UNIVERSAL MECHANISM 9

User`s manual

Manchester Benchmarks for Rail Vehicle Simulation

2020

Contents

10. Manchester Benchmarks for rail vehicle simulation

10.1. General information on Manchester Benchmarks

Manchester Benchmarks have been developed in 1998 to let researchers compare different software for simulation of railway vehicle dynamics. Detailed information about the benchmarks, the models, their parameters, track cases and list of evaluated variables can be found in the following book: Iwnicki, Simon D. The Manchester benchmarks for rail vehicle simulation / ed. by S. Iwnicki. – Lisse: Swets & Zeitlinger, 1999[1]. The benchmark results for ADAMS/Rail, MEDYNA, GENSYS, NUCARS, SIMPACK and VAMPIRE are also published in the book.

The Manchester Benchmarks contain two models of rail vehicles:

- Vehicle 1 – simplified model of a passenger car;
- Vehicle 2 – model of a two-axle freight coach with load dependent friction.

This chapter of the User's Manual contains description of UM models of the benchmark vehicles as well as the corresponding simulation results.

UM models of the benchmark vehicles are included in the UM and available for full dynamic analysis. Paths to models:

{UM Data}\SAMPLES\Rail_Vehicles\Manchester_Benchmarks\Vehicle1;

{UM Data}\SAMPLES\Rail_Vehicles\Manchester_Benchmarks\Vehicle2.

Together with description of models and simulation results, this chapter includes instructions to the users how to get the results with UM.

[1] The book is available at Amazon.com

10.2. UM benchmark models

10.2.1. Vehicle 1

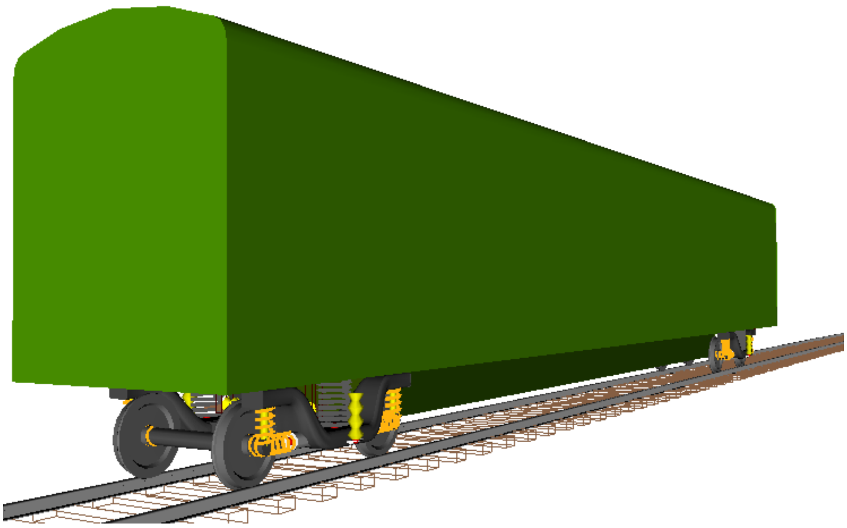


Figure 10.1. Benchmark Vehicle 1

Model of Vehicle 1 (Figure 10.1), has been developed with the help of subsystem technique. A tree of subsystems has three levels, Figure 10.2. The vehicle model includes two bogies as subsystems (Bogie1, 2, Figure 10.3). Each of the subsystems, in their turn, includes two wheel-sets as the standard subsystems (Wheelset 1,2,3,4).

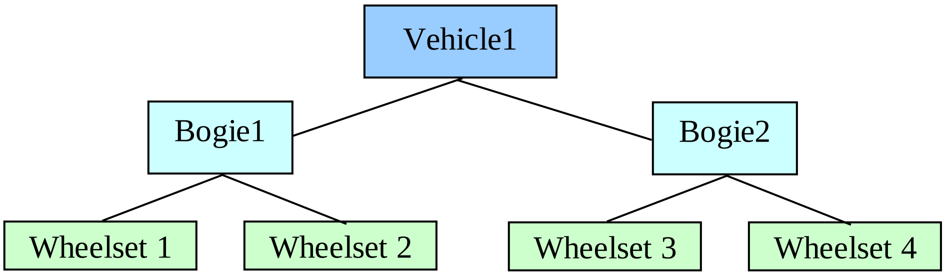


Figure 10.2. Hierarchy of Vehicle 1 model

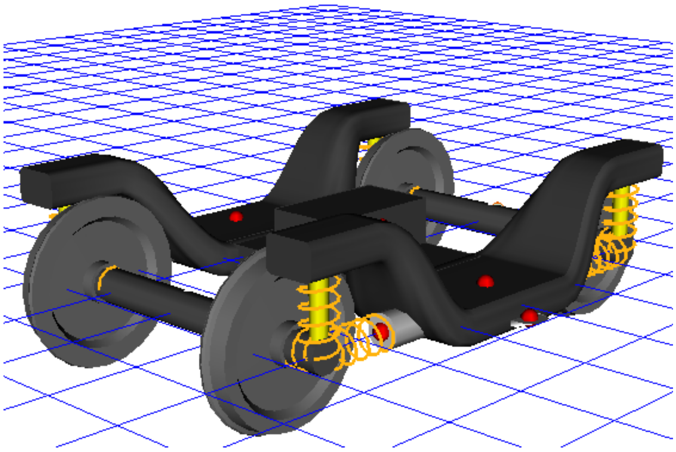


Figure 10.3. Bogie as a subsystem

Description of the model force elements is listed in the Table 10.1. Force elements are fully parameterized.

Table 10.1

Models of force elements

Force	Type of force element	Name	Comments
Primary suspension, elements are described in bogies as subsystems			
Vertical stiffness	Bipolar, linear	Spring1Z_1L, Spring1Z_1R Spring1Z_2L, Spring1Z_2R	Forces are under static load when vehicle coordinates are zeroes
Longitudinal stiffness	Bipolar, expression	Spring1X_1L, Spring1X_1R Spring1X_2L, Spring1X_2R	Forces vanish when vehicle coordinates are zeroes. Elements include damping in parallel
Lateral stiffness		Spring1Y_1L, Spring1Y_1R Spring1Y_2L, Spring1Y_2R	
Vertical dampers	Bipolar, viscous-elastic	Damper1Z_1L, Damper1Z_1R Damper1Z_2L, Damper1Z_2R	Damping in series with linear stiffness
Secondary suspension, elements are described in the main object			
Springs	Generalized linear force element	Spring1Z_1L, Spring1Z_1R Spring1Z_2L, Spring1Z_2R	Defined by a non-diagonal stiffness matrix. Forces are under static load when vehicle coordinates are zeroes

Roll bar		Roll bar 1, Roll bar 2	
Vertical dampers	Bipolar, viscous-elastic	Damper2Z_1L, Damper2Z_1R Damper2Z_2L, Damper2Z_2R	Damping in series with linear stiffness
Lateral dampers		Damper2Y_1L, Damper2Y_1R Damper2Y_2L, Damper2Y_2R	
Traction rods	Bipolar, expression	Traction rod 1, Traction rod 1	Elements include damping in parallel
Lateral bumpstop	Bipolar, set of points	Bumpstop1, Bumpstop2	

10.2.2. Vehicle 2

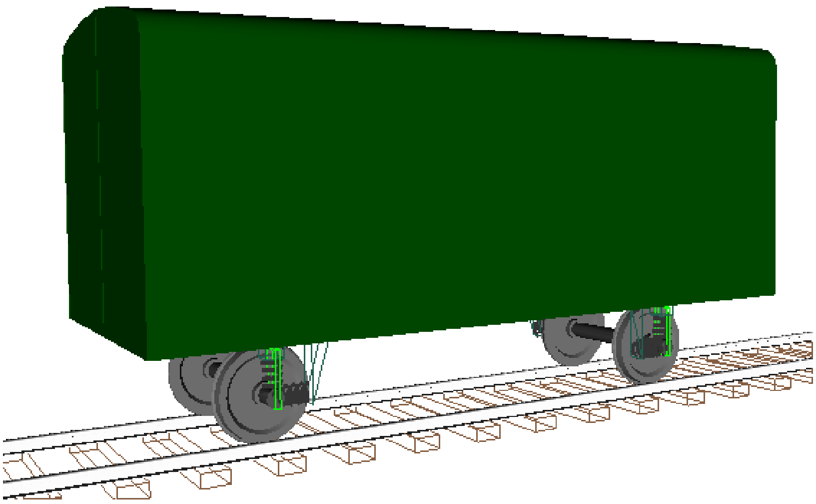


Figure 10.4. Benchmark Vehicle 2

UM model of benchmark Vehicle 2 is shown in Figure 10.4. This is a very simple model, and the only difficulty consists in modeling load dependent friction damping. According to benchmark requirements, the ‘friction is represented by a single vertical friction surface. Friction breakouts occurs as a consequence of the combined lateral and vertical relative motion across this surface’. In particular, this means that the friction cannot be represented by two independent force elements. A strict modeling of such element is possible in UM with the help of a pair of special force elements of the *Combined friction* type. A half of the vertical load accepted by the friction is considered as an axial force for each of the pair of force elements. Axial forces in the pair of combined friction force elements are loaded in opposite longitudinal directions and compensate one another. That is why the summary force produced by the pair of elements exactly corresponds to the benchmark requirements.

Description of the model force elements is listed in Table 10.2. Force elements are fully parameterized.

Table 10.2

Models of force elements

Force	Type of force element	Name	Comments
Vertical stiffness	Bipolar, linear	Vert1bFrc, Vert2bFrc, Vert3bFrc. Vert4bFrc	Forces are under static load when vehicle coordinates are zeroes
Longitudinal stiffness		Long1bFrc, Long2bFrc, Long3bFrc, Long4bFrc	Forces vanish when vehicle coordinates are zeroes.
Lateral stiffness		Later1bFrc, Later 2bFrc, Later 3bFrc, Later 4bFrc	
Frictional dampers	Special force, combined friction	sFrc1_1, sFrc1_2, sFrc2_1, sFrc2_2, sFrc3_1, sFrc3_2, sFrc4_1, sFrc4_2	In pairs accept a half of 35% of the corresponding vertical load

10.2.3. Modeling rail/wheel contact interaction

Text files with wheel and rail profiles are available with the Manchester Benchmarks. Figure 10.5 shows these profiles in the UM-specific system of coordinates.

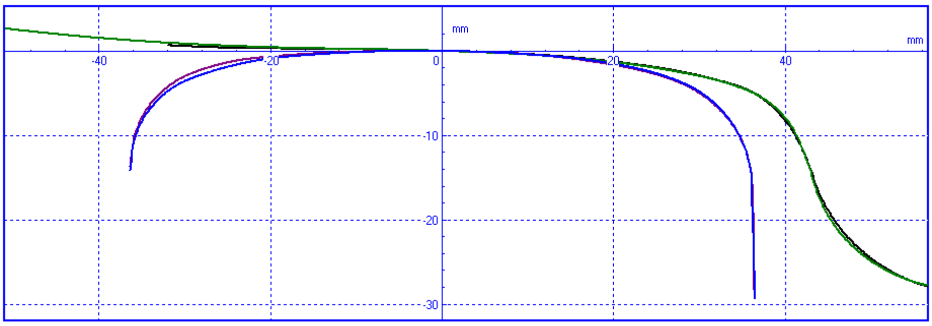


Figure 10.5. Wheel and rail profiles

Profiles allow two types of contacts: a one-point contact on running surfaces and a two-point contact on flange. A semi-analytic modification of FASTSIM algorithm is used for evaluation of creep forces. The modification of the well-known algorithm consists in realization of analytic solutions of the FASTSIM differential and differential-algebraic governing equations in a separate slice. These solutions are exact in the adhesion region and approximate in the sliding one. The realized semi-analytic procedure is faster than the classical FASTSIM algorithm. For example, it is 1.5 times faster in the case of 10 elements in a slice and 2.6 times faster for 20 elements.

Coefficient of friction in contacts is 0.4.

10.2.4. Track cases

A number of simulations should be made for each of the vehicle. Variants differ in track geometry, irregularities, and speeds.

10.2.4.1. Track Case 1

This case corresponds to running Vehicle 1 in a curve at a constant 4.4 m/s speed. Curve parameters are as follows.

- Straight section 50 m;
- Transition 30 m;
- Steady curve R = 150m, length 60 m, 100 mm cant;
- Run-off transition 30 m.

A linear 20 mm dip at the end of the run-off transition is considered as an irregularity (Figure 10.6).

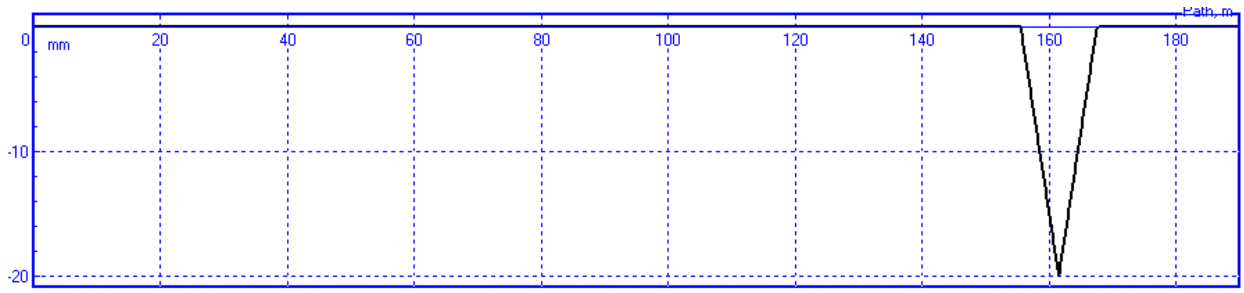


Figure 10.6. Irregularity for the outer rail

10.2.4.2. Track Case 2

Both vehicles run in a straight section of the following successive structure:

- ideal straight 50 m;
- 5 mm lateral shift over a distance 0.1 m;
- ideal straight.

Speed should be 45 m/s (Vehicle 1) and 22.5 m/s (Vehicle 2).

10.2.4.3. Track Case 3

Both vehicles run in a straight section with horizontal sinusoidal irregularities in phase for rails (Figure 10.7) with gauge widening 25.4 mm (in UM corresponds to a 12.7 mm semi-widening). Speed 22.5 m/s.

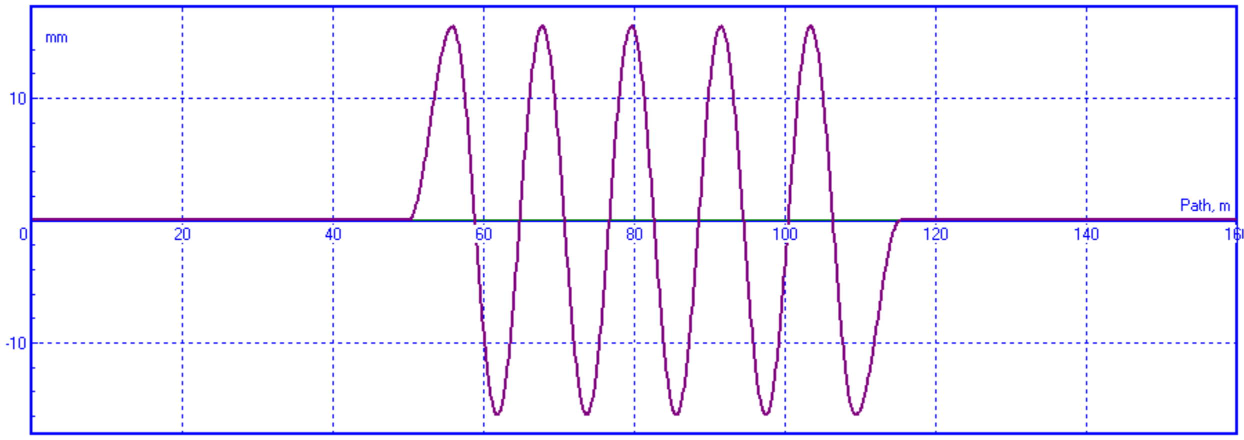


Figure 10.7. Horizontal rail irregularities

10.2.4.4. Track Case 4

Vehicle 2 runs in a straight section with vertical sinusoidal irregularities in phase for the left and right rails (Figure 10.8). Speed increases over the irregularities from 20 to 24 m/s.

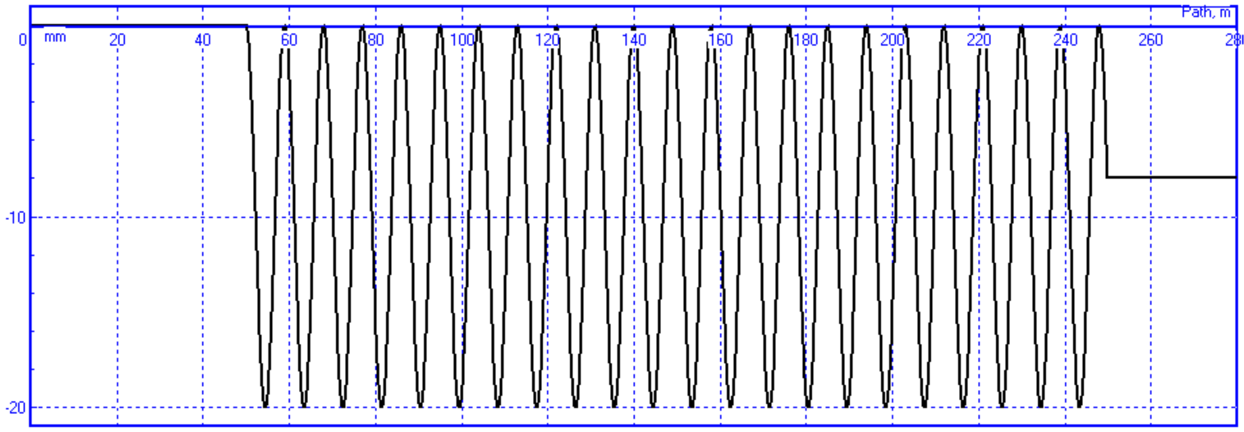


Figure 10.8. Vertical rail irregularities

10.3. CPU time

Table 10.3

	CPU time, s		
	UM P4 – 2,4 GHz	**MSC.ADAMS/Rail 12.0 P3 – 500 MHz**	**SimPack P II – 450 MHz**
Vehicle 1			
Track Case 1	22.5	138.1	90.6
Track Case 2	0.90	79.3	33.5
Track Case 3	1.95	233.5	252.0
Vehicle 2			
Track Case 2	0.8	42.9	17.9
Track Case 3	1.7	90.2	130.8
Track Case 4	5.36	171.7	406.2

These data show that UM is faster than ADAM/Rail 12.0 and SimPack for the most cases.

10.4. Vehicle 1 simulation results

10.4.1. Frequencies and eigenvalues

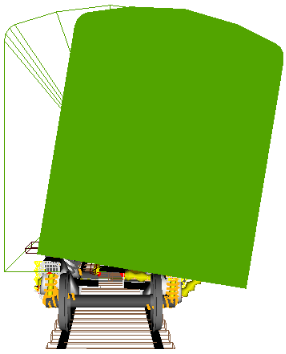
10.4.1.1. Results

While computing natural frequencies, degrees of freedom of wheelsets are blocked by additional elastic constraints with large stiffness. As a result, only natural frequencies of the car body and the bogies can be considered as a result. Simultaneously, all non-conservative elements such as dampers, frictional elements etc. are switched off.

