CHAPTER 4:

OPTIMISATION MODULE

4. OPTIMISATION MODULE

This chapter describes the optimisation module that is coupled to the simulation program Vehsim2d described in the previous chapter. In particular a general description of the optimisation algorithm will be given, the input to the program will be described and finally an example of an optimisation exercise will be presented.

4.1 Optimisation of vehicle / suspension parameters

Use the "LFOPC: Optimisation of vehicle/suspension parameters" button on the main input screen (see figure 3.1) to display the LFOPC optimisation input screen as shown in figure 4.1. The LFOPC algorithm is an extremely robust gradient based optimisation method for constrained optimisation.

When clicking the "LFOPC: Optimisation of vehicle/suspension parameters" button the user will be prompted to save the vehicle file. Save the vehicle if the data have not been saved previously or was changed before clicking the button. The data as saved in the vehicle file will be used as baseline and optimisation will be done starting with the saved vehicle and suspension characteristics.

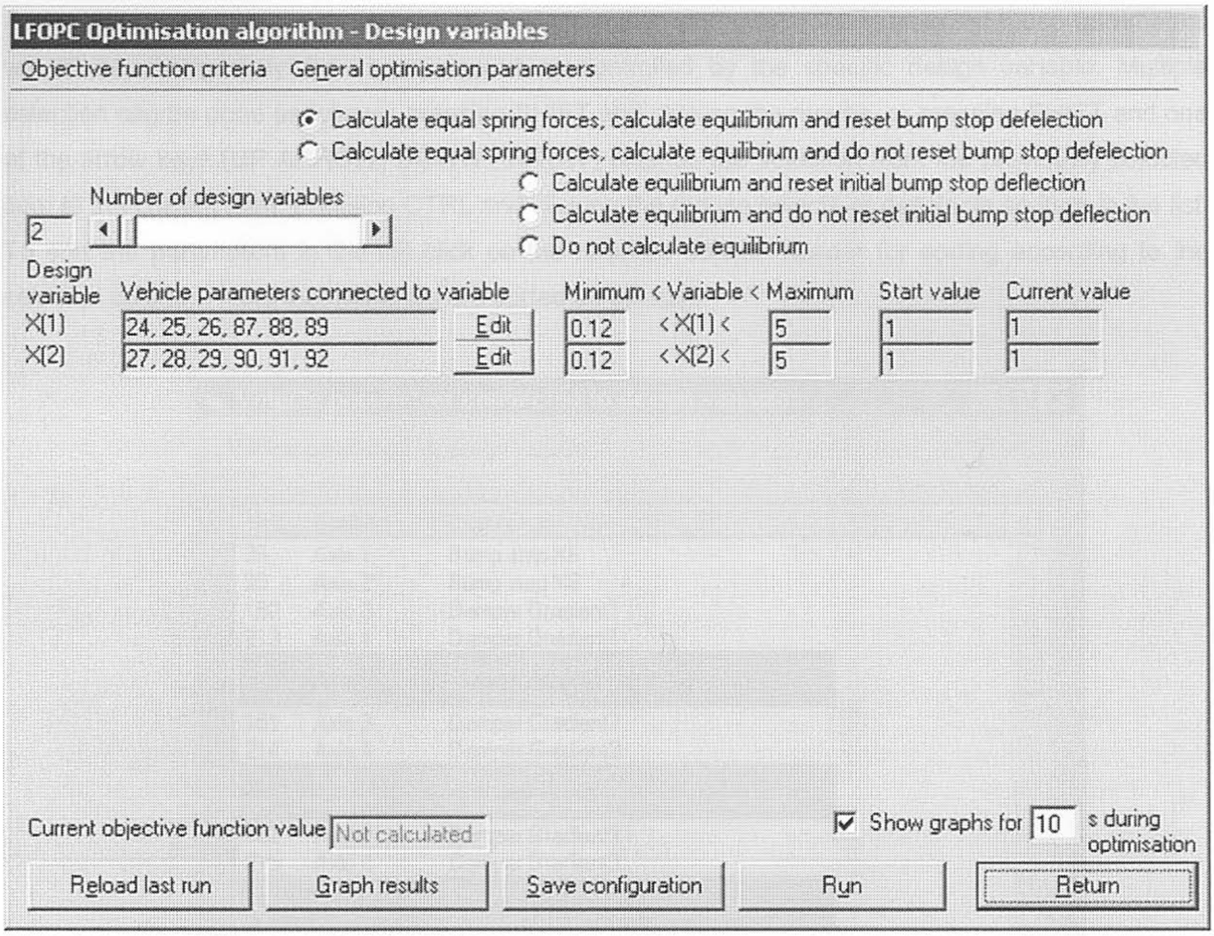
4.1.1 General description

For a more detailed description of the LFOPC algorithm the user is refer to section 2.2 and section A.5 of Appendix A.

Optimisation takes place with reference to a well-defined objective function. The objective function is prescribed by using certain objective criteria, for example the vibration dose values. The purpose of the optimisation is to minimise the objective function through a systematic variation of the design variables. The user specifies the appropriate objective function that must be minimised during the optimisation.

The optimisation starts by computing the objective function value for the starting values of the design variables (the base line values). The next step is to calculate the influence of each design variable on the objective function. This is done by changing each design variable separately by a small specified value, performing the simulation and calculating the new corresponding objective function value. This allows for the computation of an approximation to each component of the gradient vector of the objective function through forward finite differences. This gradient is used by the optimisation algorithm in computing the next set of design variables, which represents a step (iteration) in the direction of the optimum set. This iterative procedure is continued until no further improvement in the objective function is possible and convergence is obtained. The set of design variables at convergence corresponds to the optimum design for the specific objective function. Note that, because of the use of finite differences for computing the gradients, one iteration of the optimisation process corresponds to $n + 1$ simulations, where n is the number of design variables.

4.1.2 LFOPC Main Input



LFOPC Optimisation algorithm - Design variables

Objective function criteria | General optimisation parameters

● Calculate equal spring forces, calculate equilibrium and reset bump stop defelection
○ Calculate equal spring forces, calculate equilibrium and do not reset bump stop defelection
○ Calculate equilibrium and reset initial bump stop deflection
○ Calculate equilibrium and do not reset initial bump stop deflection
○ Do not calculate equilibrium

Number of design variables: 2

Design variable	Vehicle parameters connected to variable		Minimum	< Variable <	Maximum	Start value	Current value
X(1)	24, 25, 26, 87, 88, 89	Edit	0.12	< X(1) <	5	1	1
X(2)	27, 28, 29, 90, 91, 92	Edit	0.12	< X(2) <	5	1	1

Current objective function value: Not calculated

☑ Show graphs for 10 s during optimisation

Figure 4.1: LFOPC Main input

Select the required option for calculation of equilibrium on the options available on the input window (figure 4.1) – see section 3.11 for a detailed description on the options available.

