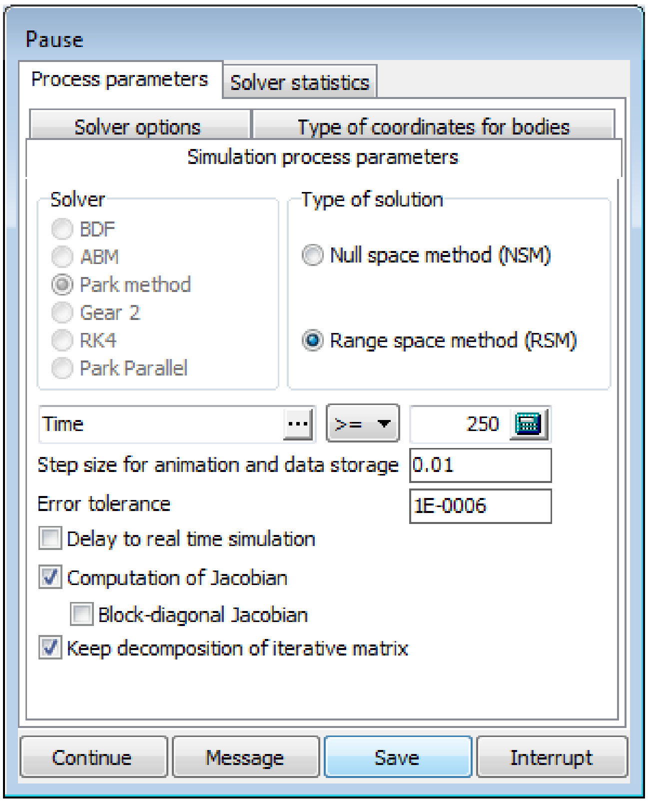


Figure 15.70. Save coordinates and speeds.

It normally takes about 150-250 seconds to let the whole train settle down from the initial state. The criteria of assessing the equilibrium of train might be, for example, speed of the last car – it must tend to zero, or total kinetic energy of the train. When the equilibrium test is completed the current coordinates and velocities should be saved by using **Save** button in **Pause** window, see Figure 15.70. Then, these results should be loaded from the file at **Initial conditions | Coordinates** tab of **Object simulation inspector**. The velocities should be set to zero by using **Set zero values to velocities** button, see Figure 15.71. After that save these initial conditions separately or whole model settings via **File | Save configuration | All options** menu command.

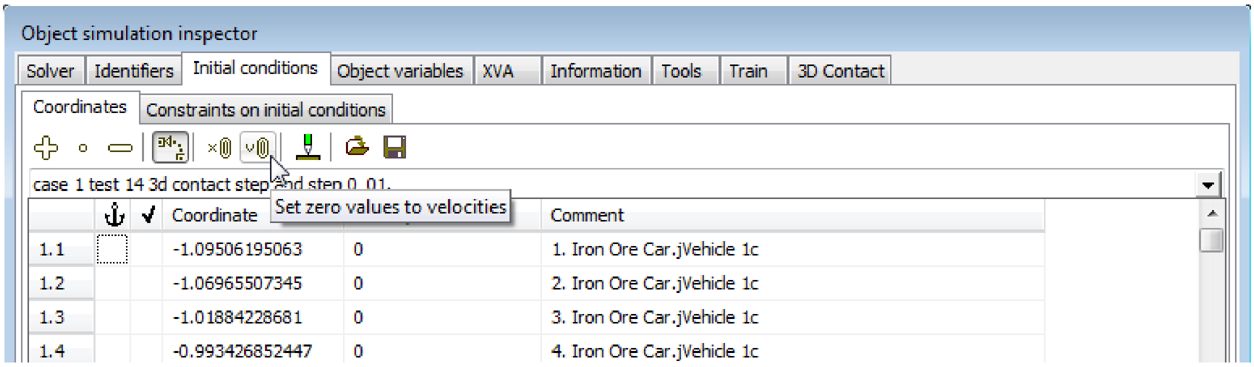


Figure 15.71. Set all speeds to zero.

15.7.2.3. Basic model parameters

Use the *Eq_time* parameter to define the pause before the start of movement of the positioning arm. The default pause is 10 seconds. It is recommended to keep at least 10 seconds time slot prior the first cycle for all calculations. It is related to that fact that hysteresis force elements in draft gears have two modes: "sliding" and "sticking". At the end of equilibrium test some of them change its state. However the final state of force elements is not saved anyhow and lost. Any next simulation will start with default "sliding" state. That is why some minor dynamical processes can arise in the train even if it is started from preliminarily calculated equilibrium position.