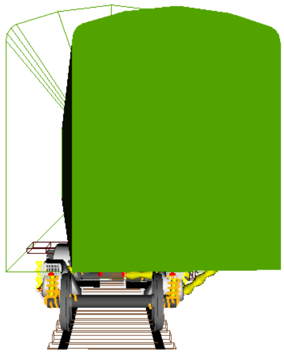
Table 10.4

Natural frequencies

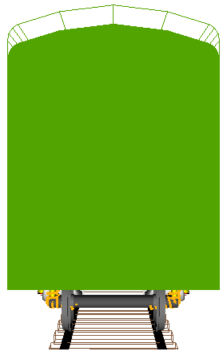
Modes	Frequencies, Hz
Car body	
Lower sway	0.56
Yaw	0.84
Bounce	1.07
Upper sway	1.27
Pitch	1.28
Longitudinal	2.85
Bogies	
Bounce in phase	7.47
Bounce out of phase	7.48
Lower sway out of phase	9.68
Lower sway in phase	9.70
Pitch out of phase	11.68
Pitch in phase	11.69
Upper sway out of phase	12.64
Upper sway in phase	12.64
Yaw out of phase	35.14
Yaw in phase	35.17



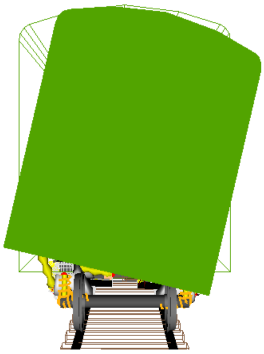
Lower sway



Yaw

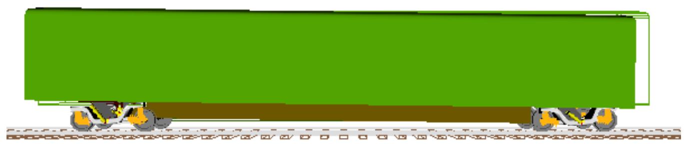


Bounce

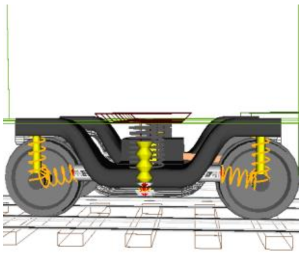


Upper sway

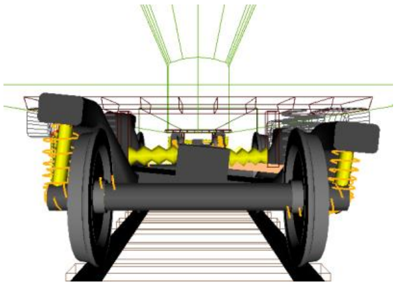
Pitch



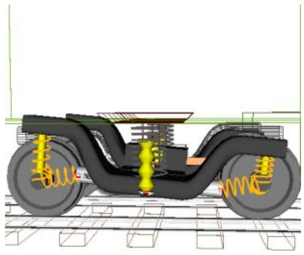
Longitudinal



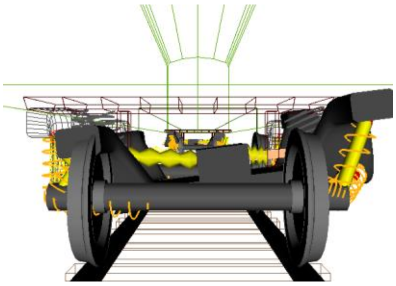
Bounce



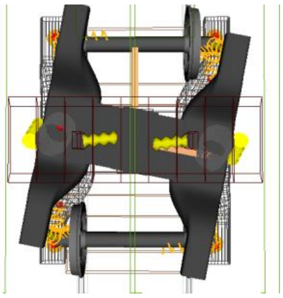
Lower sway



Pitch



Upper sway



Yaw

Two modes for computation of rail vehicle eigenvalues are available in UM:

- with wheelsets blocked by large stiffness (about $1\cdot10^{10}$ Н/м)
- without blocking wheelsets (or rather an elastic constraint with a small stiffness is set in longitudinal direction for the first wheelset only).

Vehicle 1 eigenvalues and comparison with other participants is given in Table 10.5. Upper/lower UM results correspond to blocked/free wheelsets.

Table 10.5

Eigenvalues

Mode	**Frequency (Hz)**			**Damping ratio (%)**		
	UM	**Adams/ Rail**	**Other participants**	**UM**	**Adams/ Rail**	**Other participants**
Car body						
Lower sway	0.58	0.60	0.53÷0.59	21.1	22.8	21.0÷22.0
Yaw	0.73	0.71	0.73÷0.86	53.6	54.6	52.3÷54.6
Bounce	1.07	1.07	1.07÷1.08	13.5	13.5	13.4÷13.5
Upper sway	1.10	1.09	1.10÷1.23	45.4	45.3	41.1÷43.9
Pitch	1.28/1.2	1.28	1.28÷1.3	15.9/16.	15.9	15.9÷16.3

	9		0	1		
Longitudinal	2.85/-	2.85	-**)	4.288/-	42.84*)	-
Bogies						
Longitudinal out of phase	-/4.22	-**)	4.20÷4.27	-/6.2	-	6.1÷6.2
Longitudinal in phase	-/5.11	-	5.13÷5.16	-/7.5	-	7.4÷9.8
Bounce out of phase	7.51/7.42	7.50	7.33÷7.60	24.6/24.8	24.6	23.9÷24.8
Bounce in phase	7.53/7.44	7.52	7.35÷7.62	24.1/24.3	24.1	23.5÷24.3
Roll out of phase	9.92/9.62	9.93	9.25÷9.72	41.4/41.8	41.8	39.6÷41.9
Roll in phase	9.95/9.66	9.93	9.32÷9.84	41.7/42.0	41.6	39.8÷42.2

*) Evidently a misprint.

**) Some participants give longitudinal frequencies of bogies and do not give the longitudinal frequency of the car body. In contrary, ADAMS/Rail give the longitudinal frequency of the car body. Apparently this choice depends on the method of fixing the vehicle in the longitudinal direction. UM results on the car body frequency were obtained for fixed wheelset, and in case of bogies – for free wheelsets.

10.4.1.2. User's instructions

Here we consider instructions how the user can obtain the result of the previous section with UM.

1. Load the model {UM Data}\SAMPLES\Rail_vehicles\Manchester_Benchmarks\ Vehicle1 in the **UM Simulation** program.
2. Load the configuration using the **File | Read configuration | Eigenvalues** menu item (Figure 10.9). This operation corresponds to reading the full model configuration and includes the desktop configuration file *EigenValues.icf*, the file of parameters *EigenValues.par*, the rail vehicle configuration file *EigenValues.rwc*, and the file of initial conditions *EigenValues.xv*.

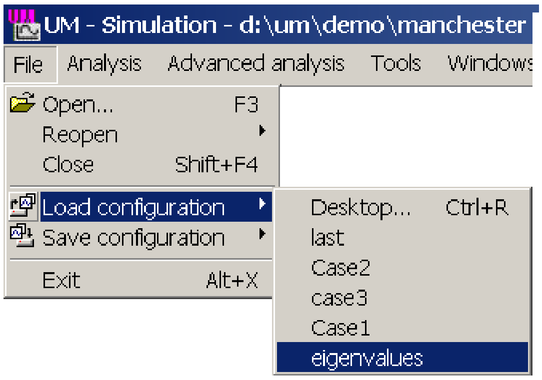


Figure 10.9. Read full configuration

3. Start the mode of linear analysis with the help of the **Analysis | Linear analysis…** menu item.
4. Open the *Frequencies* tab of the *Linear analysis* window and find there natural frequencies of the vehicle (Figure 10.10). A number of zero frequencies (sixteen) correspond to differential equations of some force elements (damping in series with stiffness), Sect. 10.2.1. *"Vehicle 1"*, p. 10-4). Select one of the frequencies in the list by the mouse and click the Show button (Figure 10.10) to animate the corresponding mode in an animation window. If there is no animation windows, open one using the **Tools | Animation window…** menu item. After that selecting other frequencies in the list leads to automatic animation of natural modes.

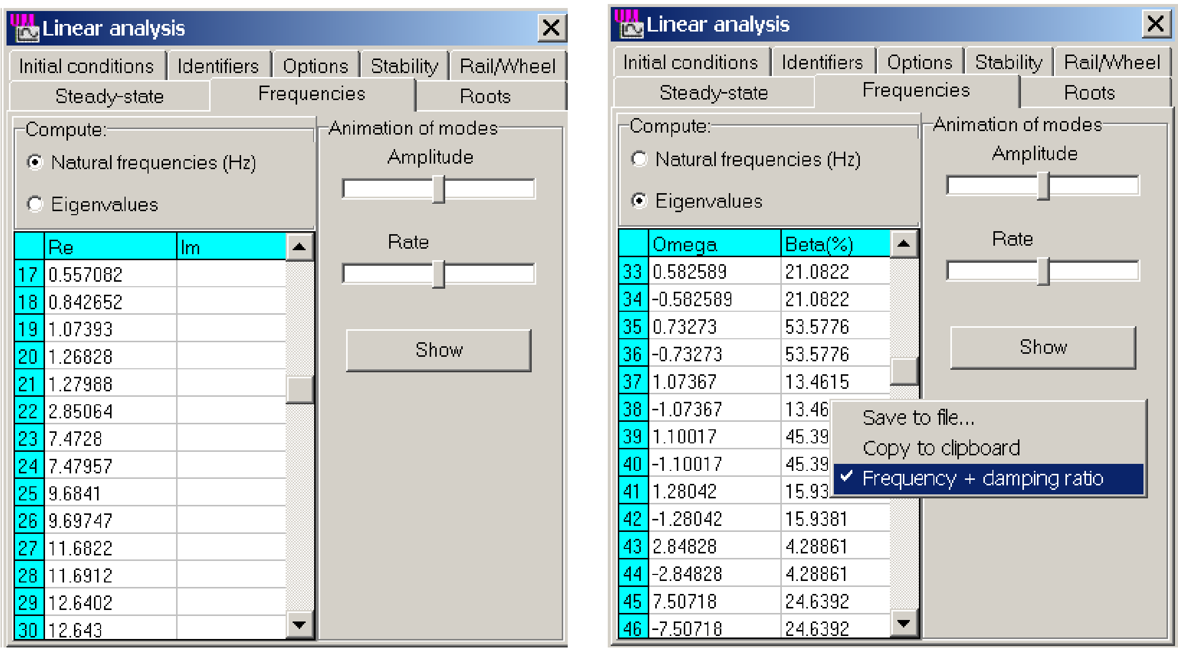


Figure 10.10. Natural frequencies (left) and eigenvalues

5. To compute eigenvalues taking into account damping, select the *Eigenvalues item* of the *Compute* group (Figure 10.10). The list of real and imagine parts of eigenvalues appears ordered on the real part value. To get the same list but in the form frequency/damping ratio, cal the pop up menu by clicking the right mouse button within the list and select the *Frequency+ damping ratio* item. In this case the eigenvalues are ordered on frequency values.

Animation of the corresponding eigenforms can be obtained analogously to the natural modes.

10.4.2. Track Case 1

Vehicle 1 runs with a constant speed 4.4 m/s in a curve with a single vertical dip at the end of the run-off transition (Sect. 10.2.4.1. *"Track Case 1"*, p. 10-8). According to the benchmark requirements, a number quasi-static values of dynamic and kinematic variables should be reported (Sect. 10.4.1.1. *"Results"*, p. 10-11), as well as a number of plots of variables over the length of the run (Sect. 10.4.2.2. *"Plotted results"*, p. 10-21).

10.4.2.1. Tabulated results

Tables below contain steady-state values of kinematic and dynamic variables in the steady curve as well as the corresponding results by ADAMS/Rail and other participants.

Table 10.6

Lateral shift and yaw angle of each wheelset relative to track at its position

Variable Wheelset	UM	ADAMS/Rail	Other participants
Lateral shift	mm		
Wheelset 1	-6.9	-7.2	-6.53÷-7.81
Wheelset 2	7.6	7.24	7.63÷8.04
Wheelset 3	-6.9	-7.19	-5.83÷-7.14
Wheelset 4	7.4	7.17	7÷7.39
Yaw angle	mrad		
Wheelset 1	-15.80	-15.52	-16.06÷-15.74
Wheelset 2	0.83	1.076	-0.83÷0.85
Wheelset 3	-14.13	-14.15	-14.18÷-13.79
Wheelset 4	2.49	2.44	2.42÷2.78

Table 10.7

Total forces at each wheel

Variable Wheelset	UM	ADAMS/Rail	Other participants
Longitudinal force	kN		
Left wheel			
Wheelset 1	2.08	3.10	2.35÷2.96
Wheelset 2	-15.97	-15.68	-16.89÷-15.68
Wheelset 3	0.91	1.902	0.877÷3.67

Wheelset 4	-17.47	-17.37	-18.39÷-16.80
Right wheel			
Wheelset 1	-3.14	3.5	-3.81÷-3.07
Wheelset 2	15.68	-15.29	15.28÷16.56
Wheelset 3	-1.72	2.21	-2.29÷1.81
Wheelset 4	17.18	-12.76	16.51÷18.05
Lateral force	kN		
Left wheel			
Wheelset 1	32.17	-31.15	30.57÷32.67
Wheelset 2	1.52	-1.571	1.17÷1.54
Wheelset 3	19.86	-18.98	18.69÷20.73
Wheelset 4	4.13	-3.28	3.68÷4.24
Right wheel			
Wheelset 1	-23.13	-22.65	-23.21÷-22.05
Wheelset 2	-21.86	-21.39	-22.24÷-21.12
Wheelset 3	-25.06	-24.6	-25.4÷-24.53
Wheelset 4	-10.82	-9.51	-10.19÷-9.86
Vertical force	kN		
Left wheel			
Wheelset 1	-54.35	54.37	-55.42÷-53.74
Wheelset 2	-39.88	39.65	-41.05÷-39.74
Wheelset 3	-49.34	49.37	-50.89÷-49.11
Wheelset 4	-44.29	44.267	-45.33÷-44.08
Right wheel			
Wheelset 1	-55.14	54.975	-55.53÷-54.50
Wheelset 2	-68.68	68.939	-69.40÷-63.78
Wheelset 3	-59.22	59.204	-59.53÷-57.98
Wheelset 4	-64.88	64.936	-65.38÷-63.73

Table 10.8

Contact angles at each contact point

Variable Wheelset	**UM**	**ADAMS/Rail**	**Other partici-pants**
Running surface	mrad		
Left wheel			
Wheelset 1	232	313.7	170.98÷-230.08
Wheelset 2	19.3	19.97	19.40÷22.05
Wheelset 3	232	315.9	170.23÷225.82
Wheelset 4	19.5	19.92	19.09÷21.06
Right wheel			

Wheelset 1	19.7	18.86	-23.88÷-20.7
Wheelset 2	197.4	334	-207.71÷-177.8
Wheelset 3	20.2	18.94	-23.92÷-20.54
Wheelset 4	197.4	331.72	-207.71÷-177.0
Flange	rad	rad	rad
Wheelset 1	1.117	1.12	1.116÷1.464
Wheelset 2	1.231	1.10	-1.225÷-1.205
Wheelset 3	1.117	1.12	1.109÷-1.125
Wheelset 4	1.231	1.10	-1.225÷-1.205

Table 10.9

Creepages and spin at each contact point

Wheelset	**ξ (1·10-3)**	**η (1·10-3)**	**φ**
Left wheel			
Wheelset 1	5.42	15.33	-0.503
Wheelset 2	14.37	-0.82	-0.049
Wheelset 3	4.20	13.73	-0.503
Wheelset 4	12.53	-2.47	-0.050
Right wheel			
Wheelset 1	2.24	15.80	0.037
Wheelset 2	-1.65	-0.82	0.416
Wheelset 3	1.02	14.15	0.038
Wheelset 4	-3.49	-2.46	0.417
Flange			
Wheelset 1(left wheel)	-12.11	41.32	-1.947
Wheelset 2(right wheel)	-22.50	-2.69	2.033
Wheelset 3(left wheel)	-13.34	37.0	-1.950
Wheelset 4(right wheel)	-24.38	-8.13	2.037

Table 10.10

Creep forces

Variable Wheelset	**UM**	**ADAMS/Rail**	**Other partici-pants**
Longitudinal force	kN		
Left wheel			
Wheelset 1	-2.15	-1.55	-2.87÷-2.48
Wheelset 2	-15.97	-15.69	-16.89÷-15.68
Wheelset 3	-2.57	-1.63	-3.67÷-2.98
Wheelset 4	-17.47	-17.35	-18.40÷-16.80
Right wheel			
Wheelset 1	-3.14	3.5	-3.81÷-3.07

Wheelset 2	7.80	-8.14	5.77÷7.15
Wheelset 3	-1.72	2.21	-2.29÷-1.65
Wheelset 4	12.31	-12.71	9.98÷10.84
Flange			
Wheelset 1	4.22	4.65	-19.35÷-16.21
Wheelset 2	7.88	-8.83	1.35÷3.68
Wheelset 3	3.48	3.47	-13.40÷-10.55
Wheelset 4	4.87	-3.51	2.15÷4.11
Lateral force	kN		
Left wheel			
Wheelset 1	-6.5	7.34	-7.37÷-6.03
Wheelset 2	0.78	-0.80	0.39÷0.77
Wheelset 3	-9.11	10.09	-9.66÷-8.63
Wheelset 4	3.26	-2.43	2.81÷2.31
Right wheel			
Wheelset 1	-22.04	-21.65	-22.05÷-20.93
Wheelset 2	8.59	15.39	10.82÷14.13
Wheelset 3	-23.86	-23.51	-24.04÷-23.30
Wheelset 4	-12.59	13.36	15.60÷17.85
Flange			
Wheelset 1	-17.40	16.67	-19.35÷-16.21
Wheelset 2	2.67	3.06	1.35÷3.68
Wheelset 3	-11.57	10.43	-13.40÷-10.55
Wheelset 4	2.48	1.47	2.15÷4.11

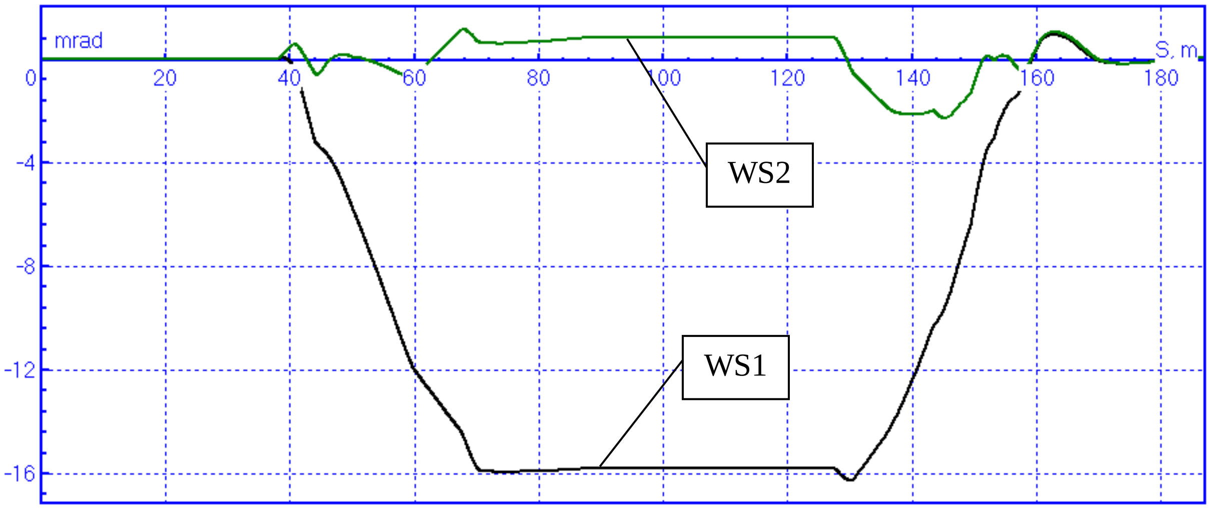
Table 10.11

Normal forces at each contact point

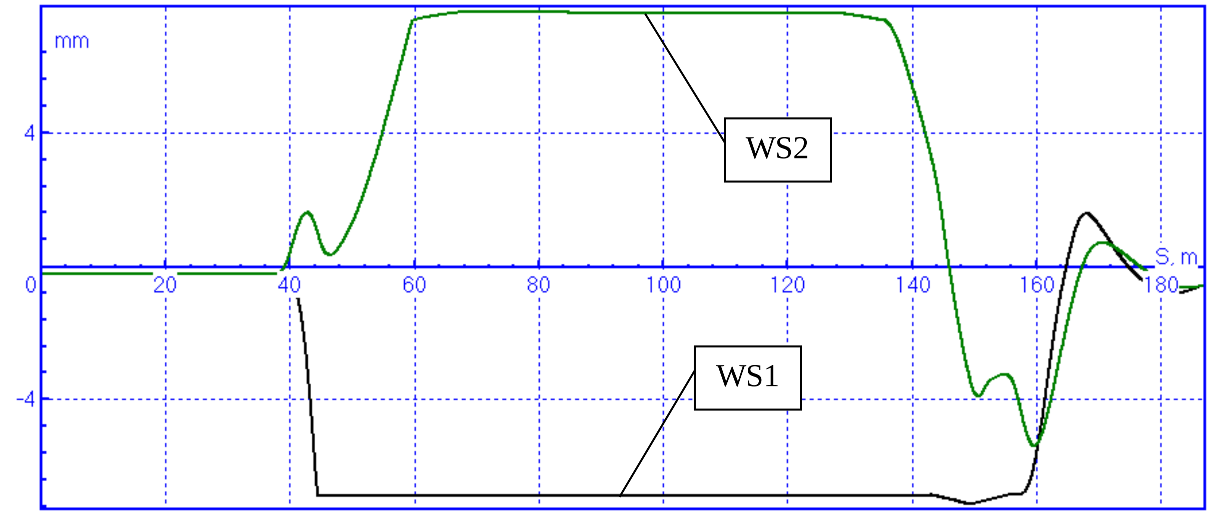
Wheelset	**UM**	**ADAMS/Rail**	**Other partici-pants**
Normal forces	kN		
Left wheel			
Wheelset 1	17.10	18.97	-20.09÷-17.01
Wheelset 2	39.91	39.67	-41.07÷-39.76
Wheelset 3	23.65	25.83	-26.13÷-22.87
Wheelset 4	44.37	44.32	-45.41÷-44.11
Right wheel			
Wheelset 1	55.58	55.38	-55.98÷-54.27
Wheelset 2	58.66	46.03	-57.62÷-52.33
Wheelset 3	59.71	59.64	-60.04÷-58.55
Wheelset 4	56.61	47.80	-54.37÷-50.03