The following input are prescribed on the main LFOPC window:

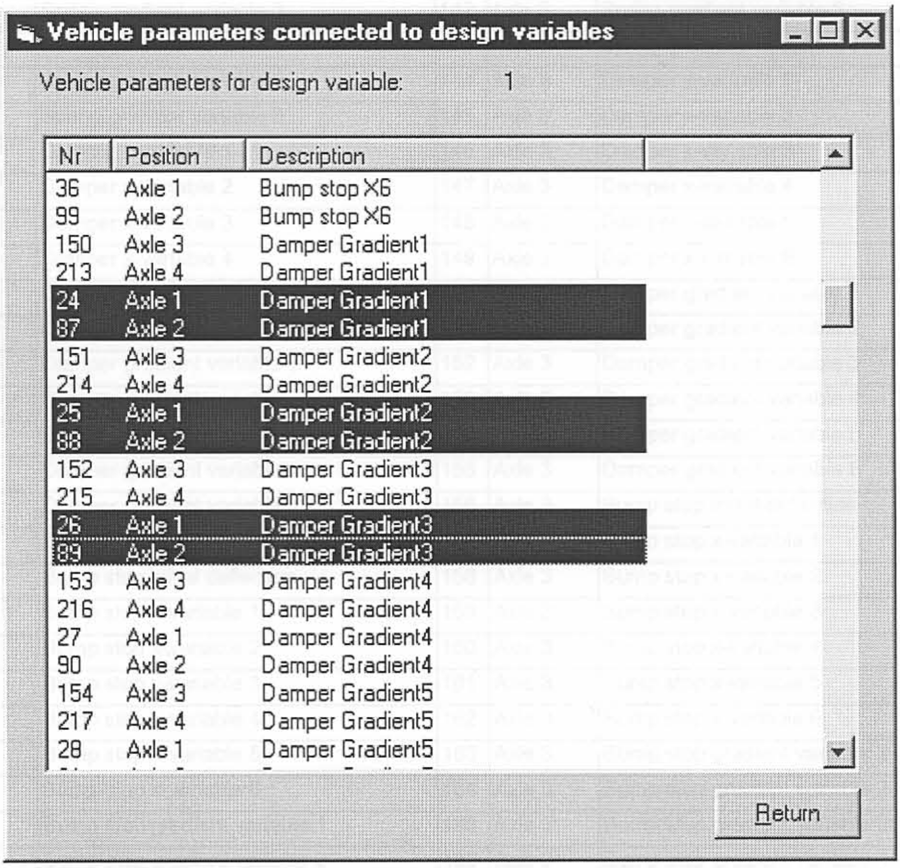
Number of design variables

Prescribe the number of design variables ($X(i)$'s) that will be used by using the scroll bar. Possible values are between 1 and 255.

For each design variable ($X(i)$) supply the following:

Vehicle parameters connected to variable

Use the "Edit" button supplied to select the required parameters from the available list that will be displayed once the "Edit" button is clicked. See figure 4.2 for a description of the vehicle parameters that may be assigned to the design variables shown in figure 4.1. Clicking on the required parameter in the parameter list makes the selection. *More than one vehicle/suspension parameter can be assigned to the same design variable X(i).* If more than one parameter is selected these parameters will all be changed by the same amount as controlled by the specific design variable. Multiple selection can be done as follows: pressing SHIFT and clicking the mouse, or pressing SHIFT and one of the arrow keys (UP ARROW, DOWN ARROW) extends the selection from the previously selected item to the current item. Pressing CTRL and clicking the mouse selects or deselects an item in the list. To sort the parameters in the list click on the required column header for sorting according to the selected column. Note that numbers are sorted as strings.



Vehicle parameters for design variable: 1

Nr	Position	Description
36	Axle 1	Bump stop X6
99	Axle 2	Bump stop X6
150	Axle 3	Damper Gradient1
213	Axle 4	Damper Gradient1
24	Axle 1	Damper Gradient1
87	Axle 2	Damper Gradient1
151	Axle 3	Damper Gradient2
214	Axle 4	Damper Gradient2
25	Axle 1	Damper Gradient2
88	Axle 2	Damper Gradient2
152	Axle 3	Damper Gradient3
215	Axle 4	Damper Gradient3
26	Axle 1	Damper Gradient3
89	Axle 2	Damper Gradient3
153	Axle 3	Damper Gradient4
216	Axle 4	Damper Gradient4
27	Axle 1	Damper Gradient4
90	Axle 2	Damper Gradient4
154	Axle 3	Damper Gradient5
217	Axle 4	Damper Gradient5
28	Axle 1	Damper Gradient5

Figure 4.2: Selection of vehicle parameters

Table 4.1 lists all the possible vehicle / suspension parameters that can be linked to the design variables.

Table 4.1: Vehicle / suspension parameters available for linking to design variables

Nr	Position	Vehicle / suspension parameter	Nr	Position	Vehicle / suspension parameter
1	Vehicle	Mass	129	Axle 2	Tyre damping gradient variable 6
2	Vehicle	Pitch inertia	130	Axle 3	Unsprung mass
3	Vehicle	Position of cg behind front axle centre	131	Axle 3	Distance between axle 2 and axle 3
4	Vehicle	Height of cg above ground	132	Axle 3	Spring x-variable 1
5	Axle 1	Unsprung mass	133	Axle 3	Spring x-variable 2
6	Axle 1	Spring x-variable 1	134	Axle 3	Spring x-variable 3
7	Axle 1	Spring x-variable 2	135	Axle 3	Spring x-variable 4
8	Axle 1	Spring x-variable 3	136	Axle 3	Spring x-variable 5
9	Axle 1	Spring x-variable 4	137	Axle 3	Spring x-variable 6
10	Axle 1	Spring x-variable 5	138	Axle 3	Spring gradient variable 1
11	Axle 1	Spring x-variable 6	139	Axle 3	Spring gradient variable 2
12	Axle 1	Spring gradient variable 1	140	Axle 3	Spring gradient variable 3
13	Axle 1	Spring gradient variable 2	141	Axle 3	Spring gradient variable 4
14	Axle 1	Spring gradient variable 3	142	Axle 3	Spring gradient variable 5
15	Axle 1	Spring gradient variable 4	143	Axle 3	Spring gradient variable 6
16	Axle 1	Spring gradient variable 5	144	Axle 3	Damper x-variable 1
17	Axle 1	Spring gradient variable 6	145	Axle 3	Damper x-variable 2
18	Axle 1	Damper x-variable 1	146	Axle 3	Damper x-variable 3
19	Axle 1	Damper x-variable 2	147	Axle 3	Damper x-variable 4
20	Axle 1	Damper x-variable 3	148	Axle 3	Damper x-variable 5
21	Axle 1	Damper x-variable 4	149	Axle 3	Damper x-variable 6
22	Axle 1	Damper x-variable 5	150	Axle 3	Damper gradient variable 1
23	Axle 1	Damper x-variable 6	151	Axle 3	Damper gradient variable 2
24	Axle 1	Damper gradient variable 1	152	Axle 3	Damper gradient variable 3
25	Axle 1	Damper gradient variable 2	153	Axle 3	Damper gradient variable 4
26	Axle 1	Damper gradient variable 3	154	Axle 3	Damper gradient variable 5
27	Axle 1	Damper gradient variable 4	155	Axle 3	Damper gradient variable 6
28	Axle 1	Damper gradient variable 5	156	Axle 3	Bump stop initial deflection
29	Axle 1	Damper gradient variable 6	157	Axle 3	Bump stop x-variable 1
30	Axle 1	Bump stop initial deflection	158	Axle 3	Bump stop x-variable 2
31	Axle 1	Bump stop x-variable 1	159	Axle 3	Bump stop x-variable 3
32	Axle 1	Bump stop x-variable 2	160	Axle 3	Bump stop x-variable 4
33	Axle 1	Bump stop x-variable 3	161	Axle 3	Bump stop x-variable 5
34	Axle 1	Bump stop x-variable 4	162	Axle 3	Bump stop x-variable 6
35	Axle 1	Bump stop x-variable 5	163	Axle 3	Bump stop gradient variable 1
36	Axle 1	Bump stop x-variable 6	164	Axle 3	Bump stop gradient variable 2
37	Axle 1	Bump stop gradient variable 1	165	Axle 3	Bump stop gradient variable 3
38	Axle 1	Bump stop gradient variable 2	166	Axle 3	Bump stop gradient variable 4
39	Axle 1	Bump stop gradient variable 3	167	Axle 3	Bump stop gradient variable 5
40	Axle 1	Bump stop gradient variable 4	168	Axle 3	Bump stop gradient variable 6
41	Axle 1	Bump stop gradient variable 5	169	Axle 3	Tyre stiffness x-variable 1
42	Axle 1	Bump stop gradient variable 6	170	Axle 3	Tyre stiffness x-variable 2
43	Axle 1	Tyre stiffness x-variable 1	171	Axle 3	Tyre stiffness x-variable 3
44	Axle 1	Tyre stiffness x-variable 2	172	Axle 3	Tyre stiffness x-variable 4
45	Axle 1	Tyre stiffness x-variable 3	173	Axle 3	Tyre stiffness x-variable 5
46	Axle 1	Tyre stiffness x-variable 4	174	Axle 3	Tyre stiffness x-variable 6
47	Axle 1	Tyre stiffness x-variable 5	175	Axle 3	Tyre stiffness gradient variable 1
48	Axle 1	Tyre stiffness x-variable 6	176	Axle 3	Tyre stiffness gradient variable 2