Use the *Displacement* parameter to set the position of the car dumper along the way. Note that the position of the first car of train should be set at **Train | Options | Vehicle positions** tab of **Object simulation inspector**.

Slack_coupler and *slack_drawbar* parameters are used to set the total free slack between two adjacent cars.

Positioning arm is parameterized with the group of parameters that start with *Arm* prefix. A user can control speed profile of the positioning arm via such parameters like, for example, *Arm_Push_time*, *Arm_t1* etc.

Prefix *Clamp* is used for a group of parameters that control the operation mode of clamps, for instance, *Clamp_pressing_force*, *Clamp_t1* etc. *Dumper* prefix is related to parameters that describe operation mode of the car dumper. Parameters that start with *Lock* prefix controls wheel locks (*Lock_Front_angle*, *Lock_Front_t1* etc.)

The default values of basic model parameters are presented in Table 15.5.

15.7.2.4. How to speed up the model

Some tricks to make the model faster (minimize CPU-time per numerical experiment) are considered in this section.

The most evident parameters that influence on CPU-time are used solver and error tolerance. They both are set in **Object simulation inspector | Solver** tab sheet, see Figure 15.72. The most effective solver is **Park method**. The recommended error tolerance is $1 \cdot 10^{-6}$.

Maximal step size parameter that is placed in **Solver options** tab is also very important for minimization of CPU-time, see Figure 15.73. Default value of **Maximal step size** is 0.001. Please note that **Park method** is implemented in UM as a numerical method with the variable step size. Numerical method tends to make the step size as bigger as possible taking into account the upper limit that is given by **Maximal step size** and preset accuracy (error tolerance). It is important that error tolerance keeps within the preset limits regardless current step size. In other words current step size is automatically chosen so as to provide the required error tolerance. There is one thing that restricts the **Maximal step size**. It is **Step size for animation and data storage**. **Maximal step size** cannot be bigger than the chosen **Step size for animation and data storage**. Numerical tests showed the recommended **Step size for animation and data storage** is 0.01 second. That is why **Maximal step size** is also 0.01 second.