Flange			
Wheelset 1	46.95	43.84	-48.75÷-44.52
Wheelset 2	20.87	25.33	-28.52÷-24.53
Wheelset 3	31.5	27.87	-34.49÷-29.42
Wheelset 4	13.68	9.93	-21.21÷-17.54

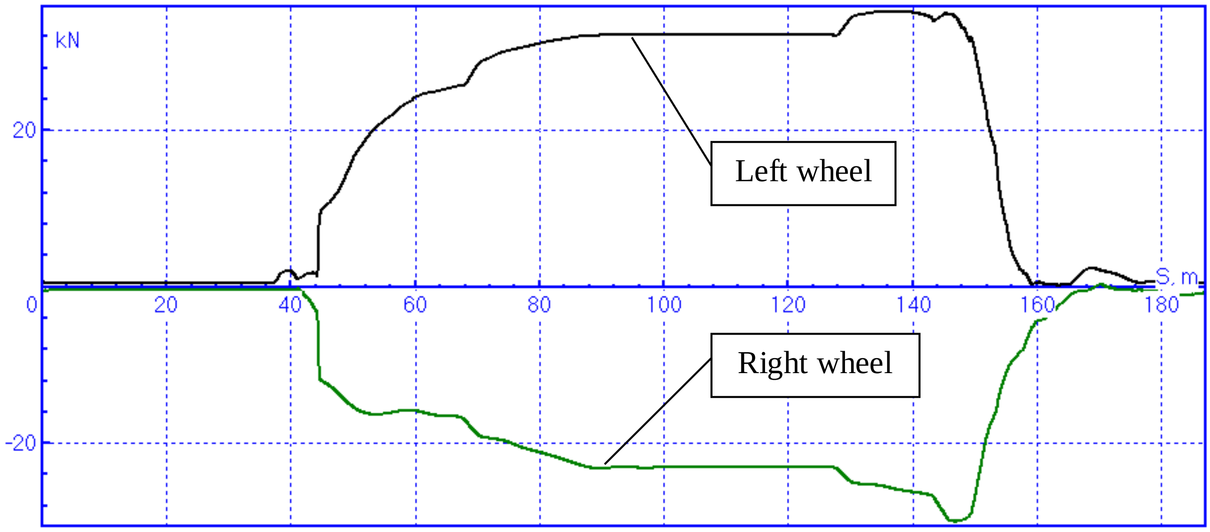
10.4.2.2. Plotted results



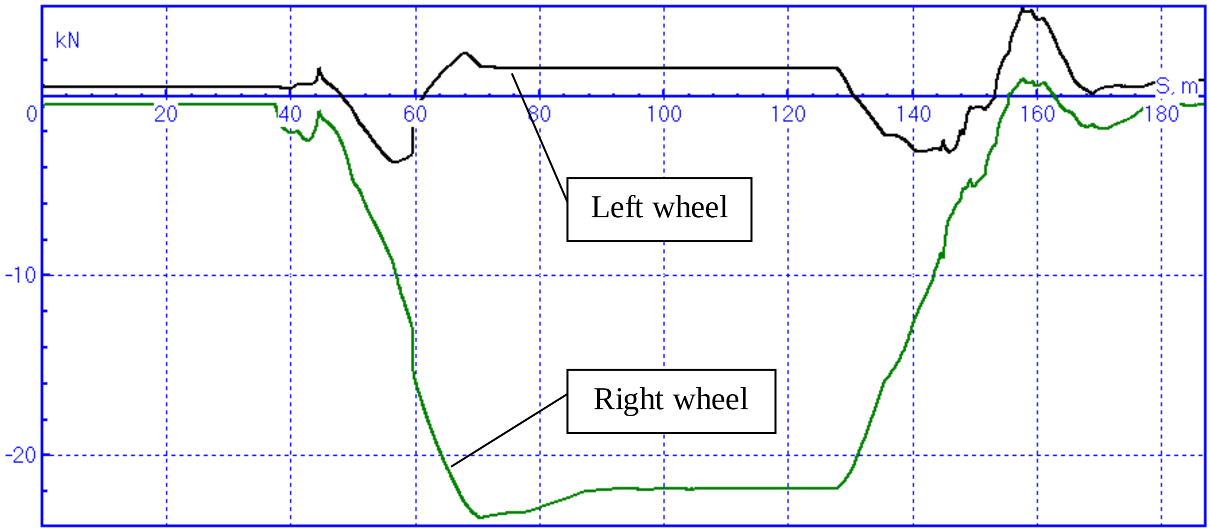
Yaw angles of Wheelsets 1,2



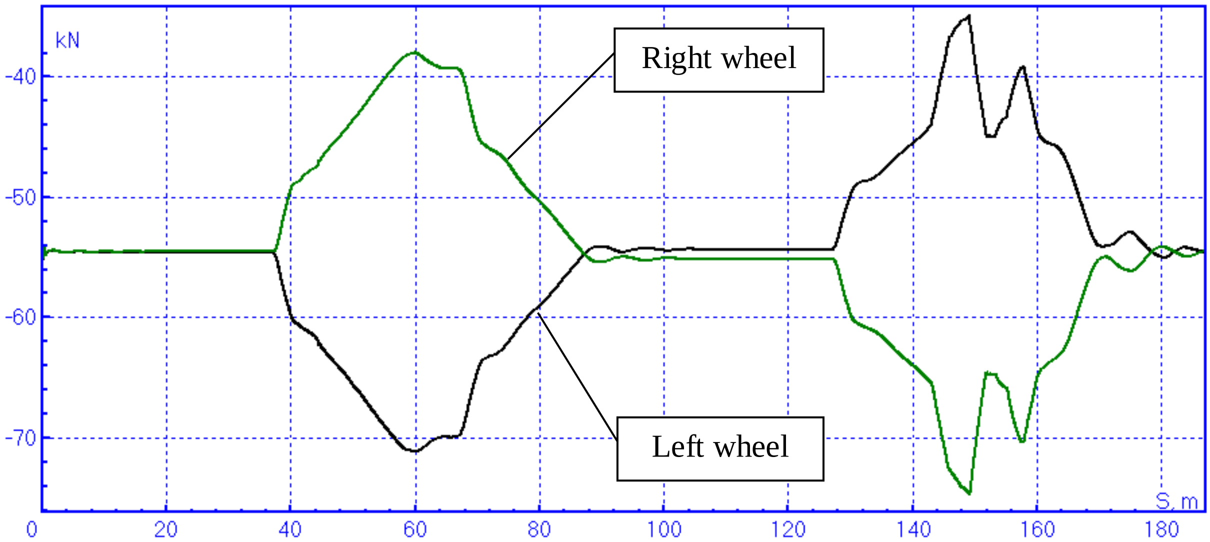
Lateral shift of wheelsets 1,2 relatively to rails



Total lateral forces for Wheelset 1

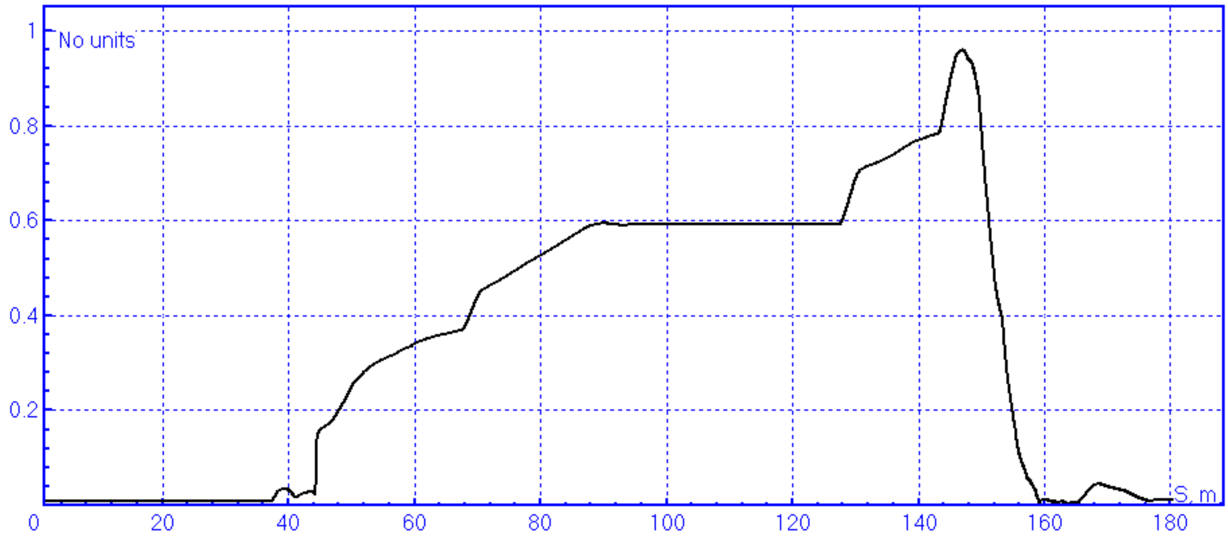


Total lateral forces for Wheelset 2

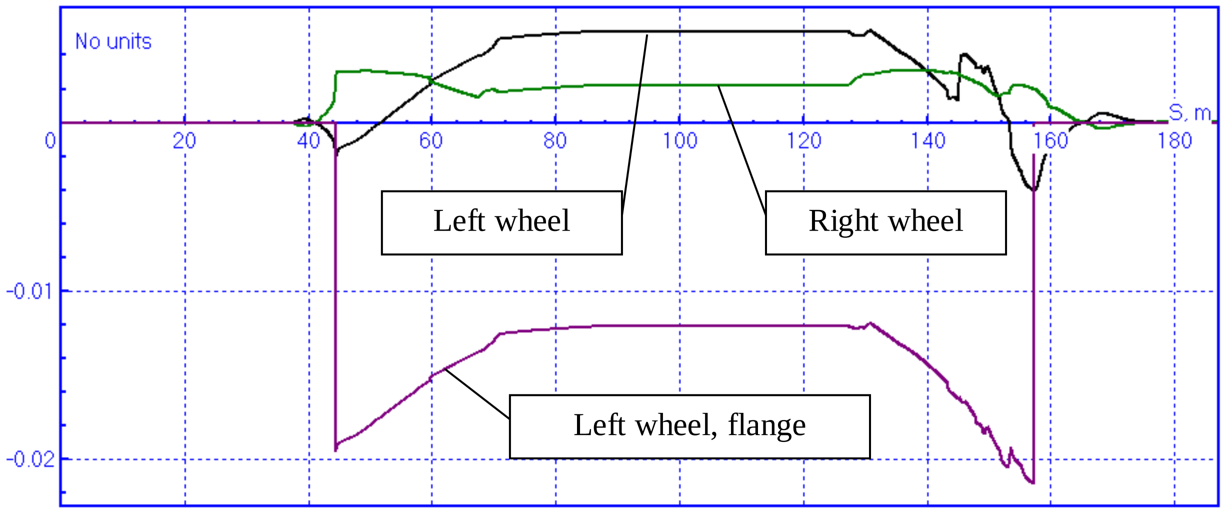


Total vertical forces for Wheelset 1

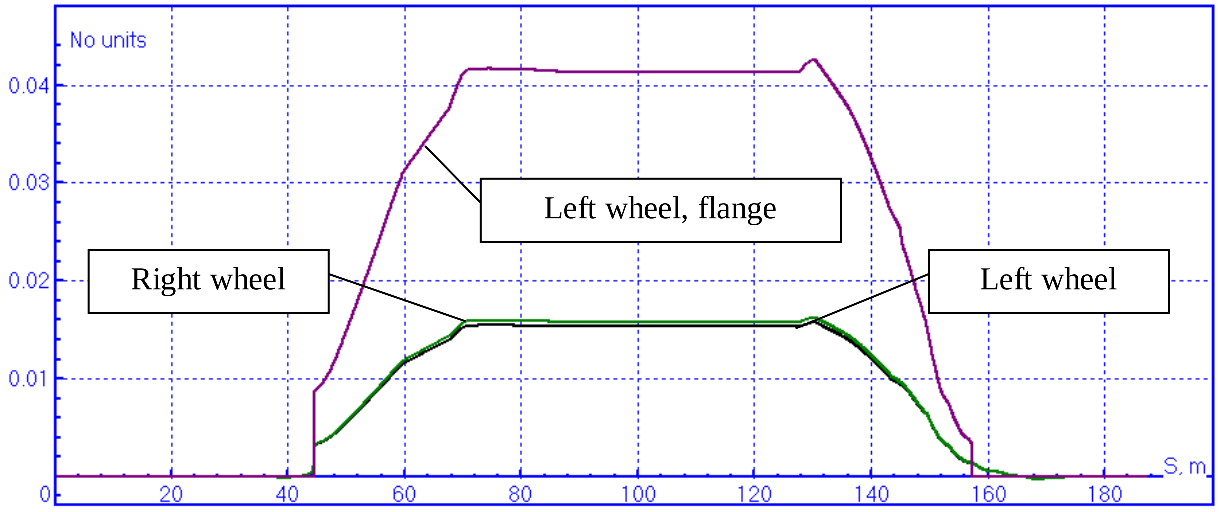
Total vertical forces for Wheelset 2



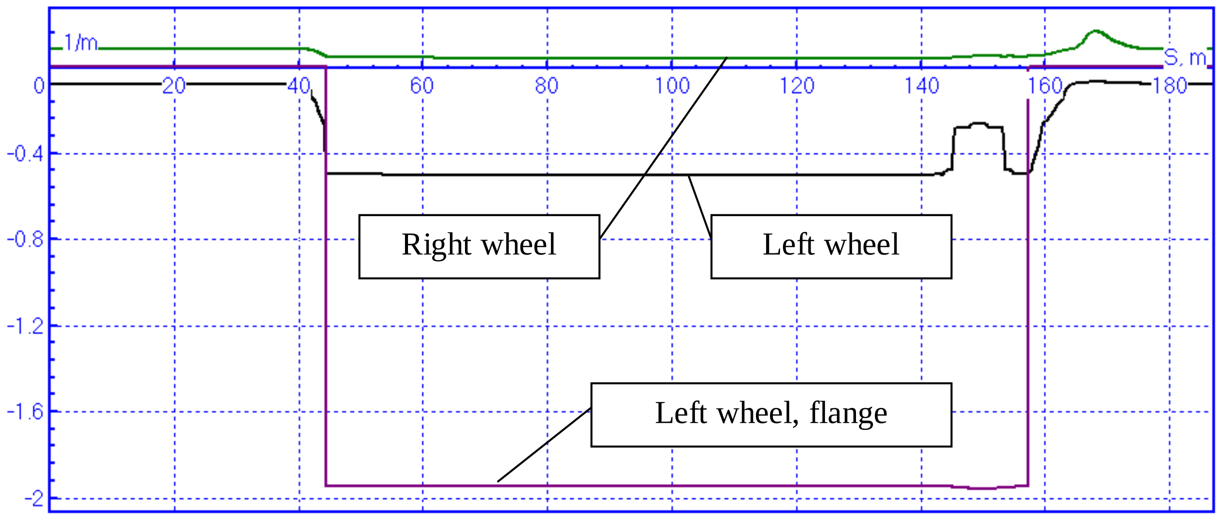
The ratio of lateral to vertical forces at the leading outer wheel of Wheelset 1
(derailment quotient)



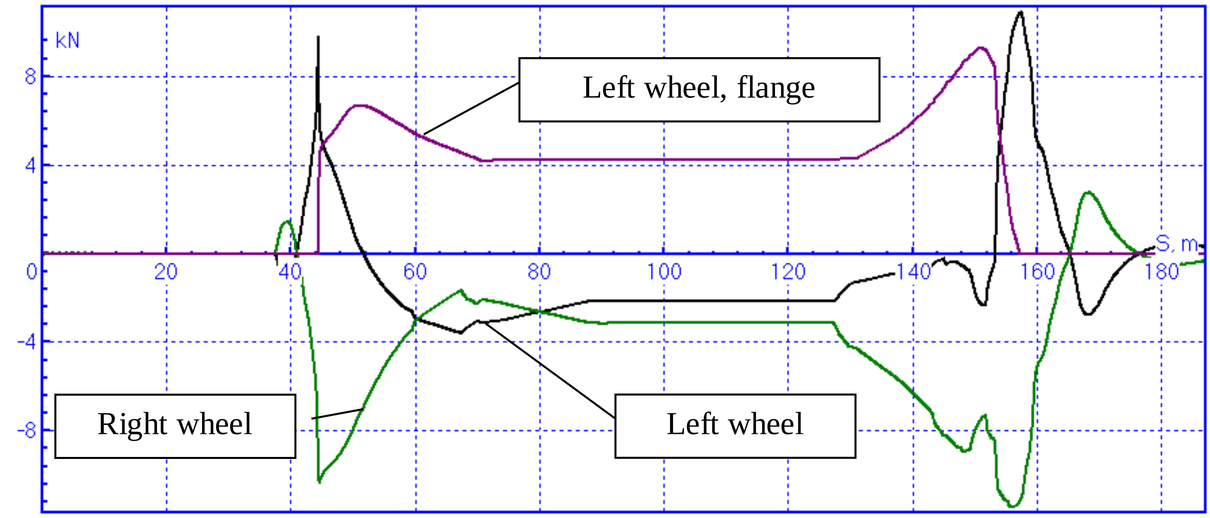
Longitudinal creepages of Wheelset 1



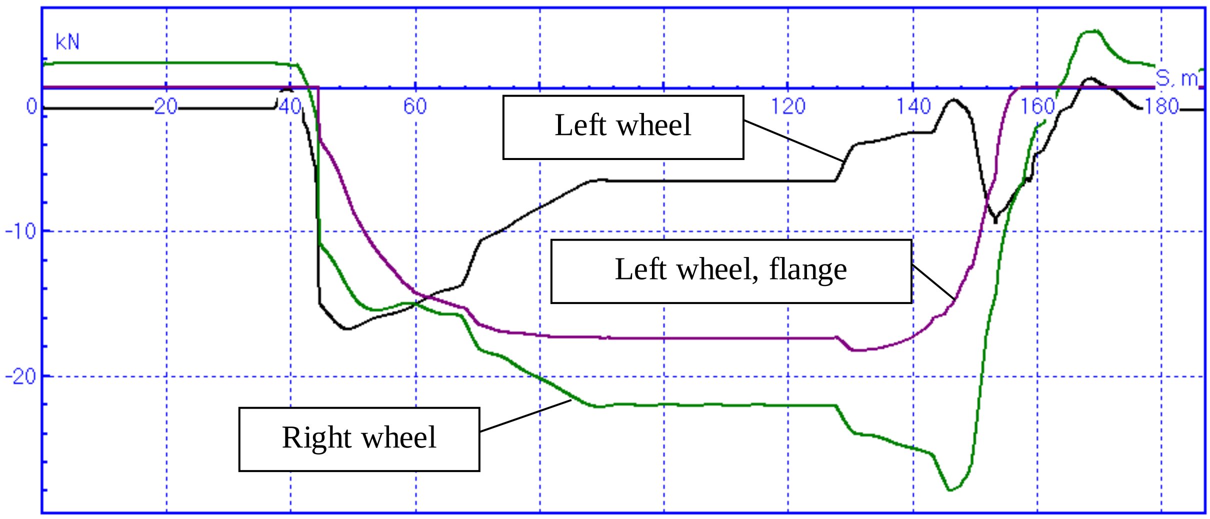
Lateral creepages of Wheelset 1



Spin creepages of Wheelset 1



Longitudinal creep forces of Wheelset 1



Lateral creep forces of Wheelset1

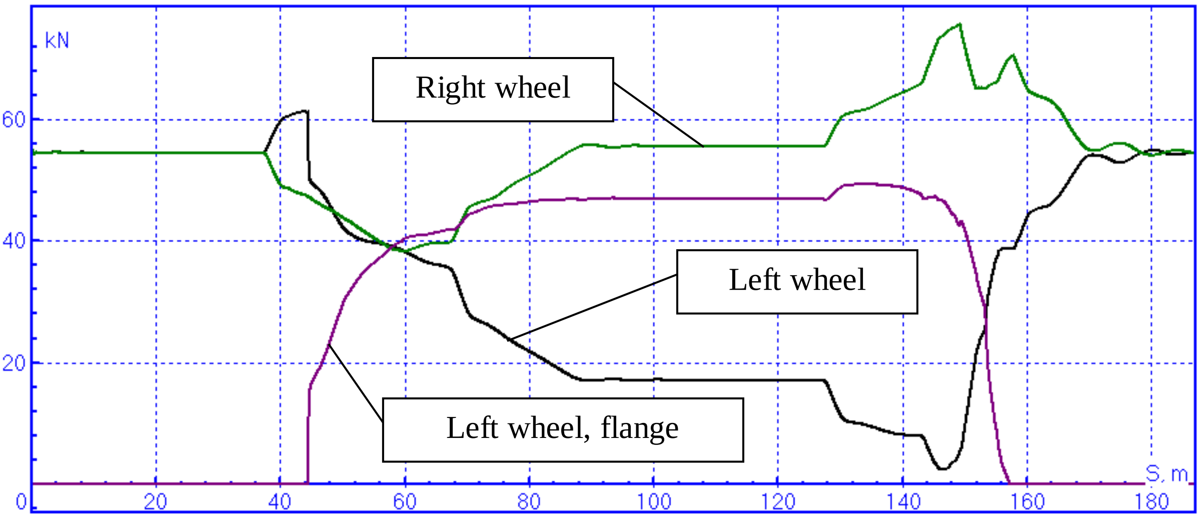


Figure 10.11. Normal forces at contacts of Wheelset 1

10.4.2.3. User's instructions

Follow the instructions to get the results of Sect. 10.4.2.1. *"Tabulated results"*, p. 10-16, 10.4.2.2. *"Plotted results"*, p. 10-21.