49	Axle 1	Tyre stiffness gradient variable 1	177	Axle 3	Tyre stiffness gradient variable 3
50	Axle 1	Tyre stiffness gradient variable 2	178	Axle 3	Tyre stiffness gradient variable 4
51	Axle 1	Tyre stiffness gradient variable 3	179	Axle 3	Tyre stiffness gradient variable 5
52	Axle 1	Tyre stiffness gradient variable 4	180	Axle 3	Tyre stiffness gradient variable 6
53	Axle 1	Tyre stiffness gradient variable 5	181	Axle 3	Tyre damping x-variable 1
54	Axle 1	Tyre stiffness gradient variable 6	182	Axle 3	Tyre damping x-variable 2
55	Axle 1	Tyre damping x-variable 1	183	Axle 3	Tyre damping x-variable 3
56	Axle 1	Tyre damping x-variable 2	184	Axle 3	Tyre damping x-variable 4
57	Axle 1	Tyre damping x-variable 3	185	Axle 3	Tyre damping x-variable 5
58	Axle 1	Tyre damping x-variable 4	186	Axle 3	Tyre damping x-variable 6
59	Axle 1	Tyre damping x-variable 5	187	Axle 3	Tyre damping gradient variable 1
60	Axle 1	Tyre damping x-variable 6	188	Axle 3	Tyre damping gradient variable 2
61	Axle 1	Tyre damping gradient variable 1	189	Axle 3	Tyre damping gradient variable 3
62	Axle 1	Tyre damping gradient variable 2	190	Axle 3	Tyre damping gradient variable 4
63	Axle 1	Tyre damping gradient variable 3	191	Axle 3	Tyre damping gradient variable 5
64	Axle 1	Tyre damping gradient variable 4	192	Axle 3	Tyre damping gradient variable 6
65	Axle 1	Tyre damping gradient variable 5	193	Axle 4	Unsprung mass
66	Axle 1	Tyre damping gradient variable 6	194	Axle 4	Distance between axle 3 and axle 4
67	Axle 2	Unsprung mass	195	Axle 4	Spring x-variable 1
68	Axle 2	Distance between axle 1 and axle 2	196	Axle 4	Spring x-variable 2
69	Axle 2	Spring x-variable 1	197	Axle 4	Spring x-variable 3
70	Axle 2	Spring x-variable 2	198	Axle 4	Spring x-variable 4
71	Axle 2	Spring x-variable 3	199	Axle 4	Spring x-variable 5
72	Axle 2	Spring x-variable 4	200	Axle 4	Spring x-variable 6
73	Axle 2	Spring x-variable 5	201	Axle 4	Spring gradient variable 1
74	Axle 2	Spring x-variable 6	202	Axle 4	Spring gradient variable 2
75	Axle 2	Spring gradient variable 1	203	Axle 4	Spring gradient variable 3
76	Axle 2	Spring gradient variable 2	204	Axle 4	Spring gradient variable 4
77	Axle 2	Spring gradient variable 3	205	Axle 4	Spring gradient variable 5
78	Axle 2	Spring gradient variable 4	206	Axle 4	Spring gradient variable 6
79	Axle 2	Spring gradient variable 5	207	Axle 4	Damper x-variable 1
80	Axle 2	Spring gradient variable 6	208	Axle 4	Damper x-variable 2
81	Axle 2	Damper x-variable 1	209	Axle 4	Damper x-variable 3
82	Axle 2	Damper x-variable 2	210	Axle 4	Damper x-variable 4
83	Axle 2	Damper x-variable 3	211	Axle 4	Damper x-variable 5
84	Axle 2	Damper x-variable 4	212	Axle 4	Damper x-variable 6
85	Axle 2	Damper x-variable 5	213	Axle 4	Damper gradient variable 1
86	Axle 2	Damper x-variable 6	214	Axle 4	Damper gradient variable 2
87	Axle 2	Damper gradient variable 1	215	Axle 4	Damper gradient variable 3
88	Axle 2	Damper gradient variable 2	216	Axle 4	Damper gradient variable 4
89	Axle 2	Damper gradient variable 3	217	Axle 4	Damper gradient variable 5
90	Axle 2	Damper gradient variable 4	218	Axle 4	Damper gradient variable 6
91	Axle 2	Damper gradient variable 5	219	Axle 4	Bump stop initial deflection
92	Axle 2	Damper gradient variable 6	220	Axle 4	Bump stop x-variable 1
93	Axle 2	Bump stop initial deflection	221	Axle 4	Bump stop x-variable 2
94	Axle 2	Bump stop x-variable 1	222	Axle 4	Bump stop x-variable 3
95	Axle 2	Bump stop x-variable 2	223	Axle 4	Bump stop x-variable 4
96	Axle 2	Bump stop x-variable 3	224	Axle 4	Bump stop x-variable 5
97	Axle 2	Bump stop x-variable 4	225	Axle 4	Bump stop x-variable 6
98	Axle 2	Bump stop x-variable 5	226	Axle 4	Bump stop gradient variable 1
99	Axle 2	Bump stop x-variable 6	227	Axle 4	Bump stop gradient variable 2
100	Axle 2	Bump stop gradient variable 1	228	Axle 4	Bump stop gradient variable 3