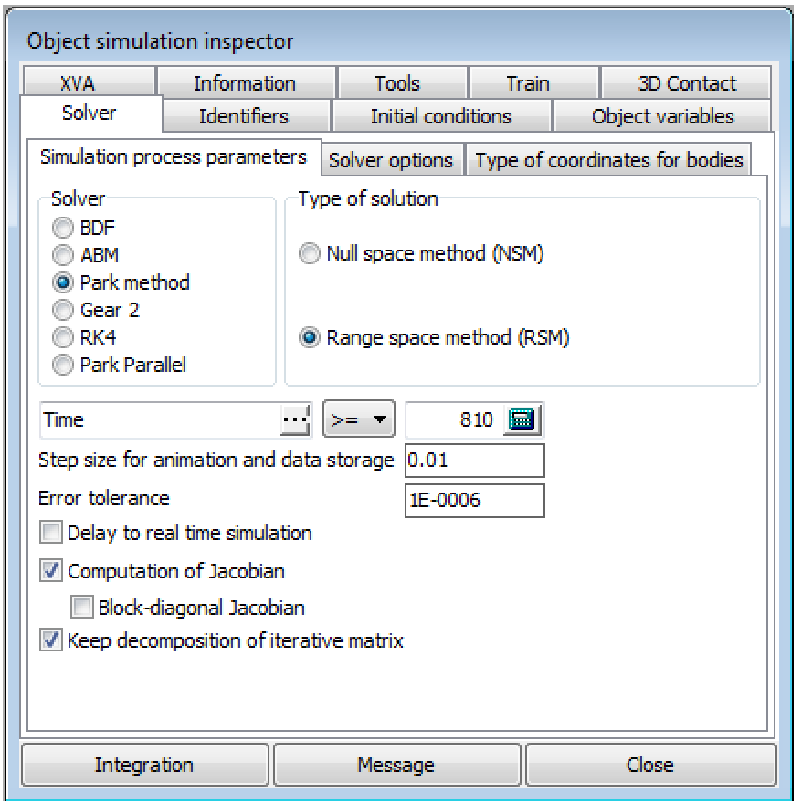


Figure 15.72. Simulation process parameters

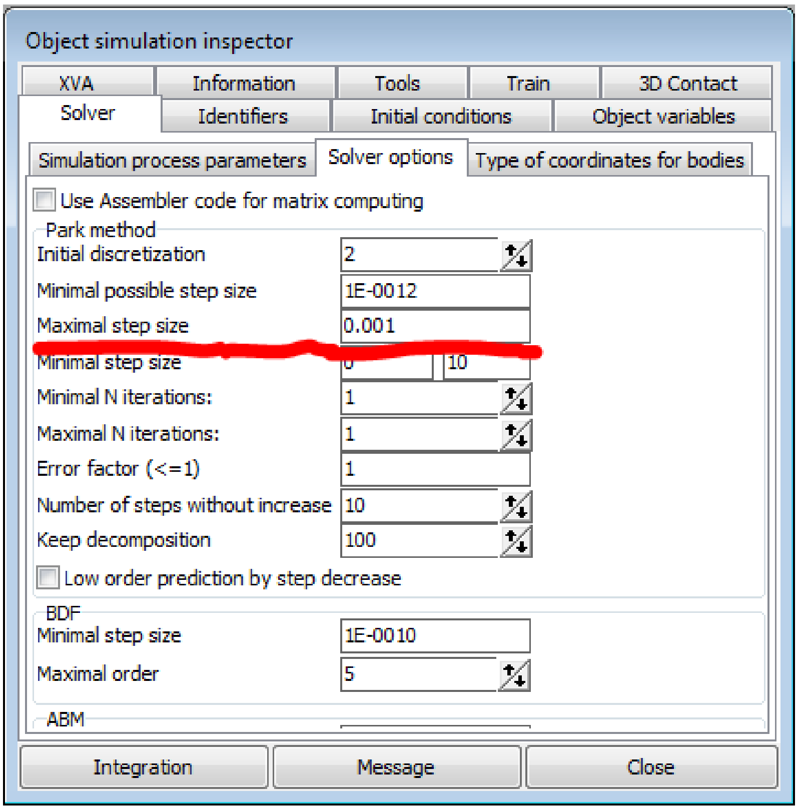


Figure 15.73. Solver options

One more opportunity to speed up the model gives optimization of **3D Contact** parameters. The most important parameter in this sense is **Distance between** (adjacent contact) **points**, see Figure 15.74. Default value of this parameter is 0.05m. Generally the closer contact points are placed to each other the smoother solution will be provided, for example, when one body rolls on surface of another one. However, regarding particular train&dumper model, all cars in the model have the only longitudinal degree of freedom. So there is no difference in sense of smooth solution between bigger or smaller values of **Distance between points**. The bigger the distance the fewer contact points will be generated and computed at every simulation time step. It is recommended to set **Distance between points** to 0.5-1 m. Numerical tests showed that using **Distance between points** of 1 m instead of 0.05 m speeds up the simulation more than 2.5 times.

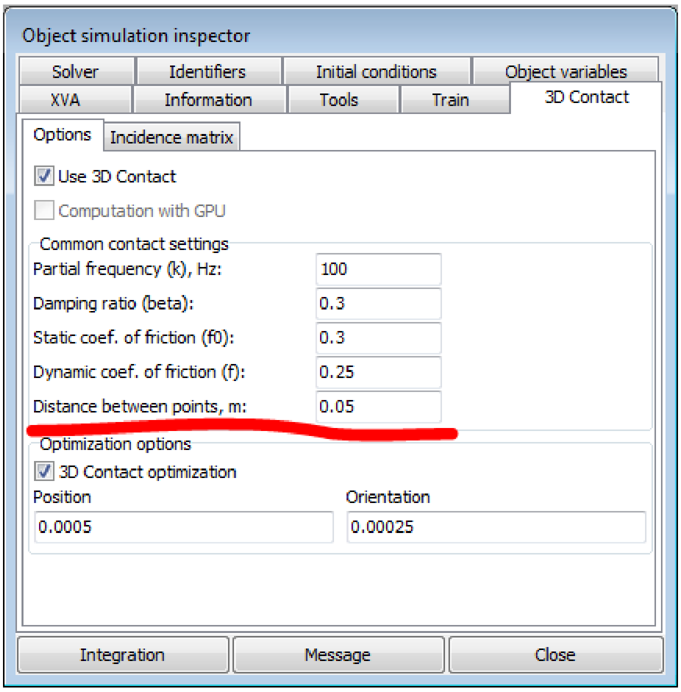


Figure 15.74. 3D Contact options

Recommendations considered in this section are shortly presented in Table 15.8.