If the Vehicle 1 model {UM Data}\SAMPLES\Rail_vehicles\Manchester_Benchmarks\Vehicle1 is not loaded in the **UM Simulation** program, do it.

1. Read the **File | Load configuration | Case1** (Figure 10.9). This operation corresponds to reading the full model configuration and includes the desktop configuration file *Case1.icf*, the file of parameters *Case1.par*, the rail vehicle configuration file *Case1.rwc*, and the file of initial conditions *Case1.xv*.
2. Run simulation mode (the **Analysis | Simulation…** menu item)
3. Load a list of variables for computation: open the Object variables tab of the Object simulation inspector and open file *\vehicle1\case1.var* by clicking the 🗁 button. Tabs with variables appear (Figure 10.12).

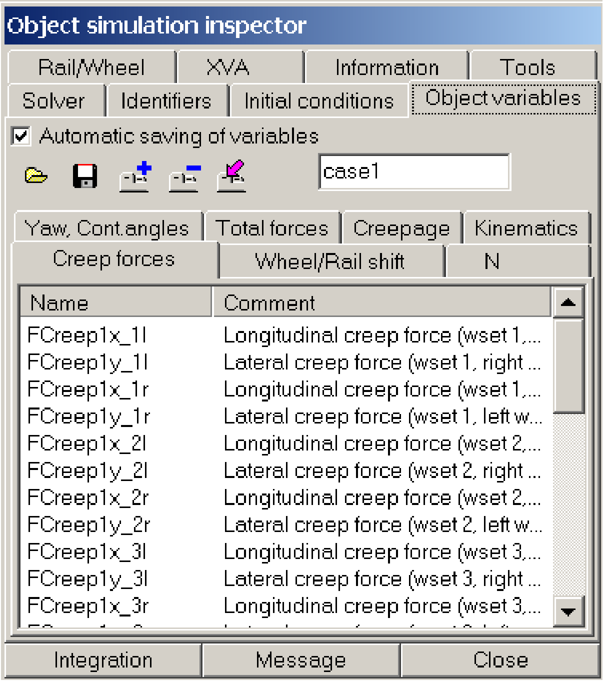


Figure 10.12. List of variables for automatic computation

4. Run simulation by the *Integration* button (Figure 10.12). Relative wheel and rail profile positioning as well as contact forces are shown in the *Contact animation* window. Some variables are plotted in graphical windows. Note that animation makes the simulation process several times slower, and the data for CPU expenses in Sect. 10.3. *"CPU time"*, p. 10-10 were obtained for simulation without animations.
5. After the simulation finishes, plots of any variables from the computed list of variables can be obtained. If the *Pause* window is not closed yet, the list is located on the *Object variables* tab. If it is closed, the list can be found on the *Object simulation inspector* tab of the same name. Open this tab and then open one of the tab of the list, e.g. *N* (normal forces at contacts). Open a new graphic window by clicking the button on the tool bar or with the help of the **Tools | Graphic window** menu item. Drag a variable or a group of variables from the list and drop into the graphic window (Figure 10.13, see Figure 10.11 as well).

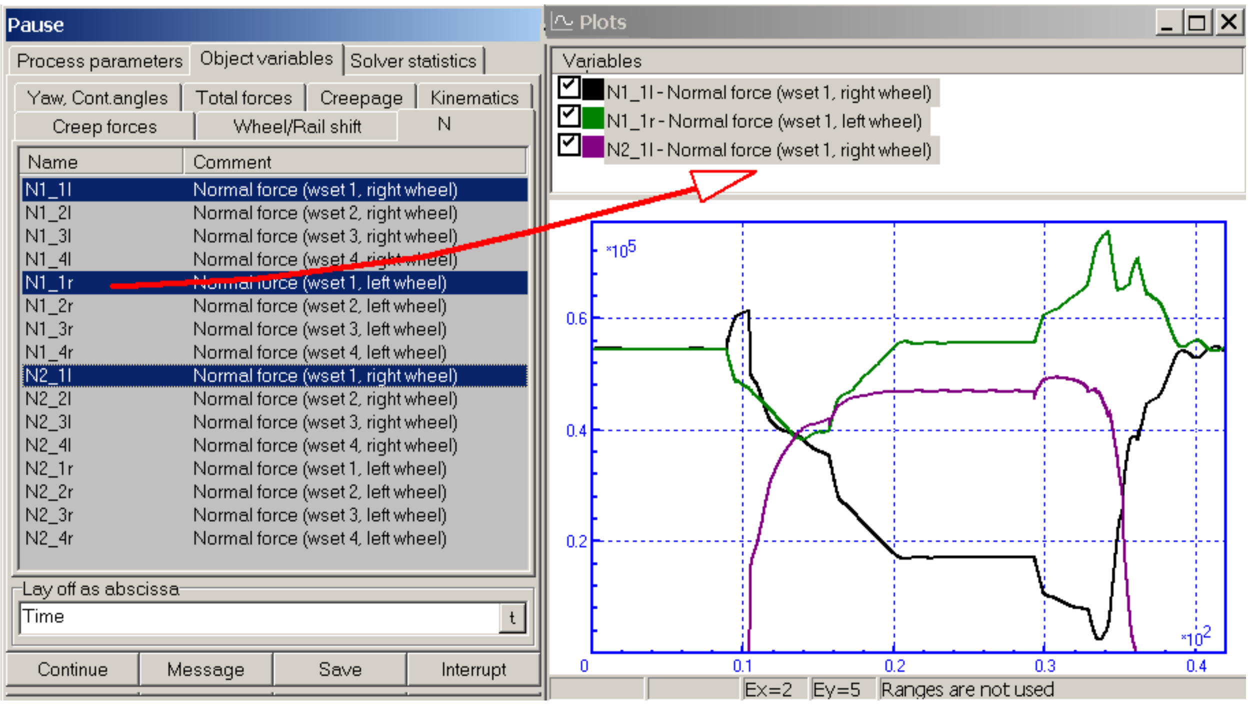


Figure 10.13. Plotting computed variables

To drag several variables from the list, use the *Shift* or *Ctrl* key simultaneously with the selection of variables by the mouse.

6. Quasi-static values of variables in Sect. 10.4.2.1. *"Tabulated results"*, p. 10-16, may be obtained directly from the plots, but a much more effective technology can be used. Close the Pause window if it is open yet. If you want to save the just computed variables for further analysis, open the Object variables tab of the inspector and rename the file of variables in a proper way in the upper box 

. After that open the *Solver* tab and change the simulation time to 28.5 sec instead of 42 sec, Figure 10.14. Note that in this simulation (Track Case 1) in contrary to other cases we use Jacobian matrices, because the vehicle speed is small and equations of motion are stiff. Use of Jacobian matrices reduces CPU expenses about two times.

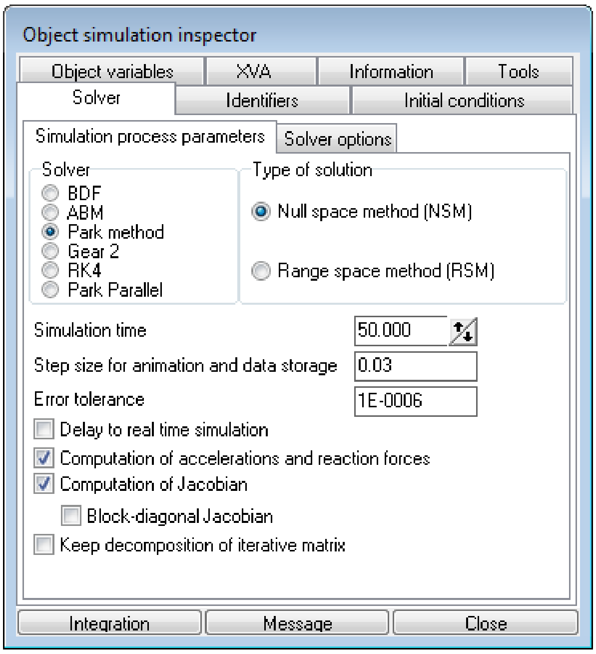


Figure 10.14. Solver parameters

7. Run simulation. After the end of simulation the quasi-static values of variables can be obtained with the help of the *Table processor*. Click the button on the tool bar or use the **Tools | Table processor…** menu item to open the table processor window. Check the *LastOrdinate* functional (the last value of a variable) in the left part of the window. Drag and drop variables into the table processor (Figure 10.15).

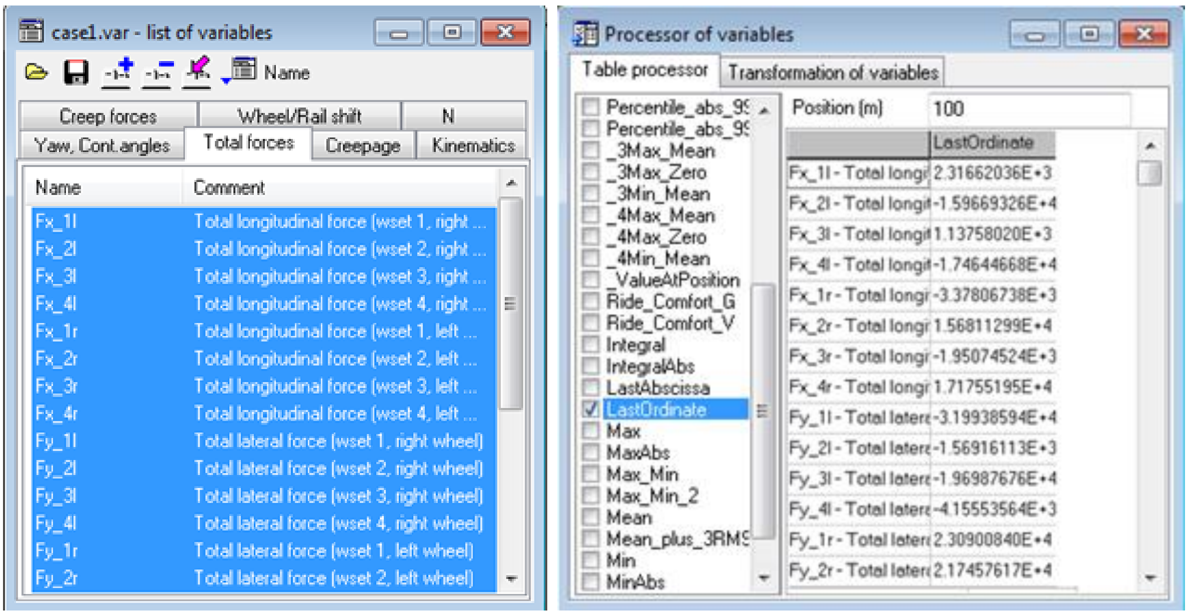


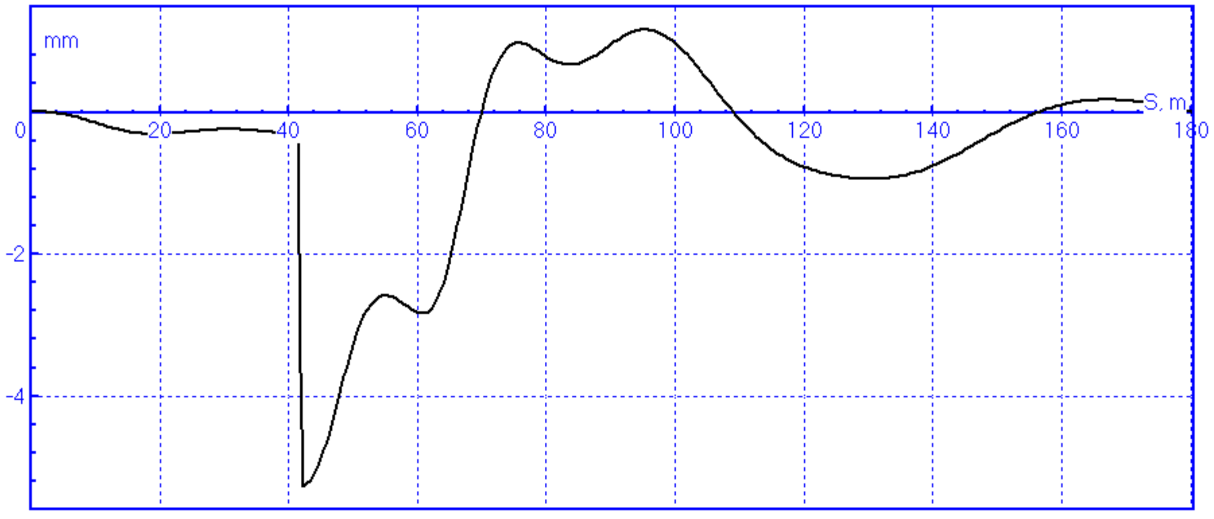
Figure 10.15. Use of a table processor for computing steady-state values of variables

10.4.3. Track Case 2

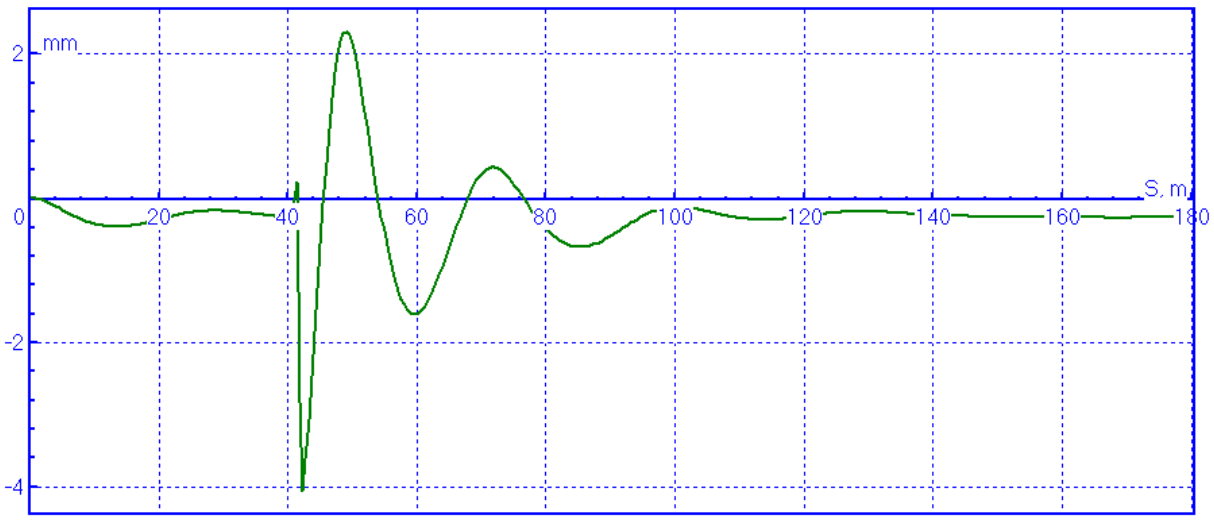
Two problems are analyzed in this section. Firstly, a dynamic response on a single lateral 5 mm shift of the track (Sect. 10.2.4.2. *"Track Case 2"*, p. 10-8). Secondly, computation of a critical velocity.

10.4.3.1. Plotted results

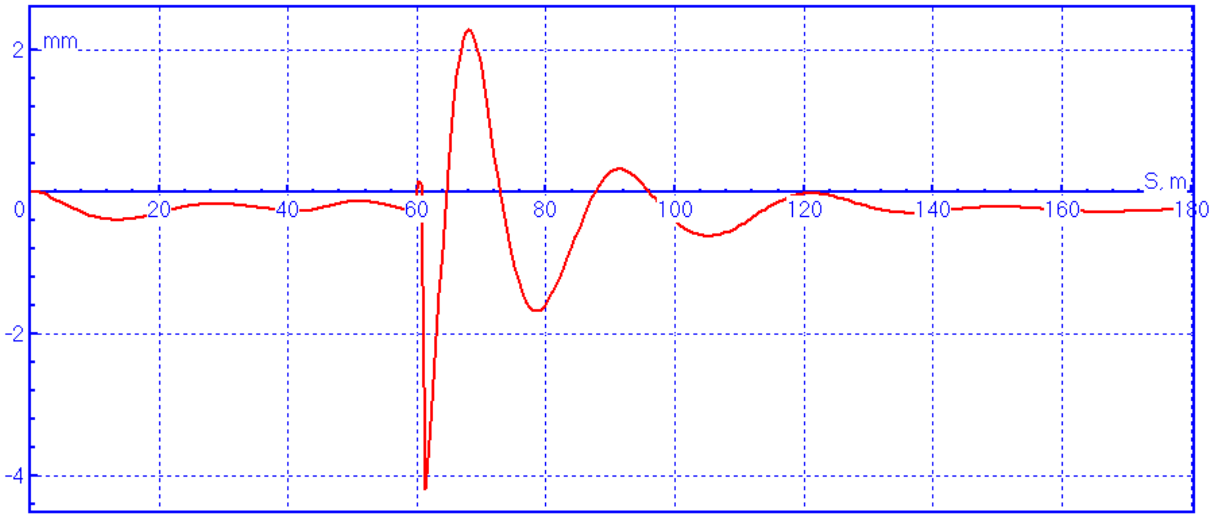
In accordance with the benchmark requirements, lateral positions of bodies should be plotted in the track system of coordinates, i.e. the reference frame is shifted in the lateral direction on 5 mm in common with the track centerline. Vehicle speed is 45 m/s, simulation time is 4 sec.