101	Axle 2	Bump stop gradient variable 2	229	Axle 4	Bump stop gradient variable 4
102	Axle 2	Bump stop gradient variable 3	230	Axle 4	Bump stop gradient variable 5
103	Axle 2	Bump stop gradient variable 4	231	Axle 4	Bump stop gradient variable 6
104	Axle 2	Bump stop gradient variable 5	232	Axle 4	Tyre stiffness x-variable 1
105	Axle 2	Bump stop gradient variable 6	233	Axle 4	Tyre stiffness x-variable 2
106	Axle 2	Tyre stiffness x-variable 1	234	Axle 4	Tyre stiffness x-variable 3
107	Axle 2	Tyre stiffness x-variable 2	235	Axle 4	Tyre stiffness x-variable 4
108	Axle 2	Tyre stiffness x-variable 3	236	Axle 4	Tyre stiffness x-variable 5
109	Axle 2	Tyre stiffness x-variable 4	237	Axle 4	Tyre stiffness x-variable 6
110	Axle 2	Tyre stiffness x-variable 5	238	Axle 4	Tyre stiffness gradient variable 1
111	Axle 2	Tyre stiffness x-variable 6	239	Axle 4	Tyre stiffness gradient variable 2
112	Axle 2	Tyre stiffness gradient variable 1	240	Axle 4	Tyre stiffness gradient variable 3
113	Axle 2	Tyre stiffness gradient variable 2	241	Axle 4	Tyre stiffness gradient variable 4
114	Axle 2	Tyre stiffness gradient variable 3	242	Axle 4	Tyre stiffness gradient variable 5
115	Axle 2	Tyre stiffness gradient variable 4	243	Axle 4	Tyre stiffness gradient variable 6
116	Axle 2	Tyre stiffness gradient variable 5	244	Axle 4	Tyre damping x-variable 1
117	Axle 2	Tyre stiffness gradient variable 6	245	Axle 4	Tyre damping x-variable 2
118	Axle 2	Tyre damping x-variable 1	246	Axle 4	Tyre damping x-variable 3
119	Axle 2	Tyre damping x-variable 2	247	Axle 4	Tyre damping x-variable 4
120	Axle 2	Tyre damping x-variable 3	248	Axle 4	Tyre damping x-variable 5
121	Axle 2	Tyre damping x-variable 4	249	Axle 4	Tyre damping x-variable 6
122	Axle 2	Tyre damping x-variable 5	250	Axle 4	Tyre damping gradient variable 1
123	Axle 2	Tyre damping x-variable 6	251	Axle 4	Tyre damping gradient variable 2
124	Axle 2	Tyre damping gradient variable 1	252	Axle 4	Tyre damping gradient variable 3
125	Axle 2	Tyre damping gradient variable 2	253	Axle 4	Tyre damping gradient variable 4
126	Axle 2	Tyre damping gradient variable 3	254	Axle 4	Tyre damping gradient variable 5
127	Axle 2	Tyre damping gradient variable 4	255	Axle 4	Tyre damping gradient variable 6
128	Axle 2	Tyre damping gradient variable 5			

Constraints:

Prescribe the **minimum, maximum and starting value** for each design variable *X(i)*. Normally the minimum value should be a small positive number. Negative values for the minimum, maximum and starting value are not allowed. The smallest minimum value must also be larger than *2 times the prescribed Delta X(i)* for numerical differentiation – see section 4.1.4. This last requirement is to enable the calculation of forward differences for the gradient of the objective function and to assure that, for example, a negative spring stiffness does not occur during the simulations.

At the top of the LFOPC main input screen (figure 4.1) two menu items are available:

* “Objective function criteria”: click to edit the selection of the required objective function criteria. See Section 4.1.3 for more detail.
* “General optimisation parameters”: click to edit general optimisation parameters, for example the convergence criteria, step sizes, etc. Section 4.1.4 gives more detail.

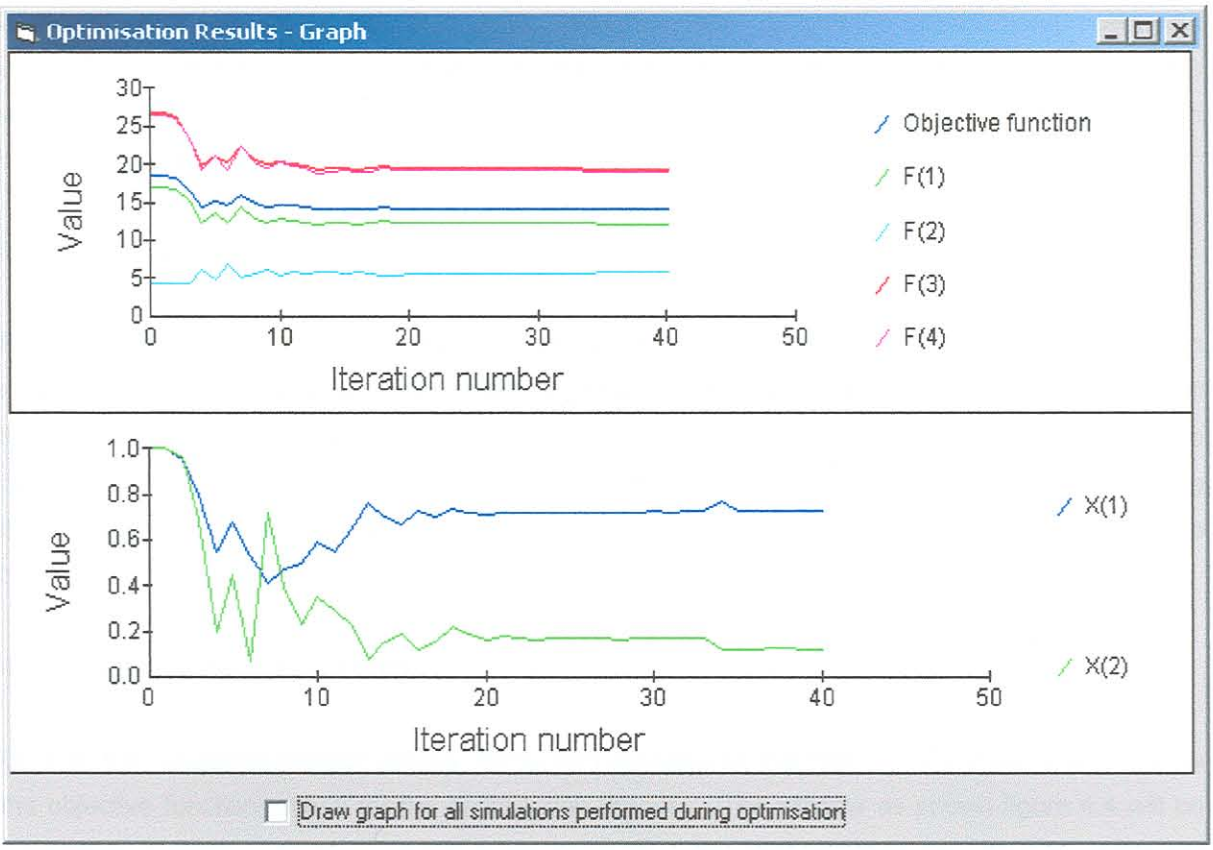
The following buttons are also available on this screen and are used as follows:

Reload last run

This button is used to reload the last optimisation run. This will only load the last values of all the design variables (*X(i)*'s) and can be used if there was an abnormal program abortion or power failure during the optimisation process. This button must be used with care due to the fact that all other optimisation internal parameters are lost and that the whole optimisation process will have to be restarted from new starting values. Do not try to perform optimisations by stopping the optimisation process, reloading the last run and restarting the optimisation. This will lead to unnecessary long optimisations. Once the optimisation process is started try to complete the whole process before stopping the program.

Graph results

Use this button to draw graphs of the last optimisation run. Two graphs will be shown – see figure 4.3 for a typical output. The top graph indicates the convergence history of the objective function value, as well as those for the different objective criteria (*F(i)*'s) used in evaluating the overall objective function value. The bottom graph indicates the convergence histories of all the design variables (*X(i)*'s) during the optimisation process.



☐ Draw graph for all simulations performed during optimisation

Figure 4.3: Graphs of convergence histories of the objective function and design variables during optimisation

The option exists to not only display the values of the functions and variables after each optimisation step (iteration), but also after each simulation (number of design variables + 1 simulation per step) required to compute the finite difference approximation to the gradient of the objective function – see option shown in figure 4.3. Right click on the graphs to start the Graph control dialog to edit the graph titles, printing, etc.