Table 15.8

The recommendations for speeding-up model

Parameter	Recommended value	Default value	Tab of Object simulation inspector
Solver	Park method	Park method	Simulation process parameters
Error tolerance	$1{\cdot}10^{-6}$	$1{\cdot}10^{-6}$	Simulation process parameters
Maximal step size (s)	0.01	0.001	Solver options
Step size for animation and data storage (s)	0.01	0.02	Simulation process parameters
Distance between points (m)	1	0.05	3D Contact | Options

15.7.3. Some results

Some results of simulation are presented in this section. For tests the "Train and Car Dumper" model was used which including in the set of UM samples.

Speed and in-train forces of car 31 for *Case 2* test when positioning arm pushes the car 31 (see Sect. 15.7.2.1. *"Predefined configurations"*, p. 15-63) are shown in Figure 15.75 and Figure 15.76.

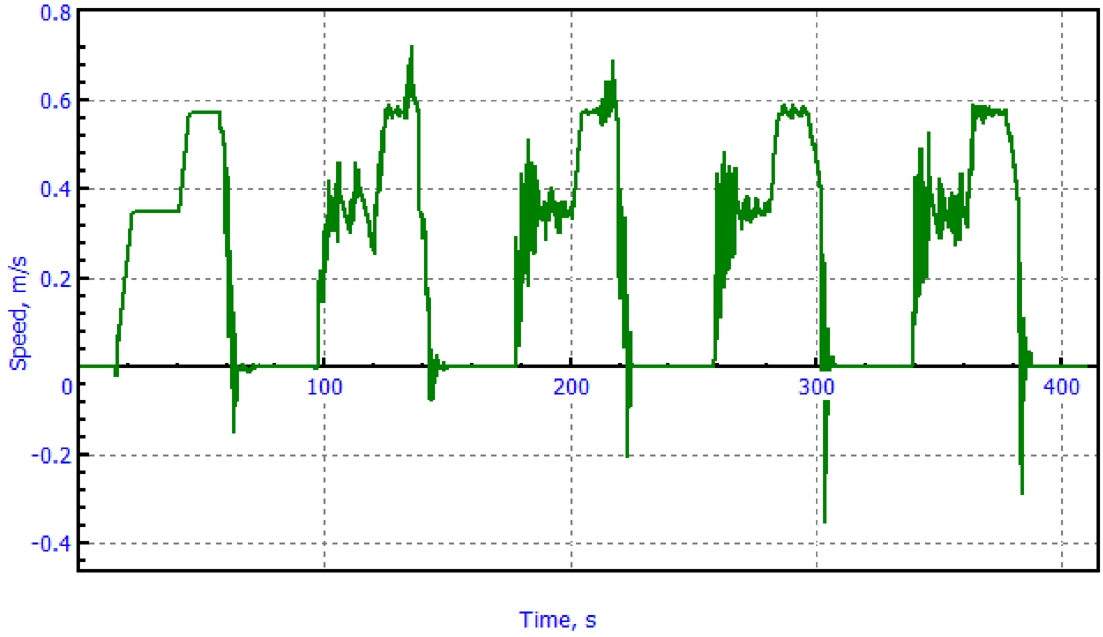


Figure 15.75. Speed of car 31

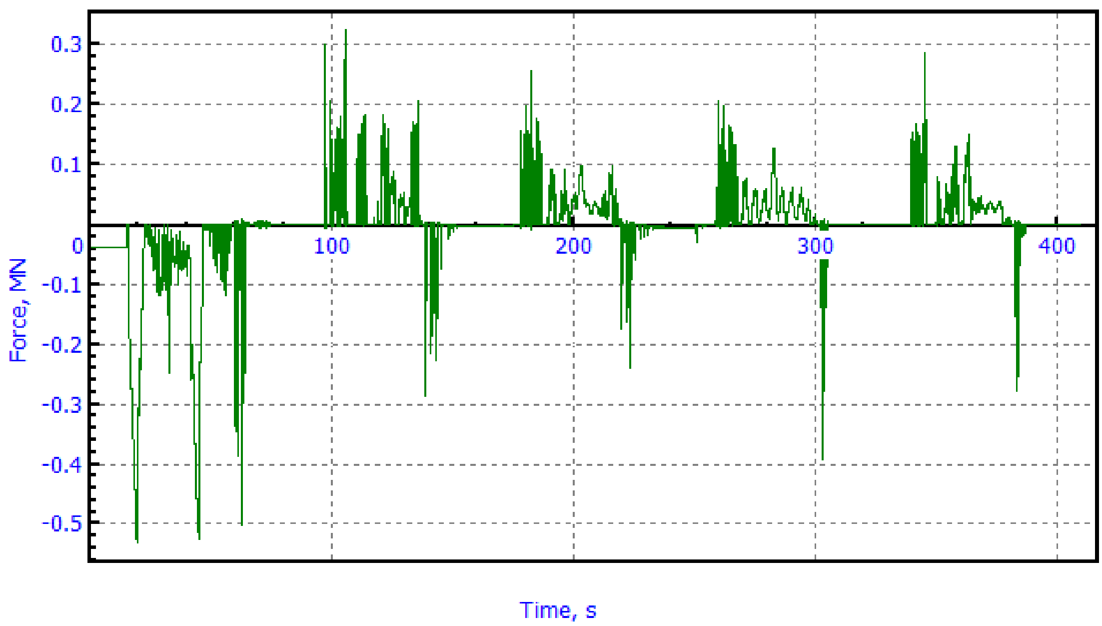


Figure 15.76. In-train forces at car 31

Histogram of in-train forces during dumping of long heavy-haul train is presented in Figure 15.77

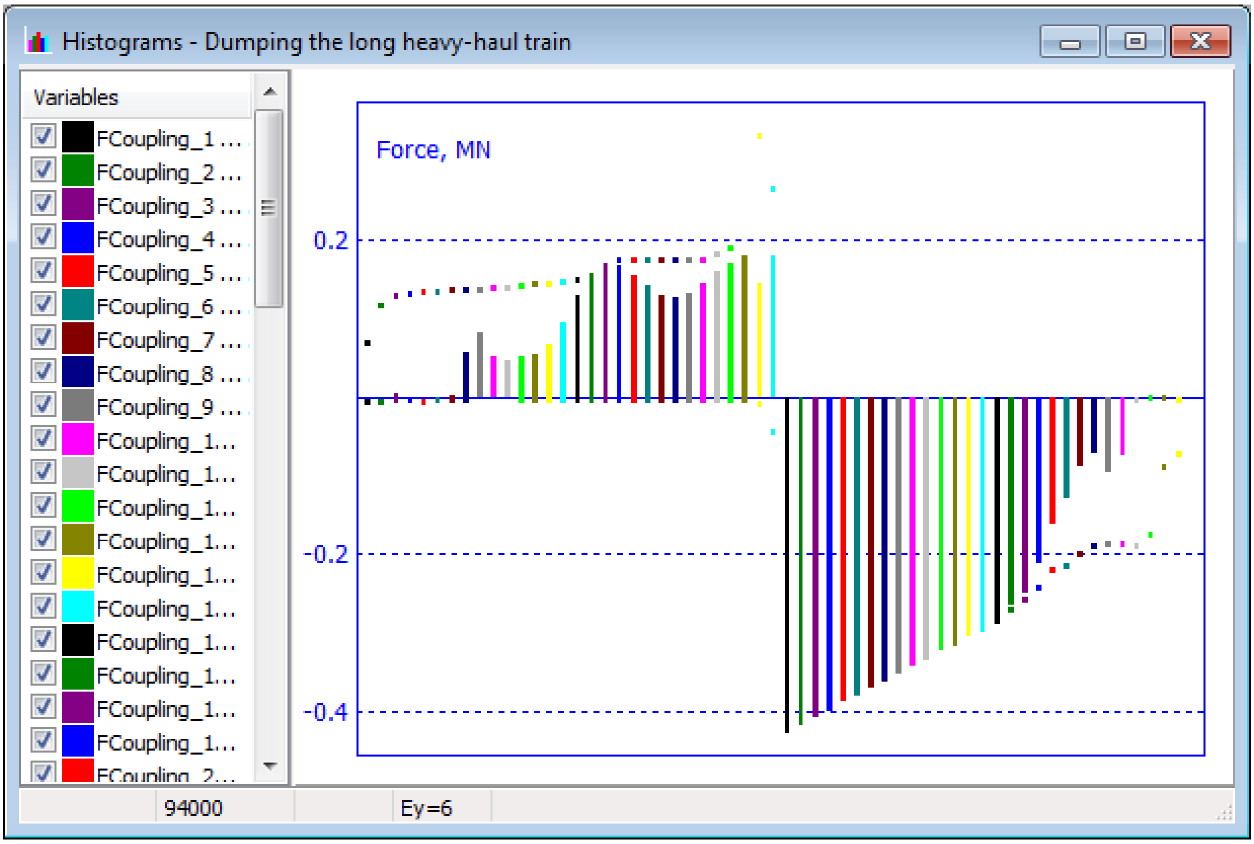


Figure 15.77. Histogram of in-train forces.

In this way the developed model of car dumper and train allows to assess a level of in-train forces during dumping process.