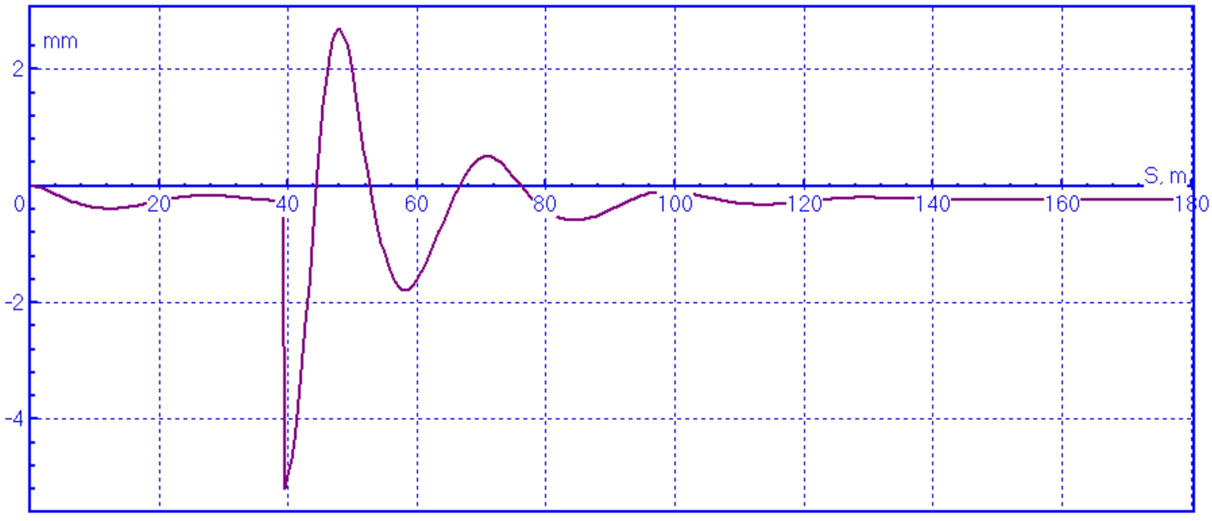
Lateral position of the car body, v = 45 m/s



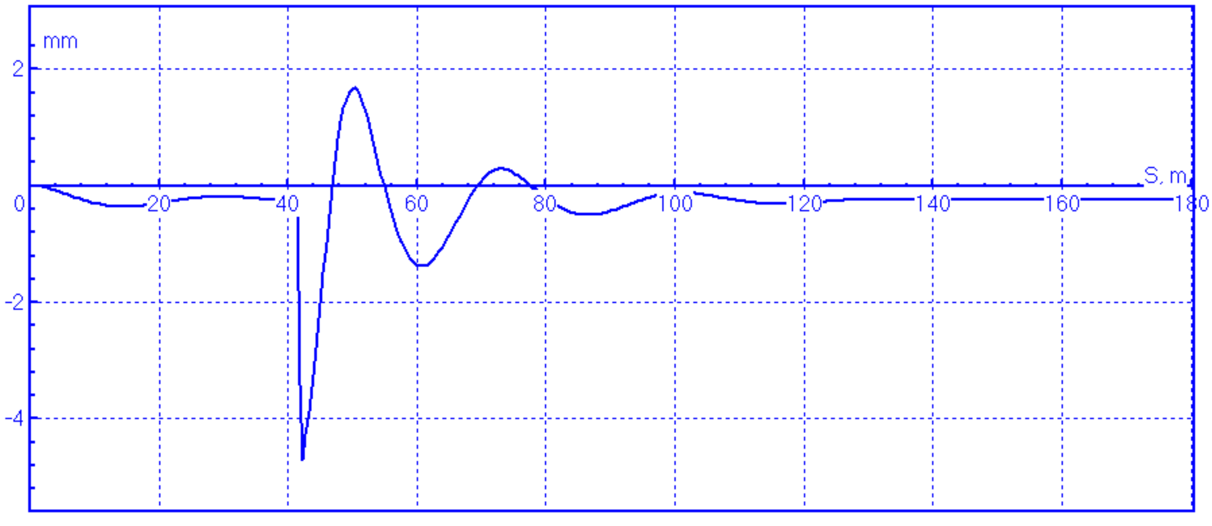
Lateral position of the leading bogie, v = 45 m/s



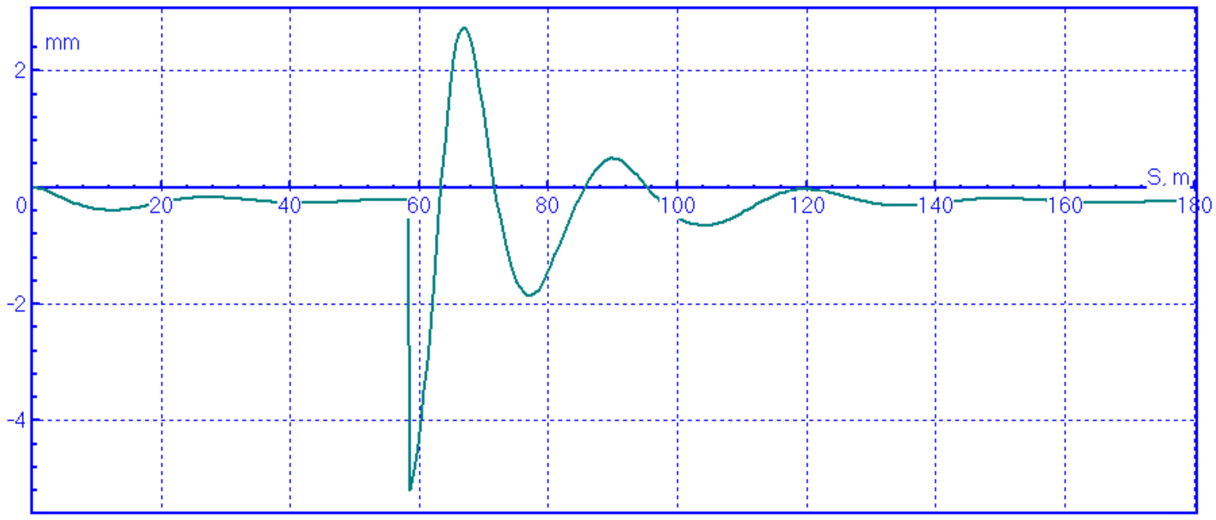
Lateral position of the trailing bogie, v = 45 m/s



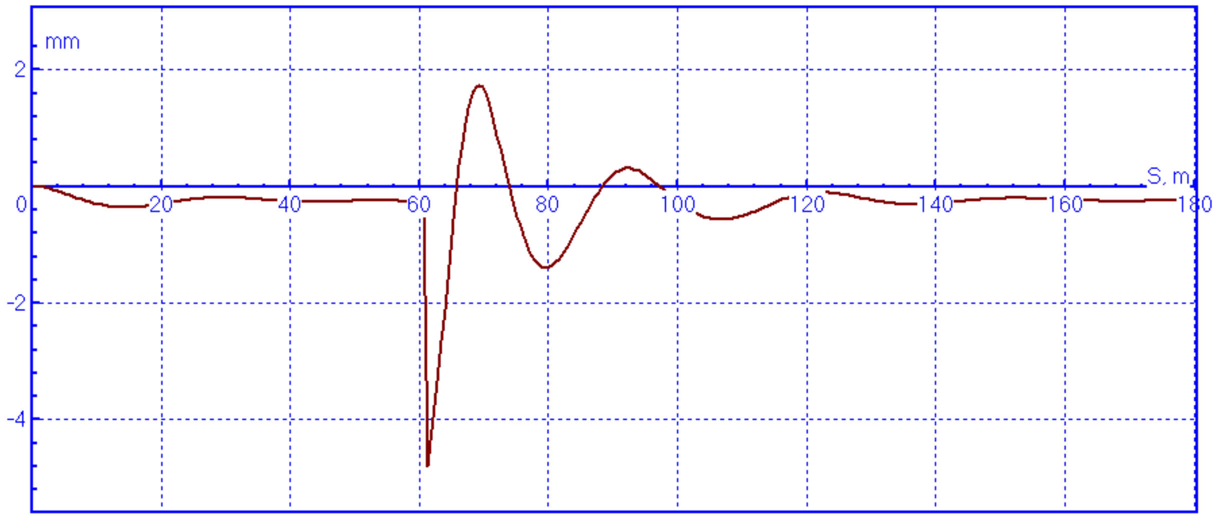
Lateral position of Wheelset1, v = 45 m/s



Lateral position of Wheelset2, v = 45 m/s

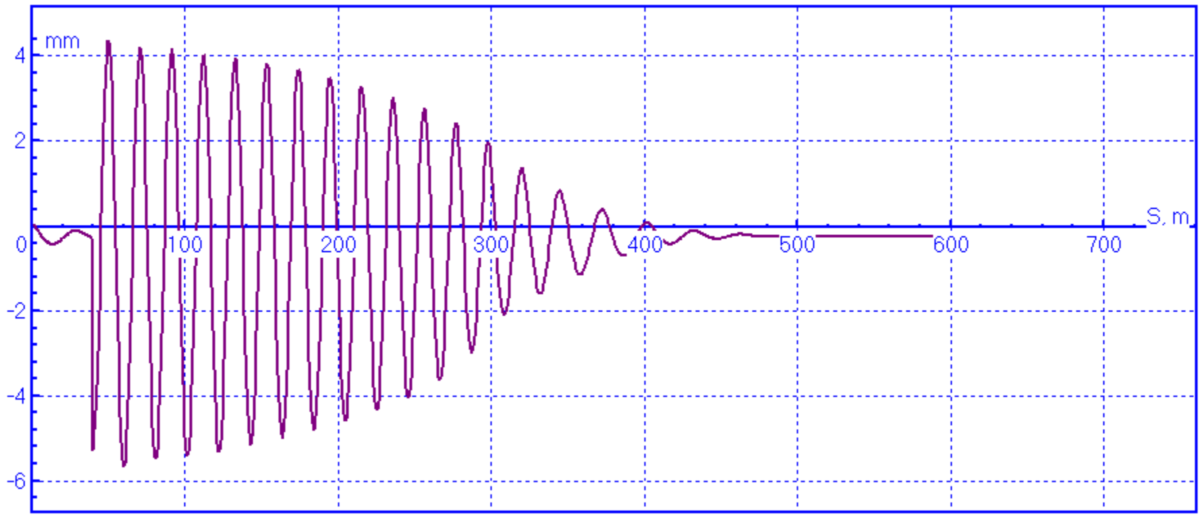


Lateral position of Wheelset3, v = 45 m/s

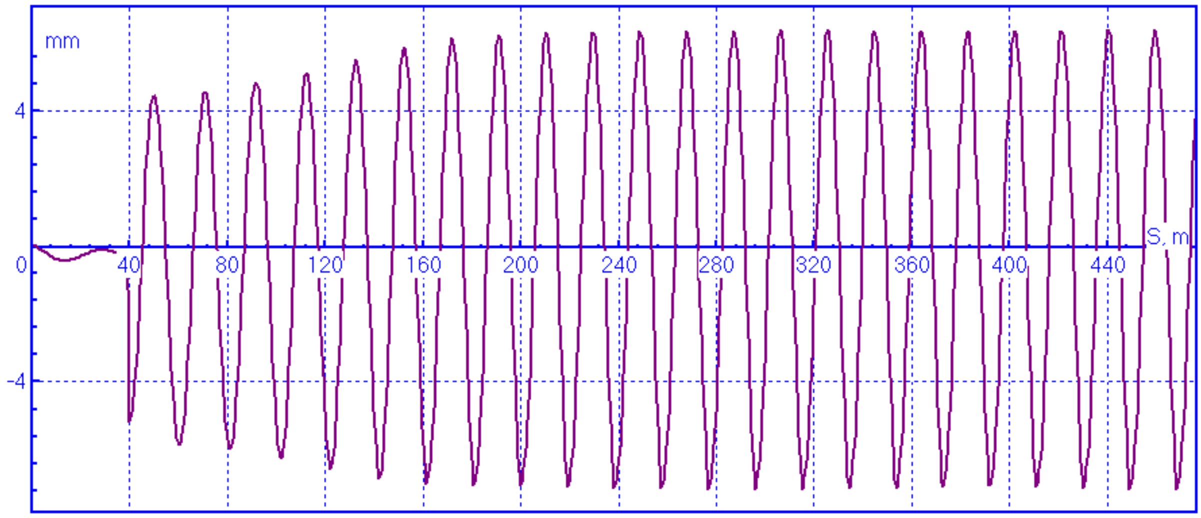


Lateral position of Wheelset4, v = 45 m/s

The next two plots are obtained for the lateral position of Wheelset 1. According to these plots the critical speed of Vehicle 1 is 74 m/s.



Lateral position of Wheelset1, v = 73 m/s



Lateral position of Wheelset1, v = 74m/s, frequency of oscillation 3.9 Hz

10.4.3.2. User's instructions

Here is the sequence of actions for obtaining the results of the previous section.

1. Repeat items 1-6 of instructions in Sect. 10.4.2.3. *"User's instructions"*, p. 10-27 with one change: open the *Case2* configuration.
2. Run simulation. All variables, which are necessary for analysis of the first problem, are located in the automatically open graphic window (Figure 10.16). Switch on/off variables in the window to get separate variables. Use a pop up menu to get useful utilities for working with plots.

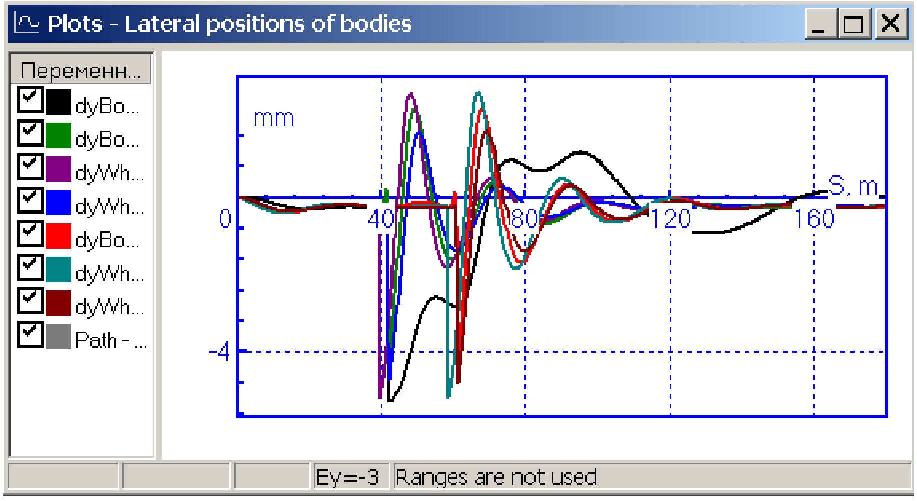


Figure 10.16. Plotted results – lateral positions of bodies

3. To compute the critical speed
   - Close the *Pause* window.
   - Increase the simulation time to 6-10 sec on the *Solver* tab (Figure 10.14),
   - Stepwise increase the speed (identifier v0) on the *Identifiers* tab (Figure 10.17) starting from 70m/s, step size 1m/s. Appearance of long lateral undamped oscillations of Wheelset 1 indicates instability of the vehicle and corresponds to the critical speed.

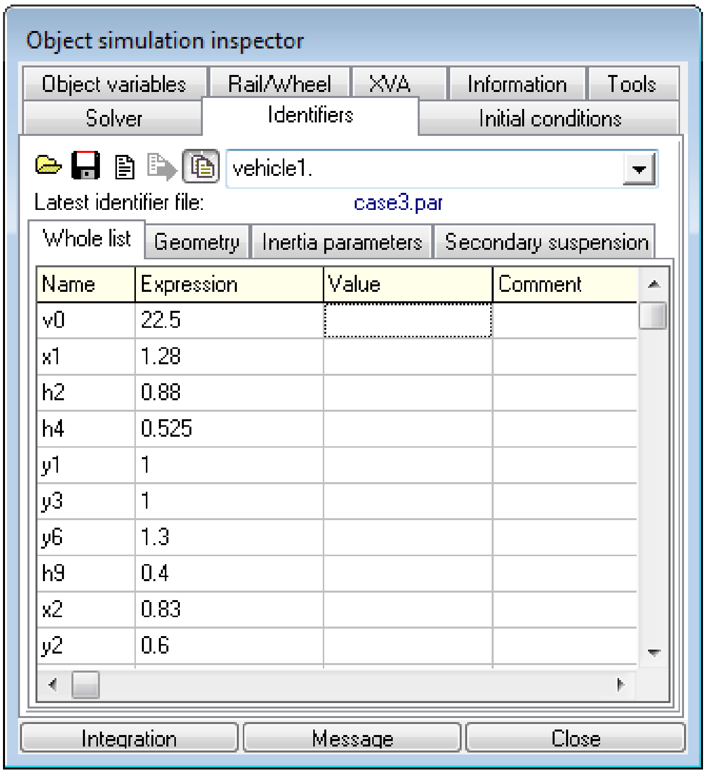
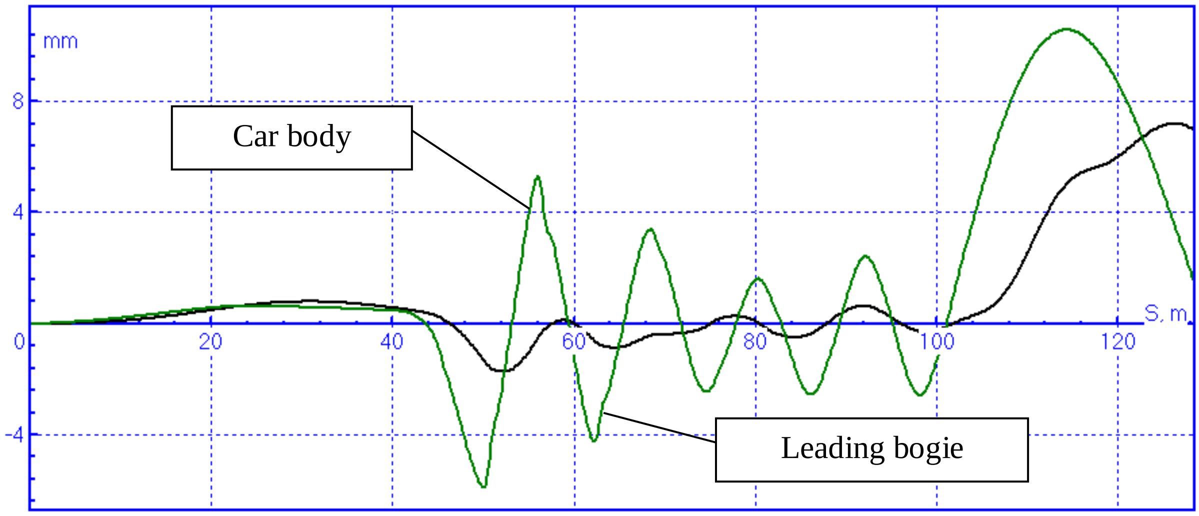


Figure 10.17. Setting speed of vehicle

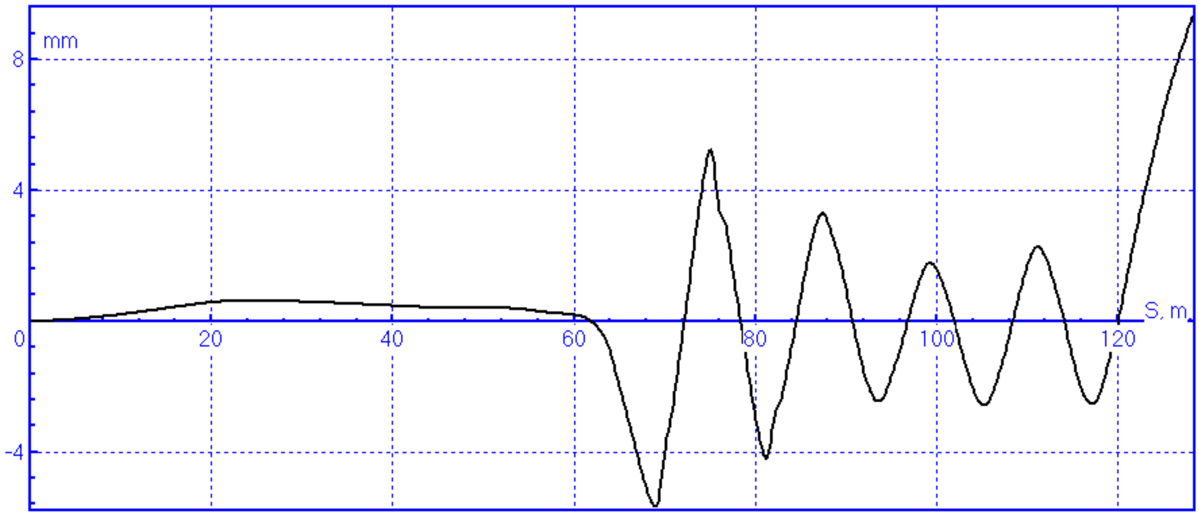
10.4.4. Track Case 3

Here we consider the case when Vehicle 1 runs in a straight section with large horizontal sinusoidal irregularities (Sect. 10.2.4.3. *"Track Case 3"*, p. 10-8). The vehicle runs with a constant speed 22.5 m/s. Simulation time is 5.7 sec. Here we analyze lateral displacements of bodies, in particular cases of two-point contacts, roll of the car body and bogies, as well as total vertical and lateral forces at wheels of Wheelset 1.