Run

Click the "Run" button to start the optimisation process. This will load the vehicle parameters, change the required vehicle/suspension parameters according to the *X(i)*'s, calculate equilibrium, perform the simulation, run the postprocessor, calculate root mean square, min and max values as well as the vibration dose values. If selected (see figure 4.1) graphs as described above (see figure 4.3) will be shown for a certain time period. The optimisation algorithm analyse the objective function value and if required adjusts the design variables and repeats the process. This loop will continue until a minimum objective function value with associated optimum design variable values (*X(i)*'s), within the prescribed bounds have been obtained.

Once the optimisation process is started all buttons and windows will be unavailable for user input and the process will automatically run through the prescribed loop. To quit the optimisation process wait until the simulation window appears and use the "Stop simulation" button to stop the process. This will end the optimisation process with resulting exit from the program. To restart the program, start the Vehsim2d program and load the required vehicle file.

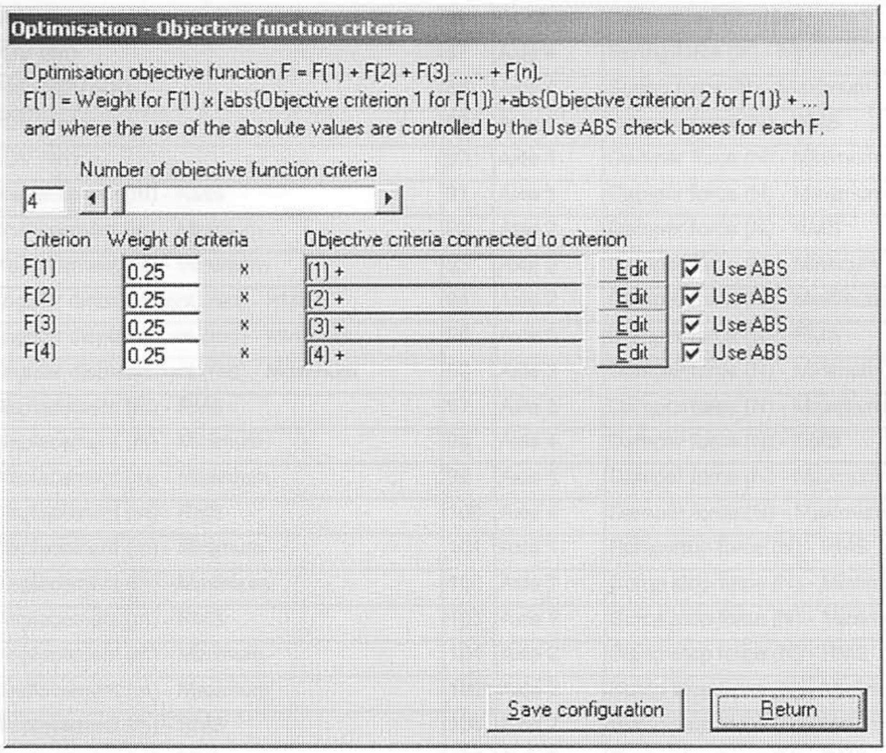
Save configuration – see Section 4.1.5 for more detail.

Return – Click to exit the LFOPC input screen. When exiting the Vehsim2d program from the main screen after an optimisation was performed, do not save the vehicle using the same file name as that for the baseline vehicle that was initially selected for optimisation. The reason is that during the optimisation some of the vehicle or suspension parameters may have been changed, and by saving this under the same file name as for the baseline vehicle may overwrite these characteristics and the baseline data may be lost.

4.1.3 Objective function criteria

Click on the "Objective function criteria" menu item available on the main LFOPC window to prescribe the objective function criteria for the optimisation process. The window as shown figure 4.4 will be displayed.

Select and prescribe the objective function *F* using the input available. The objective function can be linked to a number of objective criteria (*F(i)*'s). A prescribed weight may be assigned to each criterion. Use the scroll bar to select the number of *F(i)*'s. For each *F(i)* select the objective criteria to be used by clicking the "Edit" button which will display a list - see figure 4.5, of all the objective criteria available for each $F(i)$. Select the required criteria, *multiple selection is allowed*. Select the "Use abs" option if the absolute values of the selected objective criteria are to be used.



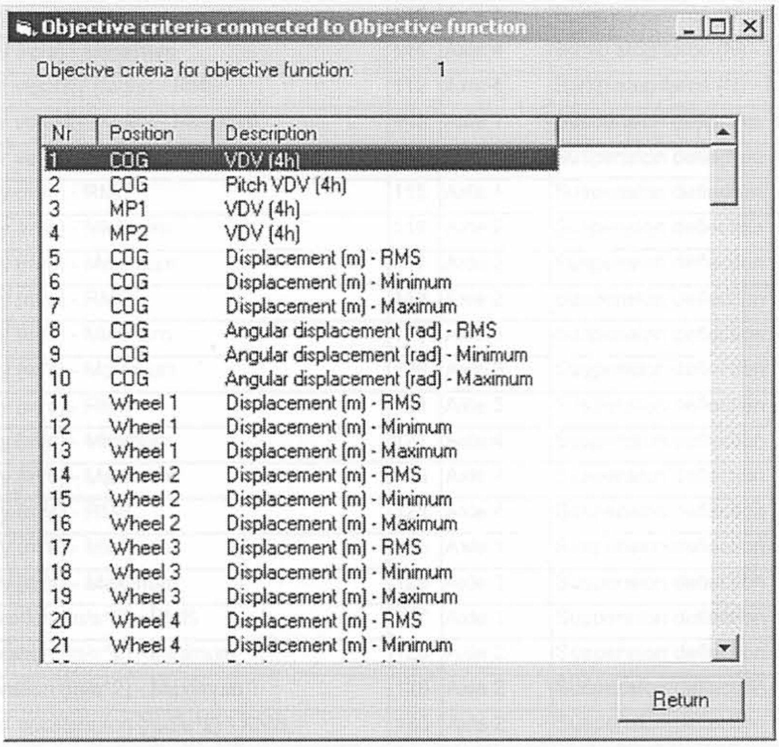
Optimisation - Objective function criteria

Optimisation objective function F = F(1) + F(2) + F(3) ...... + F(n).
F(1) = Weight for F(1) x [abs(Objective criterion 1 for F(1)) +abs(Objective criterion 2 for F(1)) + ...]
and where the use of the absolute values are controlled by the Use ABS check boxes for each F.

Number of objective function criteria: 4

Criterion	Weight of criteria		Objective criteria connected to criterion		
F(1)	0.25	x	[1] +	Edit	☑ Use ABS
F(2)	0.25	x	[2] +	Edit	☑ Use ABS
F(3)	0.25	x	[3] +	Edit	☑ Use ABS
F(4)	0.25	x	[4] +	Edit	☑ Use ABS

Figure 4.4: Objective function input



Objective criteria connected to Objective function

Objective criteria for objective function: 1

Nr	Position	Description
1	COG	VDV (4h)
2	COG	Pitch VDV (4h)
3	MP1	VDV (4h)
4	MP2	VDV (4h)
5	COG	Displacement (m) - RMS
6	COG	Displacement (m) - Minimum
7	COG	Displacement (m) - Maximum
8	COG	Angular displacement (rad) - RMS
9	COG	Angular displacement (rad) - Minimum
10	COG	Angular displacement (rad) - Maximum
11	Wheel 1	Displacement (m) - RMS
12	Wheel 1	Displacement (m) - Minimum
13	Wheel 1	Displacement (m) - Maximum
14	Wheel 2	Displacement (m) - RMS
15	Wheel 2	Displacement (m) - Minimum
16	Wheel 2	Displacement (m) - Maximum
17	Wheel 3	Displacement (m) - RMS
18	Wheel 3	Displacement (m) - Minimum
19	Wheel 3	Displacement (m) - Maximum
20	Wheel 4	Displacement (m) - RMS
21	Wheel 4	Displacement (m) - Minimum

Figure 4.5: Selection of the objective criteria

Table 4.2 lists the possible objective criteria available for linking to the objective function.