10.4.4.1. Plotted results

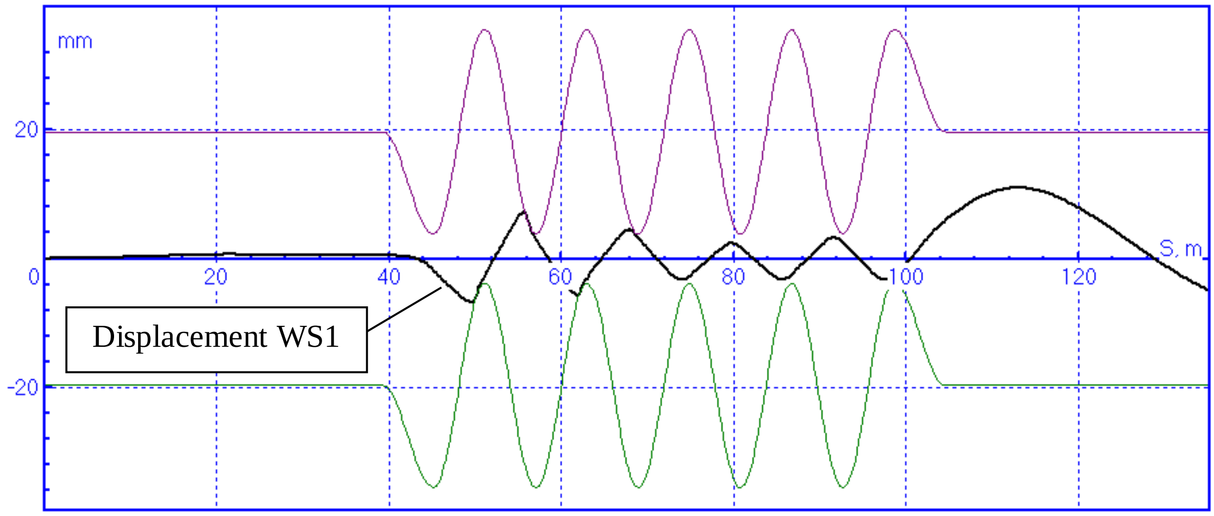


Lateral displacements of the car body and the leading bogie

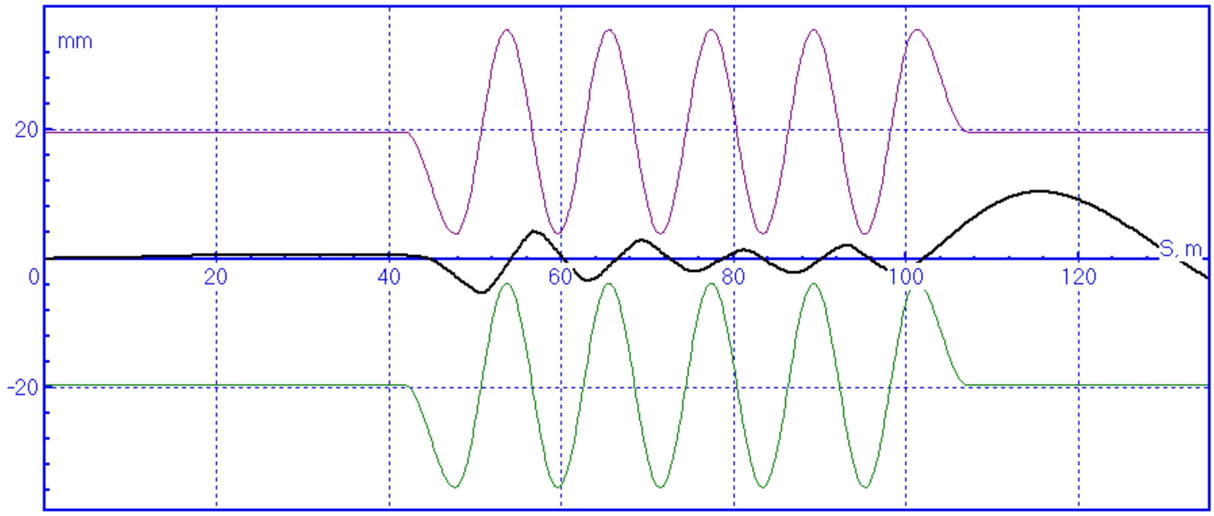


Lateral displacements of the trailing bogie

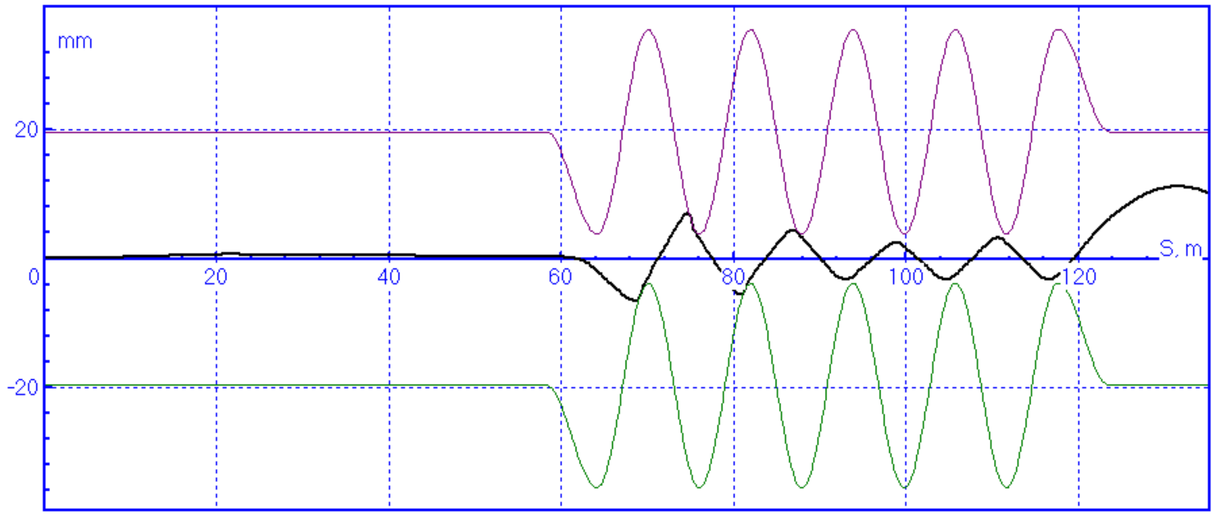
According to the benchmark requirements, ‘for the wheelset lateral displacement plots the positions of the two rails should also be plotted, separately by the flangeway clearance. This will indicate clearly the positions of the flange contact'. As it is seen in the four next figures, Wheelsets 1 and 3 get flange contact, whereas Wheelsets 2 and 4 do not have two-point contacts.



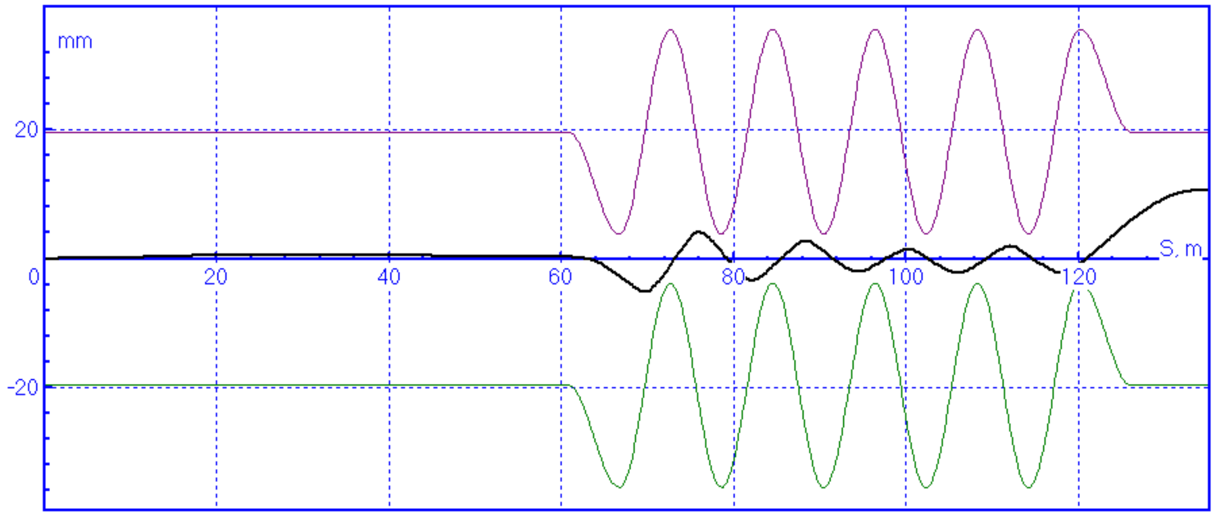
Lateral displacement of Wheelset 1



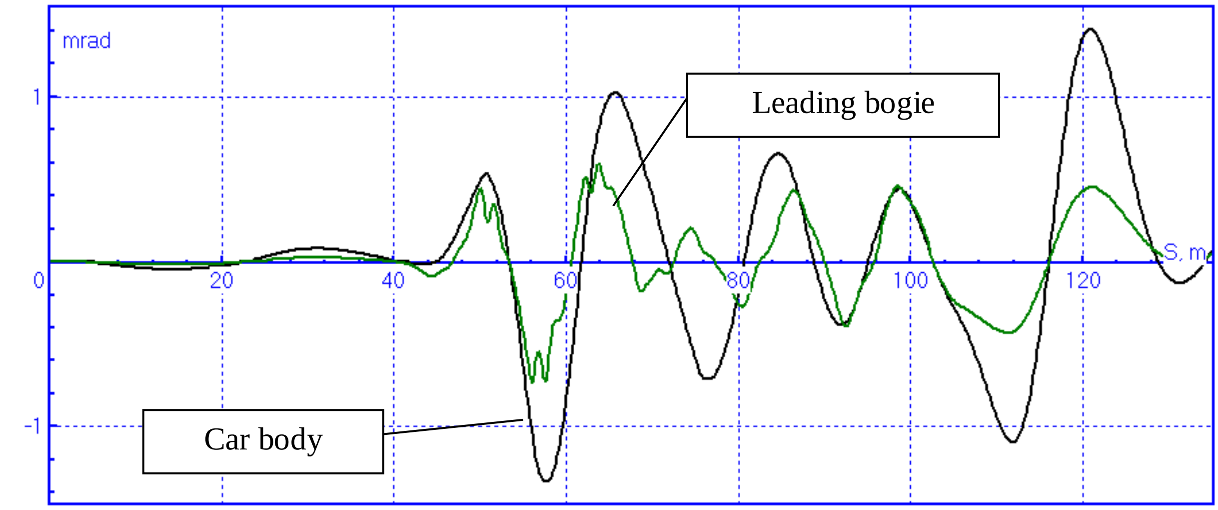
Lateral displacement of Wheelset 2



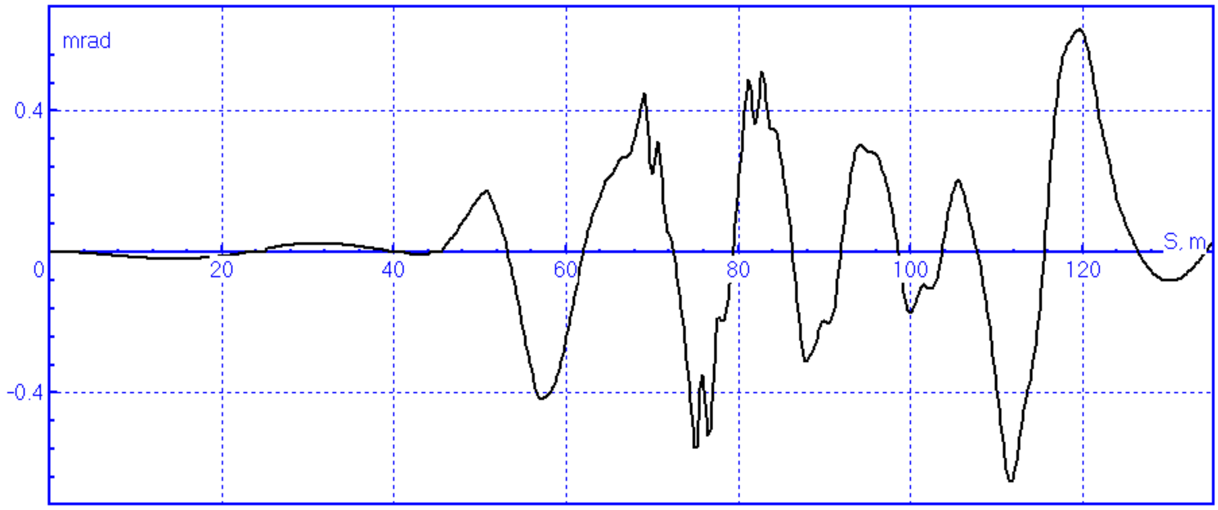
Lateral displacement of Wheelset 3



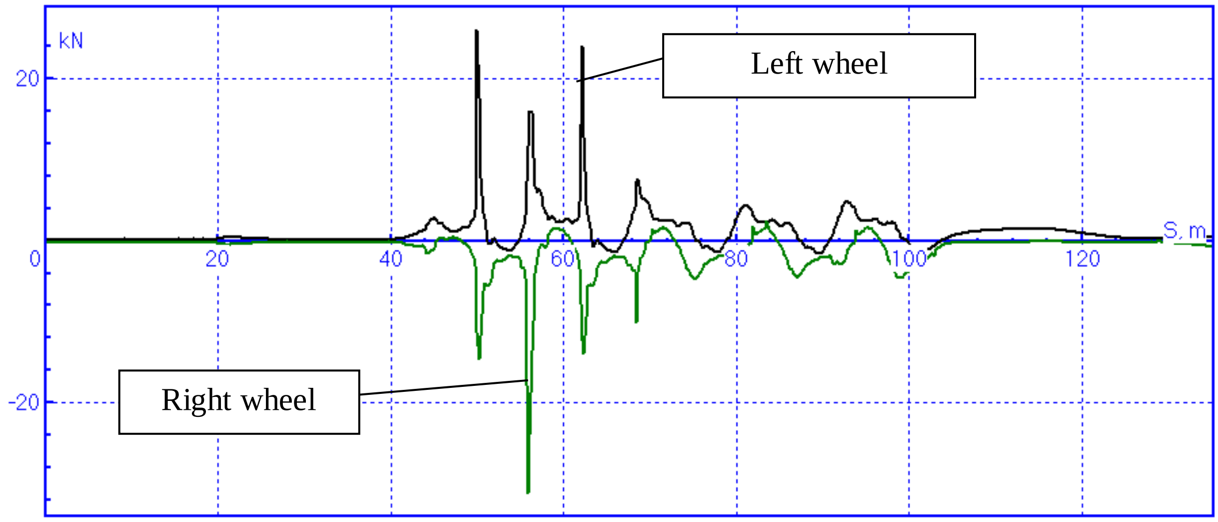
Lateral displacement of Wheelset 4



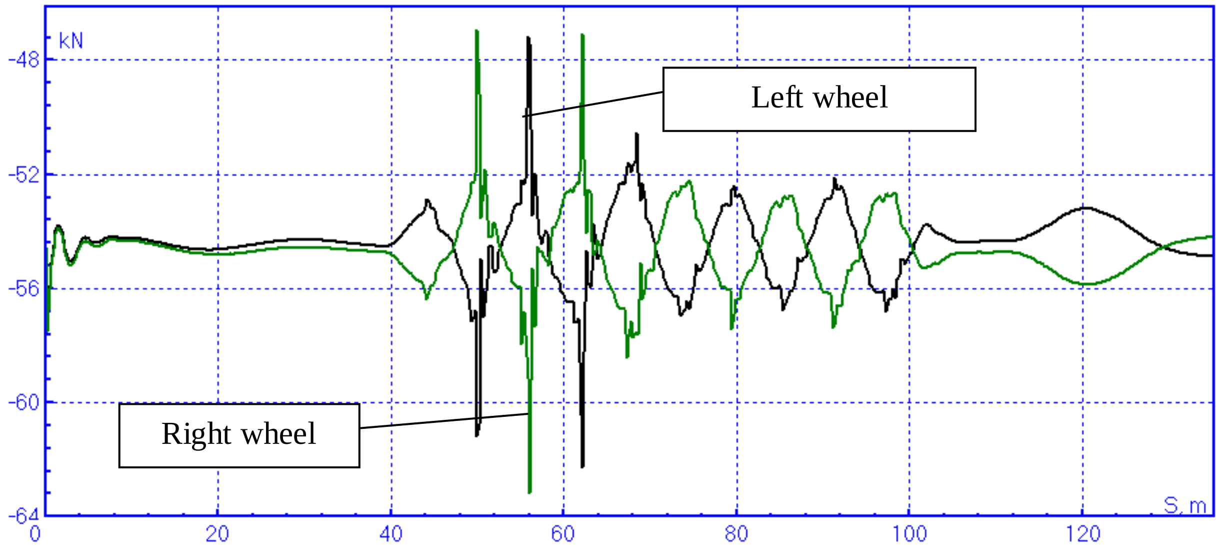
Roll angle of car body and leading bogie



Roll angle of trailing bogie



Total lateral forces, wheelset 1



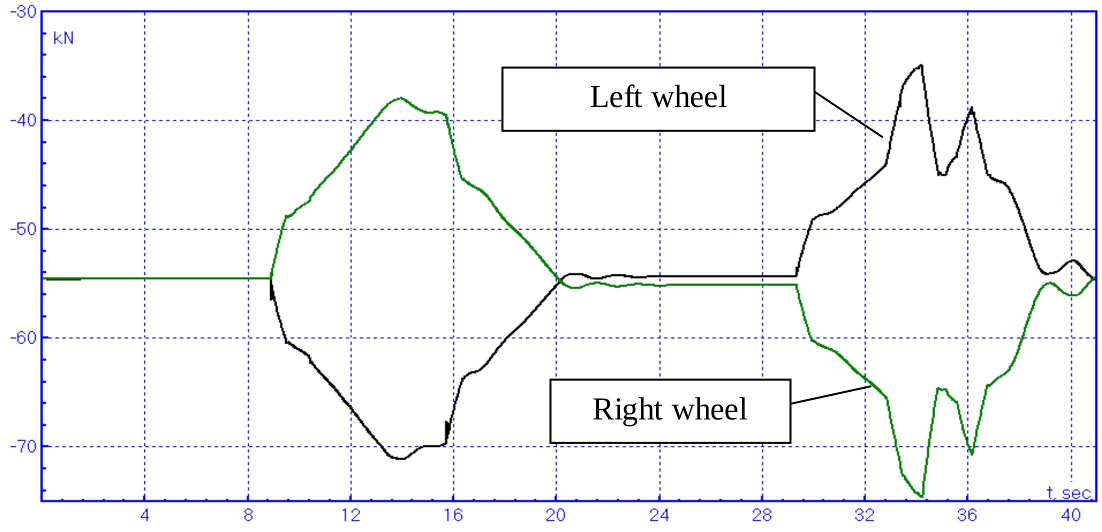
Total vertical forces, wheelset 1

10.4.4.2. User's instructions

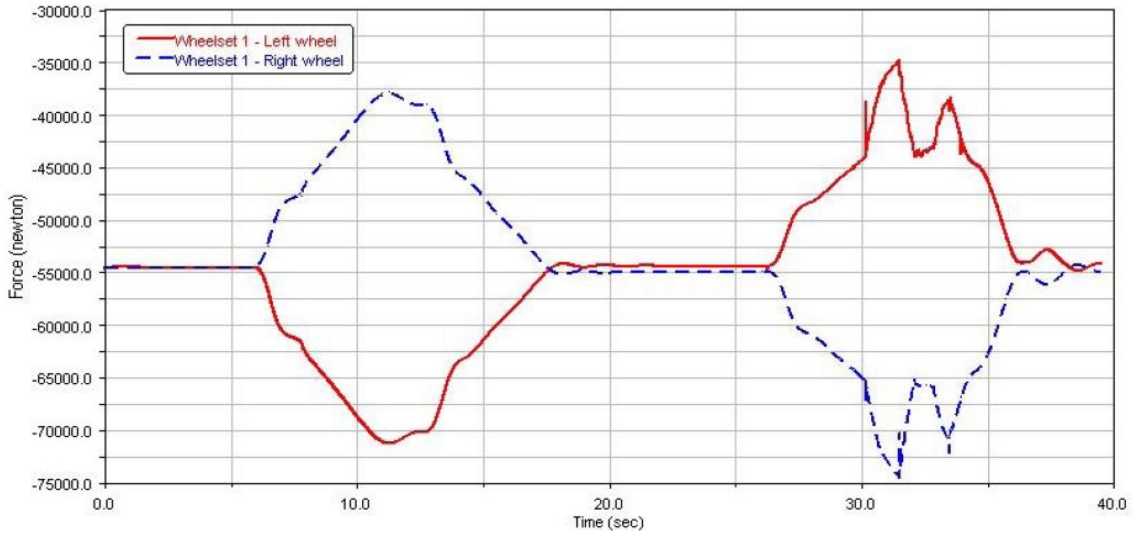
To get the results in the previous section, follow items 1–6 of instructions in Sect. 10.4.2.3. *"User's instructions"*, p. 10-27 taking into account that the *Case3* configuration should be used, and the file of variables is *Case3.var*.

10.4.5. Comparison of plotted results with results of other benchmark participants

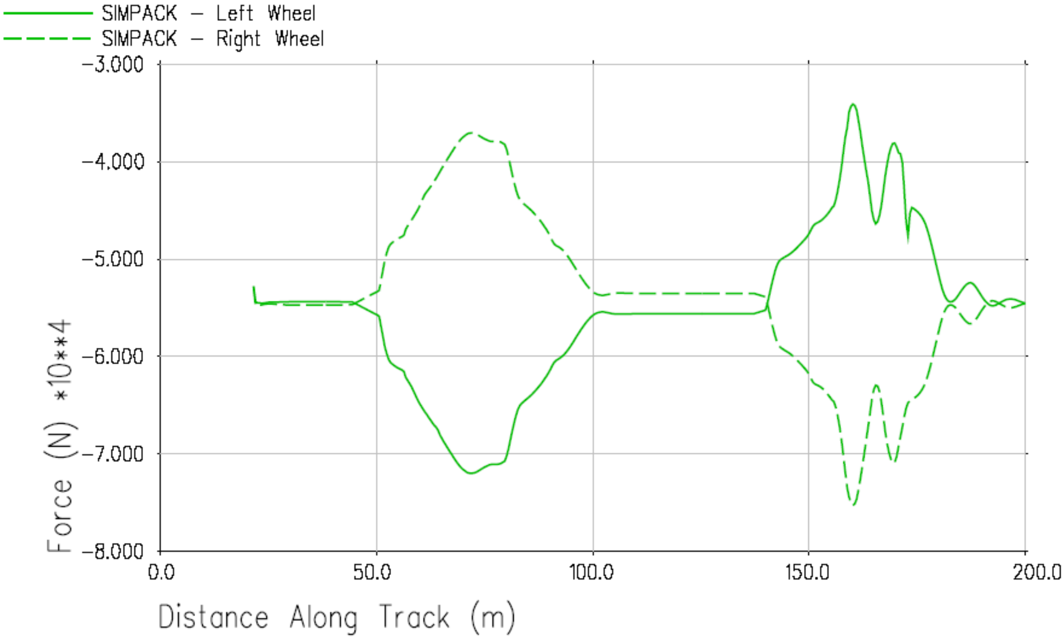
As it follows from the figures below, as well as from other result published in Internet (Sect. 10.1. *"General information on Manchester Benchmarks"*, p. 10-3), UM and ADAMS/Rail results for Vehicle 1 are both qualitative and quantitative similar. Differences in UM and Sim-Pack results are more significant though they are qualitatively similar.



Total vertical forces for Wheelset 1, Track Case 1 (UM)



Total vertical forces for Wheelset 1, Track Case 1 (ADAMS/Rail)



Total vertical forces for Wheelset 1, Track Case 1 (SimPack)

10.5. Vehicle 2 simulation results

Simulation results for Vehicle 2 are given in this section. Vehicle2 model description can be found in Sect. 10.2.2. *"Vehicle 2"*, p. 10-6. Simulations are run for the track cases 2, 3, 4 (Sect. 10.2.4.2. *"Track Case 2"*, p. 10-8 – Sect. 10.2.4.4. *"Track Case 4"*, p. 10-9). User's instructions are analogous to those for Vehicle 1 in Sect. (Sect. 10.4.1.2. *"User's instructions"*, p. 10-14, 10.4.3.2. *"User's instructions"*, p. 10-34, 10.4.4.2. *"User's instructions"*, p. 10-40).

10.5.1. Natural frequencies

The model of Vehicle 2 contains frictional dampers, which cannot be linearized. That is why natural frequencies of the model are computed with switched off dampers. The results are listed in Table 10.12.

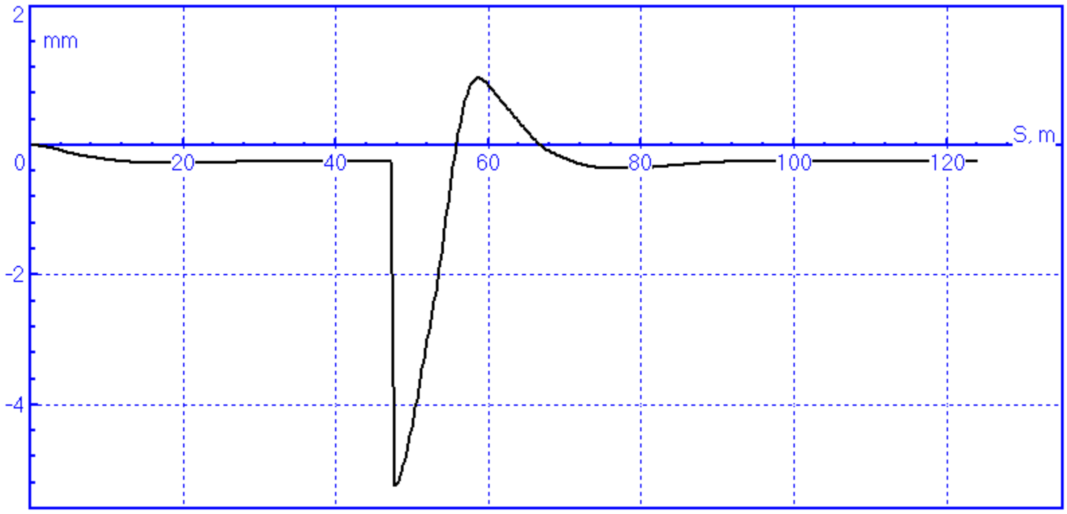
See Sect. 10.4.1.2. *"User's instructions"*, p. 10-14 for user's instructions.

Table 10.12

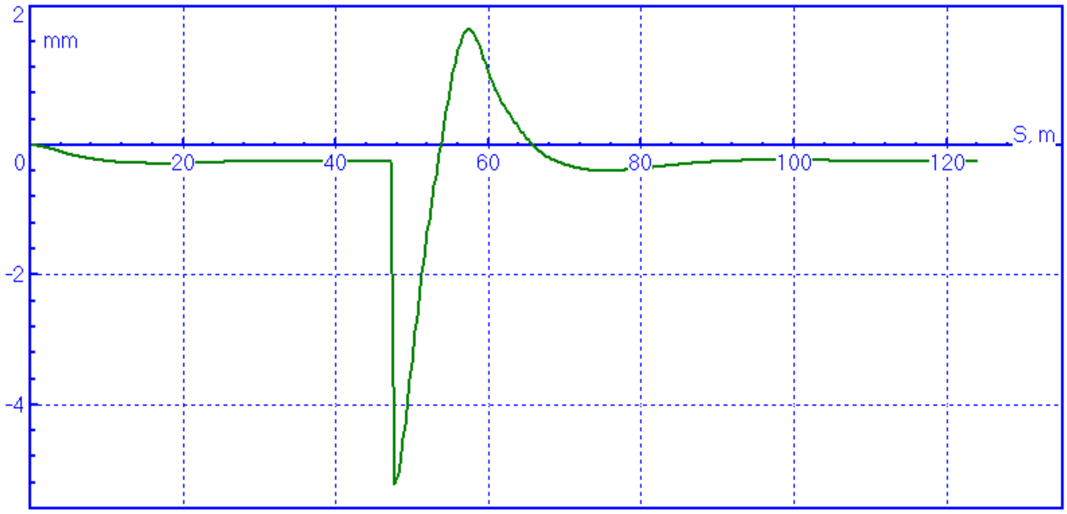
Natural frequencies of car body for fixed wheelsets

Mode	Frequency (Hz)		
	UM	Adams/ Rail	Other partici-pants
Lower sway	0.89	0.89	0.9÷1.1
Yaw	2.57	2.58	2.56÷2.8
Bounce	2.11	2.12	2.09÷2.3
Upper sway	2.46	2.46	2.58÷2.9
Pitch	2.01	2.02	2.09÷2.3
Longitudinal	6.31	6.33	-

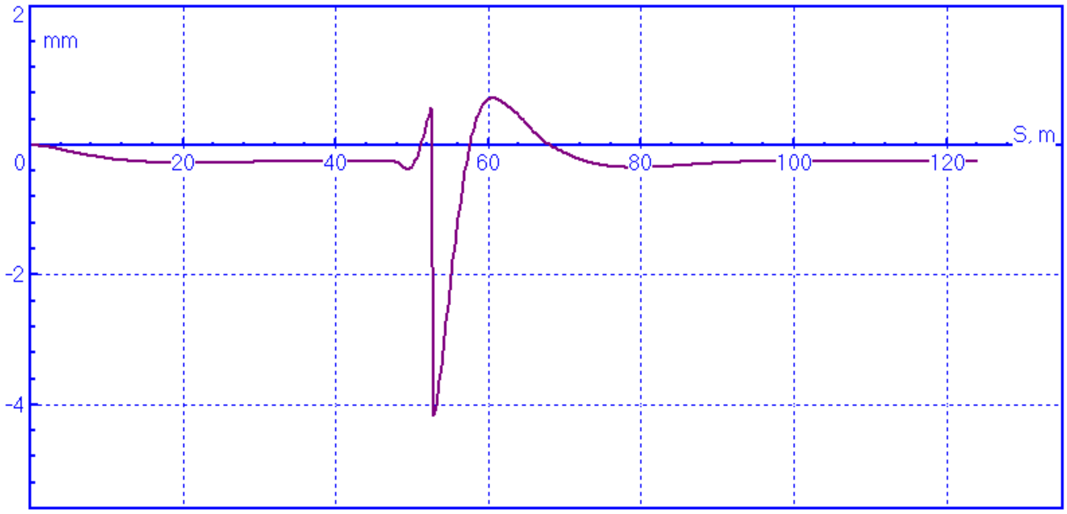
10.5.2. Track case 2



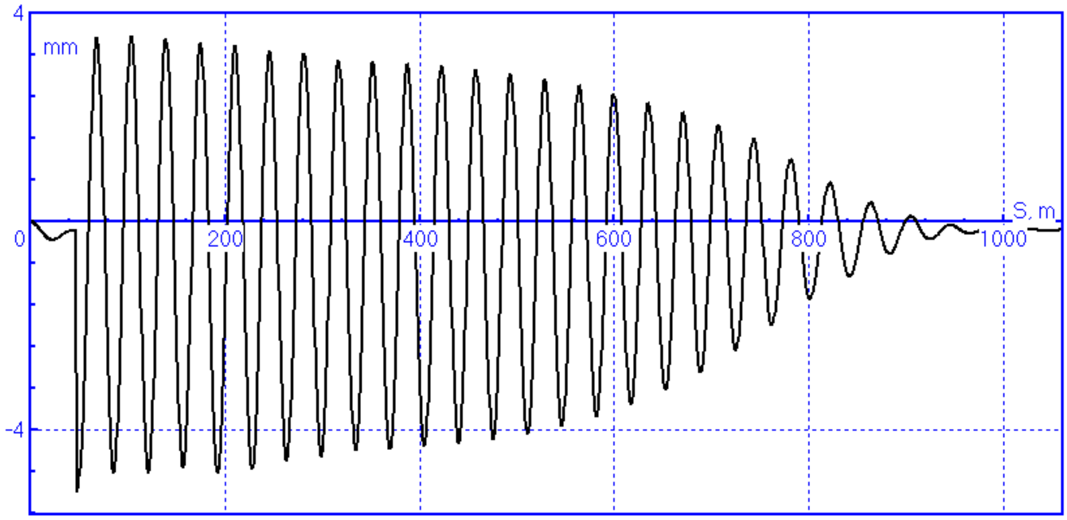
Lateral position of car body



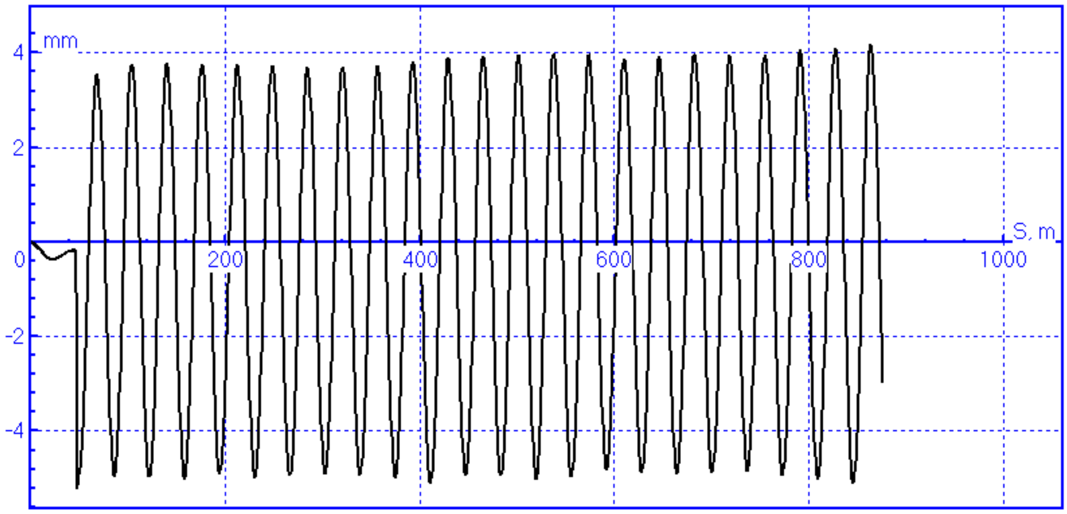
Lateral position of Wheelset 1



Lateral position of Wheelset 2

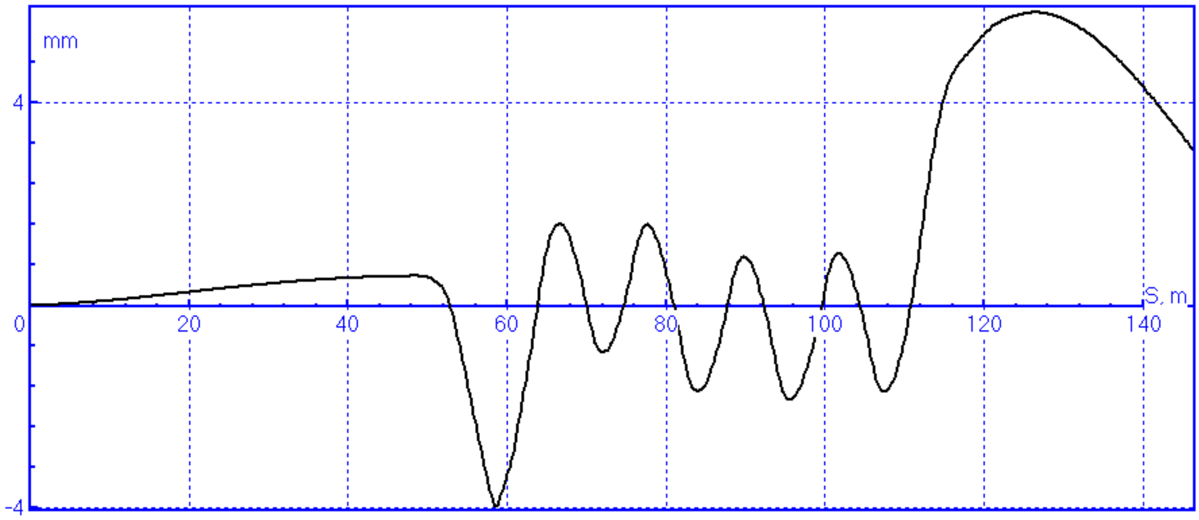


Lateral position of Wheelset 1, v = 73 m/s

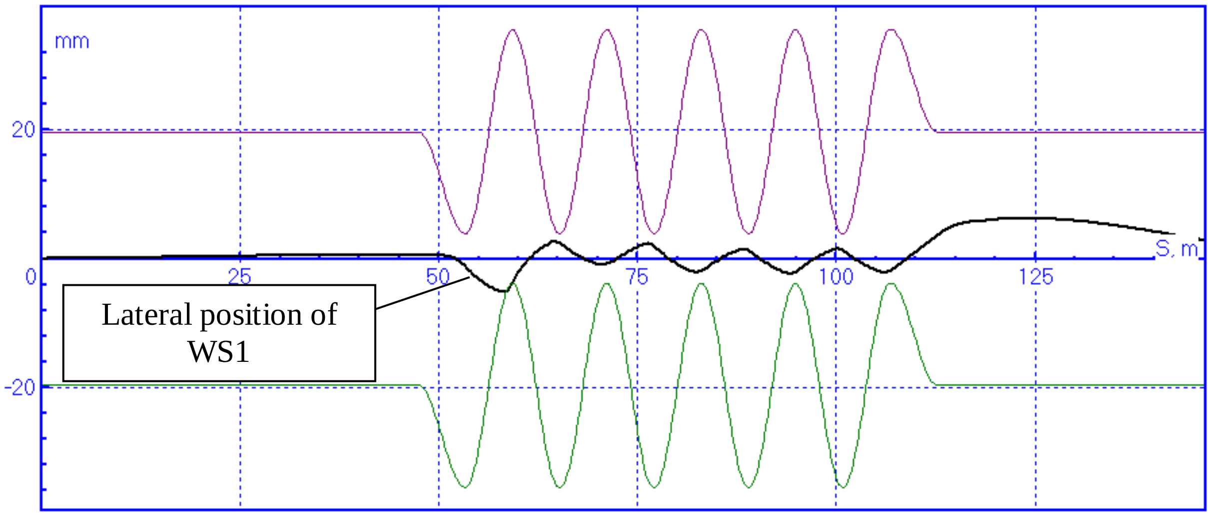


Lateral position of Wheelset 1, v = 74 m/s (critical speed), oscillation frequency 2.05 Hz