Table 4.3: Possible objective criteria available for linking to the objective function.

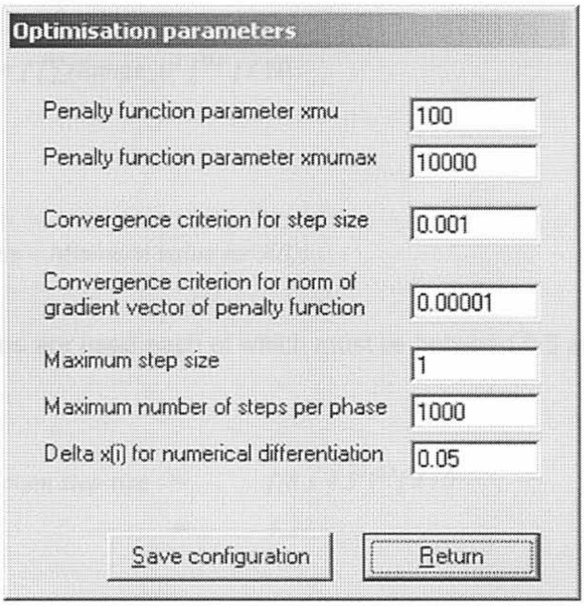
Nr	Position	Objective criterion	Nr	Position	Objective criterion
1	COG	VDV (4h)	87	Axle 4	Spring force (N) - Minimum
2	COG	Pitch VDV (4h)	88	Axle 4	Spring force (N) - Maximum
3	MP1	VDV (4h)	89	Axle 1	Damper force (N) - RMS
4	MP2	VDV (4h)	90	Axle 1	Damper force (N) - Minimum
5	COG	Displacement (m) - RMS	91	Axle 1	Damper force (N) - Maximum
6	COG	Displacement (m) - Minimum	92	Axle 2	Damper force (N) - RMS
7	COG	Displacement (m) - Maximum	93	Axle 2	Damper force (N) - Minimum
8	COG	Angular displacement (rad) - RMS	94	Axle 2	Damper force (N) - Maximum
9	COG	Angular displacement (rad) - Minimum	95	Axle 3	Damper force (N) - RMS
10	COG	Angular displacement (rad) - Maximum	96	Axle 3	Damper force (N) - Minimum
11	Wheel 1	Displacement (m) - RMS	97	Axle 3	Damper force (N) - Maximum
12	Wheel 1	Displacement (m) - Minimum	98	Axle 4	Damper force (N) - RMS
13	Wheel 1	Displacement (m) - Maximum	99	Axle 4	Damper force (N) - Minimum
14	Wheel 2	Displacement (m) - RMS	100	Axle 4	Damper force (N) - Maximum
15	Wheel 2	Displacement (m) - Minimum	101	Axle 1	Bump stop force (N) - RMS
16	Wheel 2	Displacement (m) - Maximum	102	Axle 1	Bump stop force (N) - Minimum
17	Wheel 3	Displacement (m) - RMS	103	Axle 1	Bump stop force (N) - Maximum
18	Wheel 3	Displacement (m) - Minimum	104	Axle 2	Bump stop force (N) - RMS
19	Wheel 3	Displacement (m) - Maximum	105	Axle 2	Bump stop force (N) - Minimum
20	Wheel 4	Displacement (m) - RMS	106	Axle 2	Bump stop force (N) - Maximum
21	Wheel 4	Displacement (m) - Minimum	107	Axle 3	Bump stop force (N) - RMS
22	Wheel 4	Displacement (m) - Maximum	108	Axle 3	Bump stop force (N) - Minimum
23	COG	Velocity (m/s) - RMS	109	Axle 3	Bump stop force (N) - Maximum
24	COG	Velocity (m/s) - Minimum	110	Axle 4	Bump stop force (N) - RMS
25	COG	Velocity (m/s) - Maximum	111	Axle 4	Bump stop force (N) - Minimum
26	COG	Angular velocity (rad/s) - RMS	112	Axle 4	Bump stop force (N) - Maximum
27	COG	Angular velocity (rad/s) - Minimum	113	Axle 1	Suspension deflection (m) - RMS
28	COG	Angular velocity (rad/s) - Maximum	114	Axle 1	Suspension deflection (m) - Minimum
29	Wheel 1	Velocity (m/s) - RMS	115	Axle 1	Suspension deflection (m) - Maximum
30	Wheel 1	Velocity (m/s) - Minimum	116	Axle 2	Suspension deflection (m) - RMS
31	Wheel 1	Velocity (m/s) - Maximum	117	Axle 2	Suspension deflection (m) - Minimum
32	Wheel 2	Velocity (m/s) - RMS	118	Axle 2	Suspension deflection (m) - Maximum
33	Wheel 2	Velocity (m/s) - Minimum	119	Axle 3	Suspension deflection (m) - RMS
34	Wheel 2	Velocity (m/s) - Maximum	120	Axle 3	Suspension deflection (m) - Minimum
35	Wheel 3	Velocity (m/s) - RMS	121	Axle 3	Suspension deflection (m) - Maximum
36	Wheel 3	Velocity (m/s) - Minimum	122	Axle 4	Suspension deflection (m) - RMS
37	Wheel 3	Velocity (m/s) - Maximum	123	Axle 4	Suspension deflection (m) - Minimum
38	Wheel 4	Velocity (m/s) - RMS	124	Axle 4	Suspension deflection (m) - Maximum
39	Wheel 4	Velocity (m/s) - Minimum	125	Axle 1	Suspension deflection rate (m/s) - RMS
40	Wheel 4	Velocity (m/s) - Maximum	126	Axle 1	Suspension deflection rate (m/s) - Minimum
41	COG	Acceleration (m/s^2) - RMS	127	Axle 1	Suspension deflection rate (m/s) - Maximum
42	COG	Acceleration (m/s^2) - Minimum	128	Axle 2	Suspension deflection rate (m/s) - RMS
43	COG	Acceleration (m/s^2) - Maximum	129	Axle 2	Suspension deflection rate (m/s) - Minimum
44	COG	Angular acceleration (rad/s^2) - RMS	130	Axle 2	Suspension deflection rate (m/s) - Maximum
45	COG	Angular acceleration (rad/s^2) - Minimum	131	Axle 3	Suspension deflection rate (m/s) - RMS
46	COG	Angular acceleration (rad/s^2) - Maximum	132	Axle 3	Suspension deflection rate (m/s) - Minimum

47	Wheel 1	Acceleration (m/s^2) - RMS	133	Axle 3	Suspension deflection rate (m/s) - Maximum
48	Wheel 1	Acceleration (m/s^2) - Minimum	134	Axle 4	Suspension deflection rate (m/s) - RMS
49	Wheel 1	Acceleration (m/s^2) - Maximum	135	Axle 4	Suspension deflection rate (m/s) - Minimum
50	Wheel 2	Acceleration (m/s^2) - RMS	136	Axle 4	Suspension deflection rate (m/s) - Maximum
51	Wheel 2	Acceleration (m/s^2) - Minimum	137	Wheel 1	Tyre deflection (m) - RMS
52	Wheel 2	Acceleration (m/s^2) - Maximum	138	Wheel 1	Tyre deflection (m) - Minimum
53	Wheel 3	Acceleration (m/s^2) - RMS	139	Wheel 1	Tyre deflection (m) - Maximum
54	Wheel 3	Acceleration (m/s^2) - Minimum	140	Wheel 2	Tyre deflection (m) - RMS
55	Wheel 3	Acceleration (m/s^2) - Maximum	141	Wheel 2	Tyre deflection (m) - Minimum
56	Wheel 4	Acceleration (m/s^2) - RMS	142	Wheel 2	Tyre deflection (m) - Maximum
57	Wheel 4	Acceleration (m/s^2) - Minimum	143	Wheel 3	Tyre deflection (m) - RMS
58	Wheel 4	Acceleration (m/s^2) - Maximum	144	Wheel 3	Tyre deflection (m) - Minimum
59	MP1	Displacement (m) - RMS	145	Wheel 3	Tyre deflection (m) - Maximum
60	MP1	Displacement (m) - Minimum	146	Wheel 4	Tyre deflection (m) - RMS
61	MP1	Displacement (m) - Maximum	147	Wheel 4	Tyre deflection (m) - Minimum
62	MP2	Displacement (m) - RMS	148	Wheel 4	Tyre deflection (m) - Maximum
63	MP2	Displacement (m) - Minimum	149	Wheel 1	Tyre deflection rate (m/s) - RMS
64	MP2	Displacement (m) - Maximum	150	Wheel 1	Tyre deflection rate (m/s) - Minimum
65	MP1	Velocity (m/s) - RMS	151	Wheel 1	Tyre deflection rate (m/s) - Maximum
66	MP1	Velocity (m/s) - Minimum	152	Wheel 2	Tyre deflection rate (m/s) - RMS
67	MP1	Velocity (m/s) - Maximum	153	Wheel 2	Tyre deflection rate (m/s) - Minimum
68	MP2	Velocity (m/s) - RMS	154	Wheel 2	Tyre deflection rate (m/s) - Maximum
69	MP2	Velocity (m/s) - Minimum	155	Wheel 3	Tyre deflection rate (m/s) - RMS
70	MP2	Velocity (m/s) - Maximum	156	Wheel 3	Tyre deflection rate (m/s) - Minimum
71	MP1	Acceleration (m/s^2) - RMS	157	Wheel 3	Tyre deflection rate (m/s) - Maximum
72	MP1	Acceleration (m/s^2) - Minimum	158	Wheel 4	Tyre deflection rate (m/s) - RMS
73	MP1	Acceleration (m/s^2) - Maximum	159	Wheel 4	Tyre deflection rate (m/s) - Minimum
74	MP2	Acceleration (m/s^2) - RMS	160	Wheel 4	Tyre deflection rate (m/s) - Maximum
75	MP2	Acceleration (m/s^2) - Minimum	161	Wheel 1	Wheel force (N) - RMS
76	MP2	Acceleration (m/s^2) - Maximum	162	Wheel 1	Wheel force (N) - Minimum
77	Axle 1	Spring force (N) - RMS	163	Wheel 1	Wheel force (N) - Maximum
78	Axle 1	Spring force (N) - Minimum	164	Wheel 2	Wheel force (N) - RMS
79	Axle 1	Spring force (N) - Maximum	165	Wheel 2	Wheel force (N) - Minimum
80	Axle 2	Spring force (N) - RMS	166	Wheel 2	Wheel force (N) - Maximum
81	Axle 2	Spring force (N) - Minimum	167	Wheel 3	Wheel force (N) - RMS
82	Axle 2	Spring force (N) - Maximum	168	Wheel 3	Wheel force (N) - Minimum
83	Axle 3	Spring force (N) - RMS	169	Wheel 3	Wheel force (N) - Maximum
84	Axle 3	Spring force (N) - Minimum	170	Wheel 4	Wheel force (N) - RMS
85	Axle 3	Spring force (N) - Maximum	171	Wheel 4	Wheel force (N) - Minimum
86	Axle 4	Spring force (N) - RMS	172	Wheel 4	Wheel force (N) - Maximum

Prescribing an appropriate optimisation objective function is a very important step in the optimisation process and much thought should be given in selecting the correct criteria and weight.

4.1.4 General optimisation parameters

This menu item will display an input window for input of general optimisation parameters, as shown in figure 4.6, used during the optimisation process. Normally the default values should be sufficient but the user can explicitly change the setting should the user have other requirements.



Penalty function parameter xmu: 100
Penalty function parameter xmumax: 10000
Convergence criterion for step size: 0.001
Convergence criterion for norm of gradient vector of penalty function: 0.00001
Maximum step size: 1
Maximum number of steps per phase: 1000
Delta x(i) for numerical differentiation: 0.05

Figure 4.6: General optimising parameters

The following parameters inherent to the optimisation algorithm LFOPC may be changed:

- For higher accuracy, at the expense of economy, the value of the penalty function parameter *xmumax* may be increased. On the other hand, for greater economy at the expense of accuracy, both *xmumax* and *xmu* may be lowered in the same proportion. This may be necessary if the objective function is relatively "flat".
- The optimisation is terminated when either of the convergence criteria becomes active, that is when:

  Step size = The norm of the change of the design variables vector < Convergence criterion for step size.

  or

  The norm of the gradient of the penalty function < Convergence criterion for the norm of the gradient of penalty function.

- For simulations with a low number of design variables the value for the Convergence criterion for step size may be decreased, e.g. 10^{-5}. For a high number of optimising variables the value may be increased e.g. 10^{-3}. The smaller this value is the more accurate the final result will be, but at the expense of a larger number of simulations being performed. Too large values for the convergence tolerances may lead to premature termination of the optimisation process.
- The maximum step size must be of the same order of magnitude as the "diameter of the region of interest", i.e.

$$\text{Maximum step size} = \{\,[\textstyle\sum(Range\_i)^2\,]^{0.5}\,\}\,/\,10$$

where:

$$Range\_i = (\text{Maximum} - \text{Minimum value for } X(i))$$

e.g. if 8 design variables are used each of which must lie between 0.5 and 5 then:

$$Range\ i = 4.5$$

$$\text{Recommended maximum step size} \quad = \quad [(8 \times 4.5^2)^{0.5}]\,/\,10$$

$$= \quad 1.27$$

- * Maximum number of steps per phase may be increased if the optimum values have not been determined within the prescribed number of iterations.
- * The delta $X(i)$ for numerical differentiation is the value with which each design variable ($X(i)$) is to be increased in turn to determine the influence of the specific $X(i)$ on the objective function, i.e., to determine the *i-th* component of the gradient vector. A typically large value of 0.05 is used if numerical noise is expected to be relatively dominant. In such a case the delta $X(i)$ should be larger than the wavelength of the noise. If, however, the $X(i)$'s have a strong influence on the value of the objective function and the effect on the objective function of numerical noise is negligible or small, then the value of delta $X(i)$ may be decreased to give more accurate derivatives.

Arbitrary changes to the optimisation parameter values are not recommended as such changes may require a more in-depth knowledge of the optimisation algorithm.

4.1.5 Saving configurations

On each of the input screens click the "Save configuration" button to save the input to the files. No selection of file names are allowed and the following files are used for saving the configurations:

LFOPC.DAT – Input for the main LFOPC window, i.e. selection of design variables, etc.
LFOPC_FUN.DAT – Input for the objective function criteria
LFOPC_PAR.DAT – Input for general optimisation parameters

These files are saved in the application directory (i.e. the directory in which the Vehsim2d.exe file is located). Each time the "Save configuration" buttons are used or the LFOPC main window is exited, these configuration files are overwritten with the latest selected values. Backup copies of these files can be used for later reference or to save specific configurations.