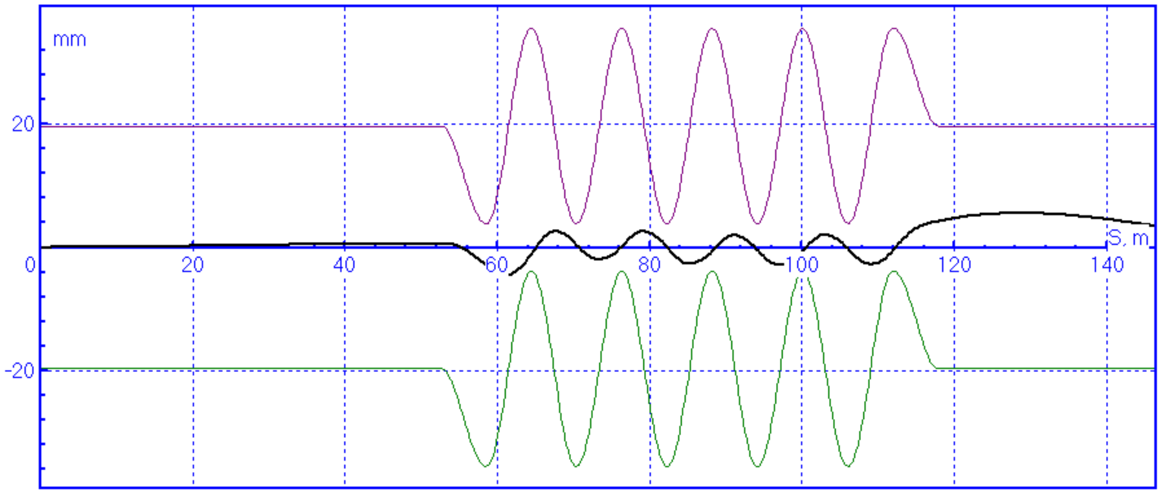
10.5.3. Track Case 3



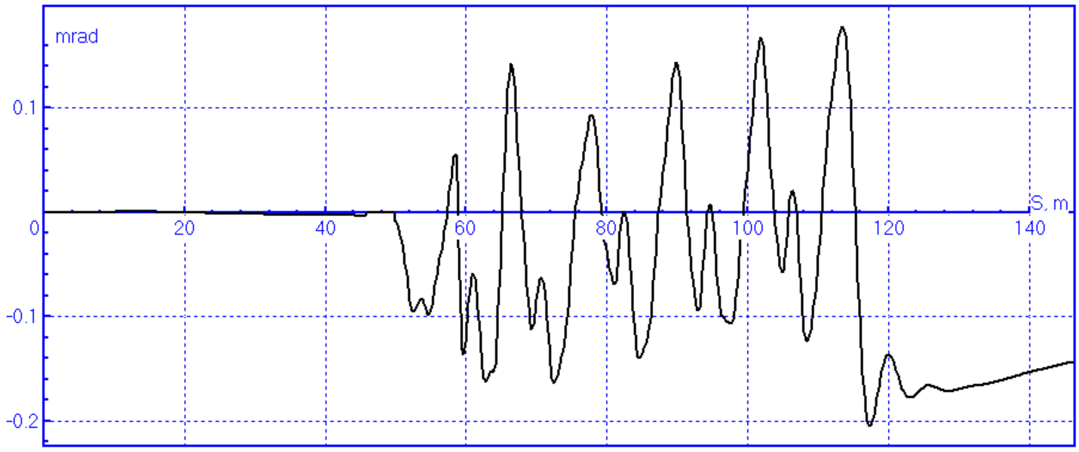
Lateral position of car body



Lateral position of Wheelset 1

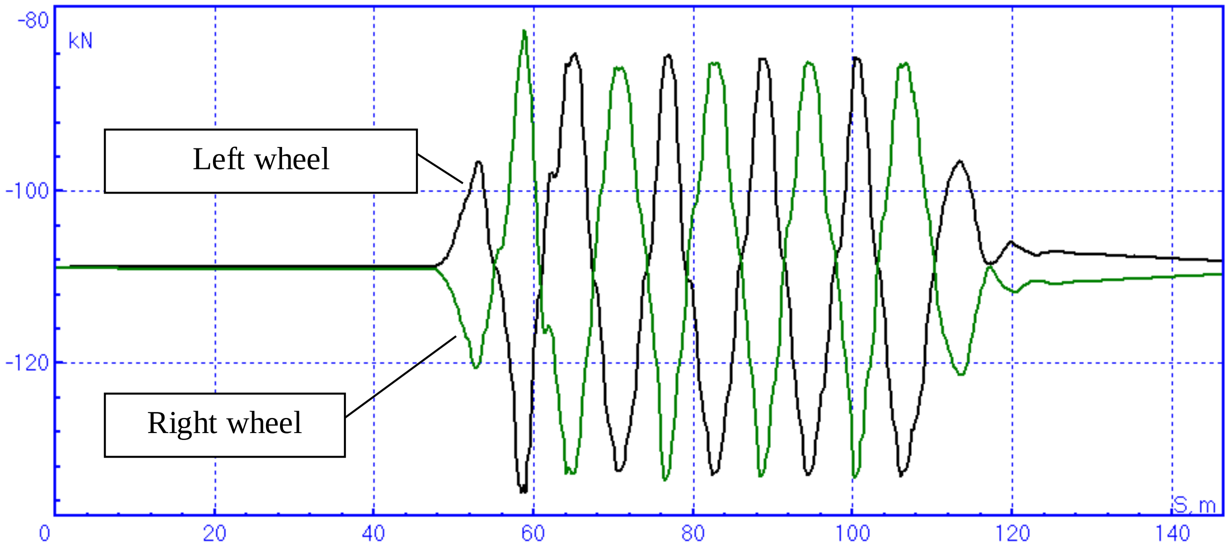


Lateral position of Wheelset 2



Roll angle of car body

Lateral forces for Wheelset 1



Vertical forces for Wheelset 1

10.5.4. Track Case 4

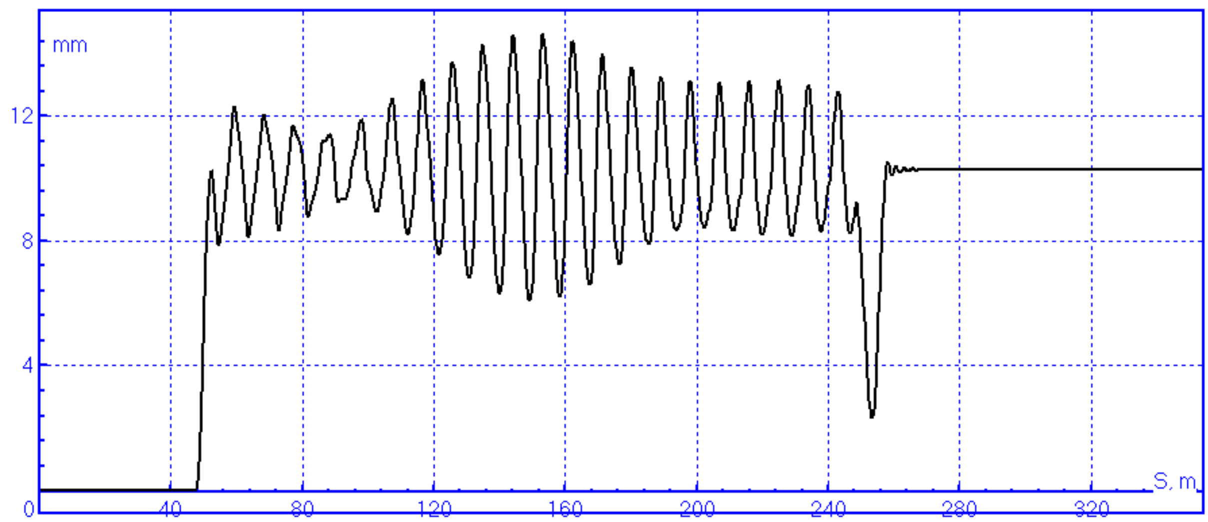
Speed is a constant 20 m/s during 50 m of travel (2.5 sec). Then from 50 to 250 m of travel the speed increased from 20 to 24 m/s. Acceleration duration is 9.0909 sec, the acceleration value is 0.44 m/s^2. The velocity profile for the P-controller is

$$v^* = \begin{cases} 20, t < 2.5 \\ 20 + 0.44(t - 2.5), t \in [2.5, 11.5909] \\ 24, t > 11.5909 \end{cases}$$

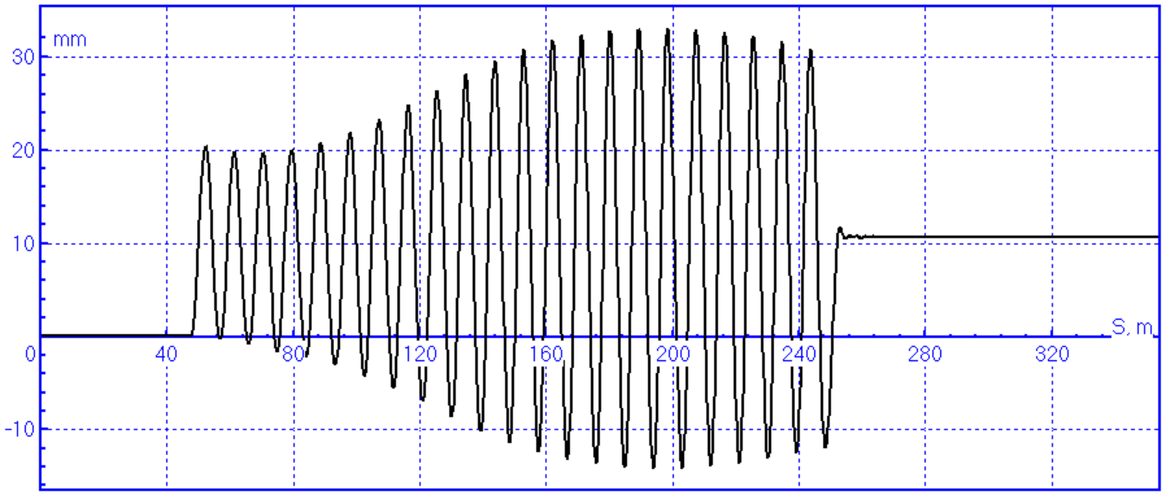
The amplification factor in the controller

$$F = -k_v(v - v^*)$$

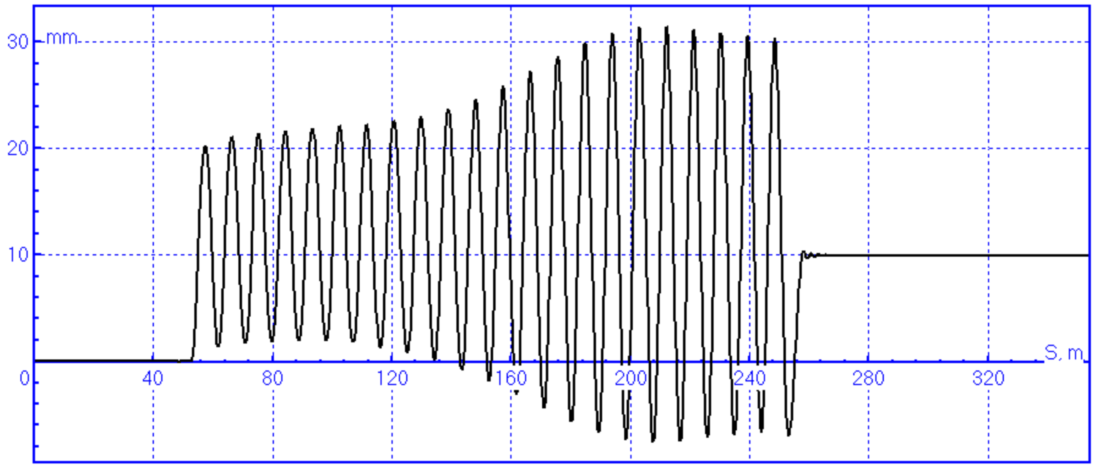
is k_v = 100 kNs/m.



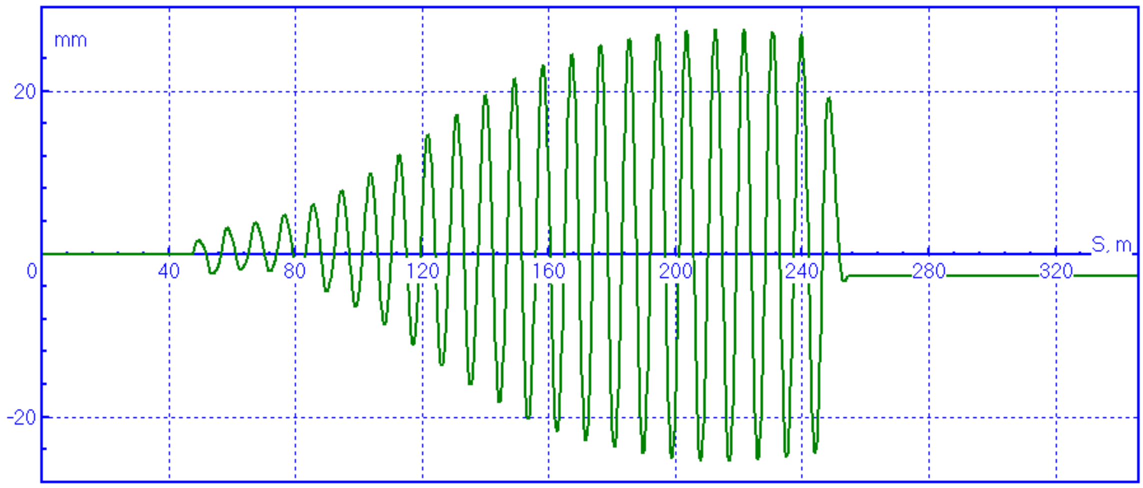
Vertical displacements of car body center



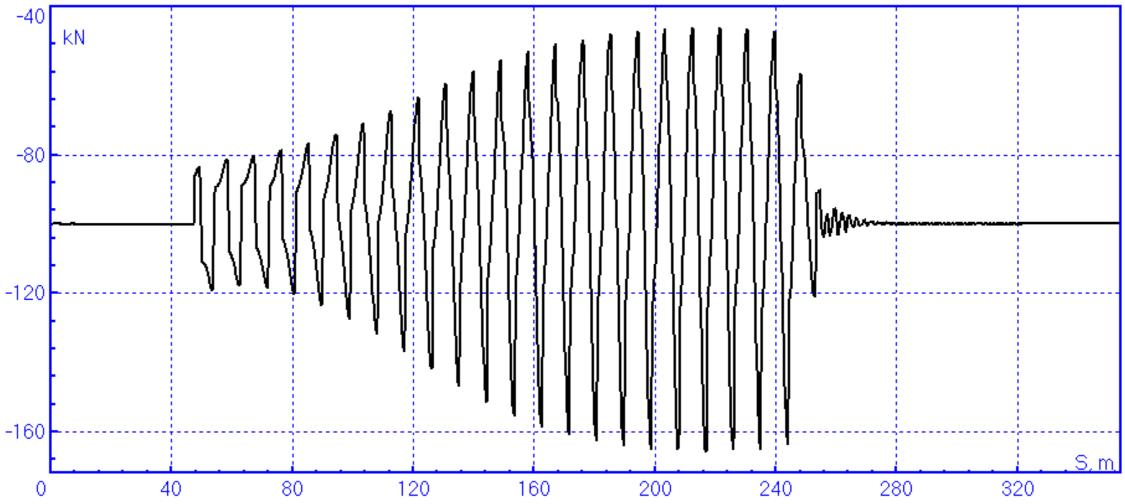
Vertical displacements of car body above the leading wheelset



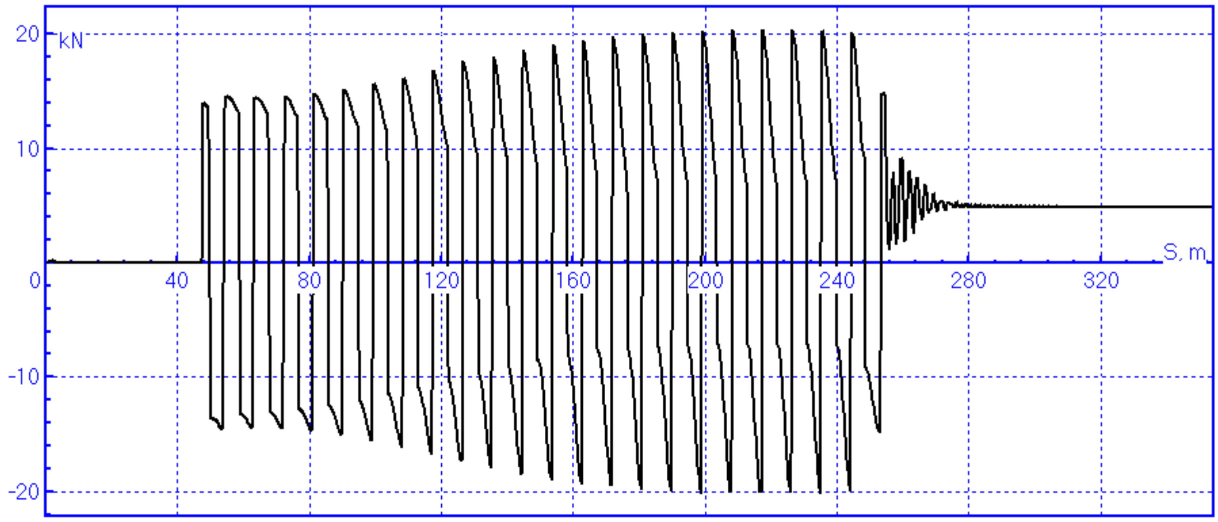
Vertical displacements of car body above the trailing wheelset



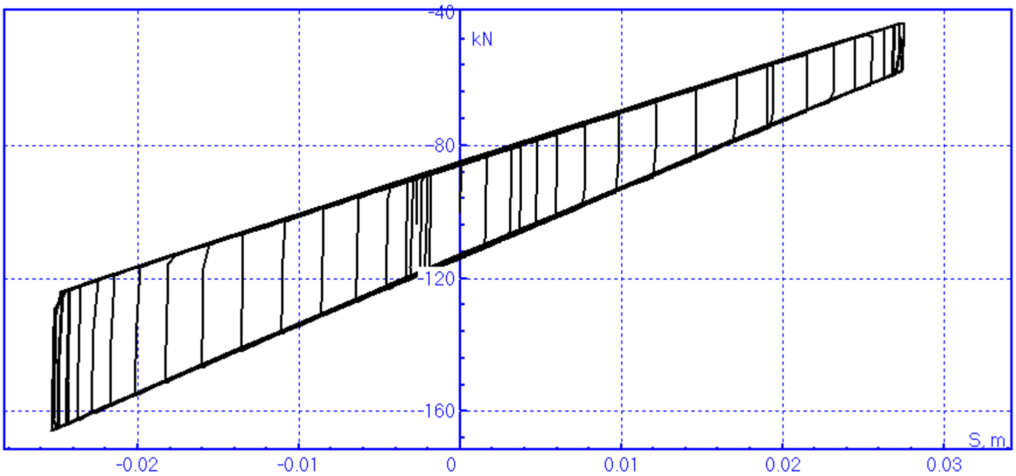
Vertical displacement across the left front suspension



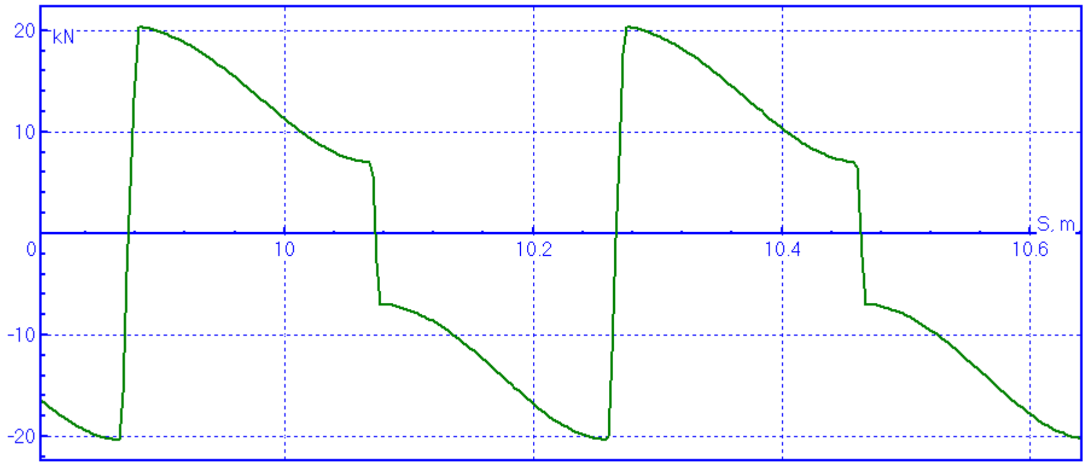
Total vertical force in the left front suspension



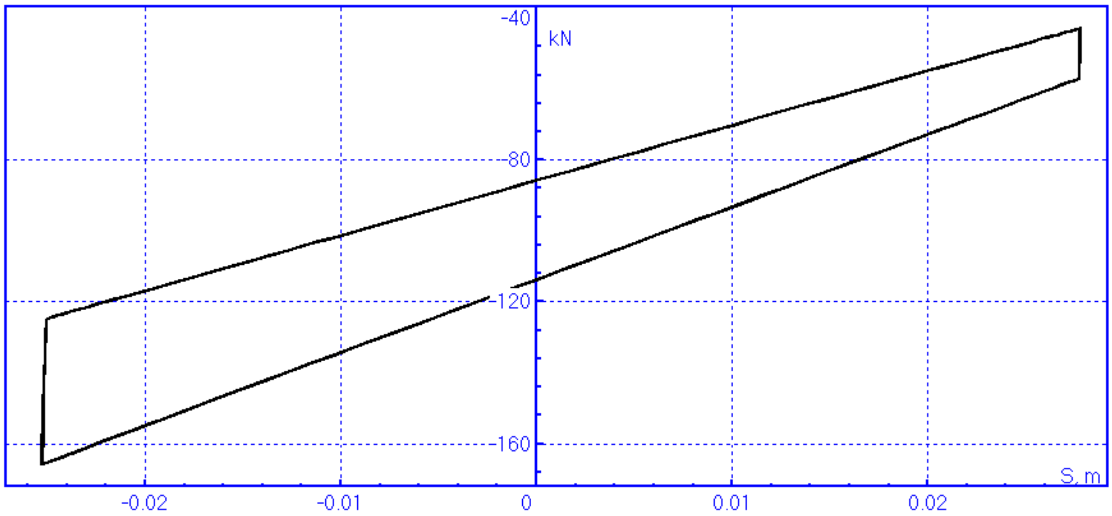
Vertical friction force in the left front suspension



Total vertical force in the left front suspension versus the corresponding displacement



Two cycles of friction in the left front suspension at the area of maximum response



Two cycles of hysteresis at the area of maximum response: total vertical force in the left front suspension versus the corresponding displacement