4.1.6 Optimisation output

During the optimisation process the following output is created:

LFOPC.OUT

This ASCII file is a summary if the output of the simulation process. Use a program for instance Notepad to view the contents of the file. Typical contents of this file are as shown below:

```
START OF PHASE : 0
STEP = 0.    GRADIENT NORM = 4.921E+00
OBJECTIVE FUNCTION VALUE : F =  18.60096
X-values:
 1       1
STEP = 1.    GRADIENT NORM = 5.335E+00
X-values:
 0.9487166    0.9140347
STEP = 2.    GRADIENT NORM = 5.571E+00
X-values:
 0.795211    0.6356146
STEP = 3.    GRADIENT NORM = 3.490E+00
X-values:
 0.5509056    0.1464902
|
|
STEP = 35.    GRADIENT NORM = 3.022E-03
OBJECTIVE FUNCTION VALUE : F =  14.22362
FINAL X-VALUES FOR CURRENT PHASE FOLLOW
X-values:
 0.6646426    0.196326

START OF PHASE :  1
STEP = 35.    GRADIENT NORM = 3.759E+00
OBJECTIVE FUNCTION VALUE : F =  14.22362
X-values:
 0.6646426    0.196326
STEP = 36.    GRADIENT NORM = 2.795E+00
X-values:
 0.6646426    0.2014112
|
|
STEP = 62.    GRADIENT NORM = 3.783E+00
OBJECTIVE FUNCTION VALUE : F =  14.23207
FINAL X-VALUES FOR CURRENT PHASE FOLLOW
X-values:
 0.6637446    0.1998436

START OF PHASE :  2
STEP = 62.    GRADIENT NORM = 1.183E+01
```

```
OBJECTIVE FUNCTION VALUE : F =  14.23207
X-values:
 0.6637446    0.1998436
STEP = 63.   GRADIENT NORM = 6.629E+01
X-values:
 0.6637446    0.2008745
|
|
STEP = 77.   GRADIENT NORM = 4.623E+01
OBJECTIVE FUNCTION VALUE : F =  14.23098
FINAL X-VALUES FOR CURRENT PHASE FOLLOW
X-values:
 0.6637446    0.1993886
FINAL INEQUALITY CONSTRAINTS FUNCTION VALUES:
C( 1 )= -4.336256
C( 2 )= -0.4637446
C( 3 )= -4.800611
C( 4 )=  6.114393E-04
```

The optimisation process is performed in three phases (See section A.5 of Appendix A). During phase 0 the optimisation is performed with a moderate penalty parameter (xmu) for violation of the specified minimum or maximum design variable bounds (constraints). Each step involves the calculation of the gradient and a new set of *X(i)* values, i.e. for each step the simulation is performed *(Number of design variables + 1)* times. Once the convergence criteria are satisfied the final values of the *X(i)*'s are printed as well as the final objective function value for phase 0. If at the end of phase 0 any of the constraints are violated the process continues to phase 1 where a more severe penalty parameter (xmumax) is applied. At the end of phase 1 the active constraints are actually identified and in phase 2 a final trajectory is followed from the solution point of phase 1 to the nearest point in the subspace of points satisfying the active constraints.

LFOPC.GRF

This is a detail output ASCII file for each simulation during the process. A typical example of such a file is shown underneath:

```
18.60096
 4
 0.25      16.9257      0.25      4.354053      0.25      26.65999      0.25      26.46409
 2
 1         1
18.72701
 4
 0.25      17.05221     0.25      4.342792      0.25      26.84885      0.25      26.6642
 2
 1.05      1
18.81226
 4
```

```
0.25    17.1101     0.25    4.397651    0.25    26.98139    0.25    26.75989
2
1.05    1
|
|
4
0.25    12.5919     0.25    5.419183    0.25    19.84062    0.25    19.62821
2
0.6637446    0.2493886
14.23098
4
0.25    12.35225    0.25    5.646798    0.25    19.61322    0.25    19.31164
2
0.6637446    0.1993886
```

The format for this file is:

Objective function value F
Number of F(i)'s
Weight for F(1)   Value for F(1)   Weight for F(2)   Value for F(2) ……
Number of X(i)'s
Value for X(1)   Value for X(2) .....

The above values are written for each simulation performed during the optimisation process including those required for the finite difference calculations.

This is the file used for graphing the optimisation results but can also be used to obtain more detail regarding the progress of the optimisation process.

Optimise_vehicle.veh

Each time the vehicle/suspension simulation parameters are changed through their coupling to the design variables, a vehicle file optimise_vehicle.veh is written. This file can be used to perform simulations with the optimised vehicle or to inspect the characteristics of the suspension and vehicle once the optimisation process is completed. Open this file as for any other vehicle file under vehsim2d.exe.

4.1.7 General optimisation considerations

Computational effort during optimisation can be excessive. Due to this fact the following should be kept in mind during the planning of the operation strategy and the selection of optimisation settings:

* Keep the number of design variables as small as possible. If possible couple more than one parameter to the same design variable. For instance if the vehicle uses the same dampers on the front and rear axles, then link them to the same design variables.
* Use the appropriate tyre model for the type of route profile being considered. Using the sector model on relative smooth surfaces will increase the computational time without improving simulation accuracy.
* When optimising the x-values (see figure 3.8) for springs, dampers, etc., consider the fact that the array of x-values for the component must remain in the sequence from small to large after adjustment of the design variables. For example if the first x-value for the damper is –5 m/s and the second value –1 m/s and the minimum and maximum value for the design variables are 0.2 and 2 then a situation may exist where the first x-value becomes –1 m/s and the second value –2 m/s. This is not allowed and will lead to inaccurate simulation results and may even cause abortion of the program. The required sequence is not enforced in the program and it is up to the user to ensure that the constraints are specified correctly.
* Ensure that the simulation time is long enough so that the complete required route profile (which will normally end with a flat road surface) is covered, and that the vehicle movement is damped out before the simulation end time, i.e. the accelerations used for calculating the VDV must all start at a value of 0 and end at a value of 0. This must be true for all the spring and damper characteristics that may be used during the optimisation process. This will improve the accuracy of the vibration dose values calculated, as no windowing is performed during the fast Fourier transform calculations during which the acceleration signals are weighed according to the required weighting functions. If the accelerations do not start and end at the same value it will lead to inaccuracy in calculating the Fast Fourier transform of the signals.
* Keep the specified minimum and maximum bounds within reasonable and practically possible limits.
* Use the correct and appropriate equilibrium calculation option – see section 3.11 for more details.
* Only one instance of the optimisation process or Vehsim2d.exe may be executed at a particular time. For example, under the Windows operating system which will allow multiple instances of the program to run, only one of the instances may be executed at a particular time. This is required to ensure that no file sharing violations occur and because multiple instances may read or write to the same file.
* The biggest problem that remains with this type of local optimisation process is the problem of finding a local minimum rather than the global minimum when starting from a given starting point. This situation is depicted for starting point 1, for the one-dimensional case in figure 4.7. One way of making sure that the lowest minimum obtained is likely to be the global minimum is to repeat

the optimisation, but starting from another starting point in the variable range, i.e., also starting from point 2. In extreme circumstances multiple starting points may be used in order to increase the probability of obtaining the global optimum.

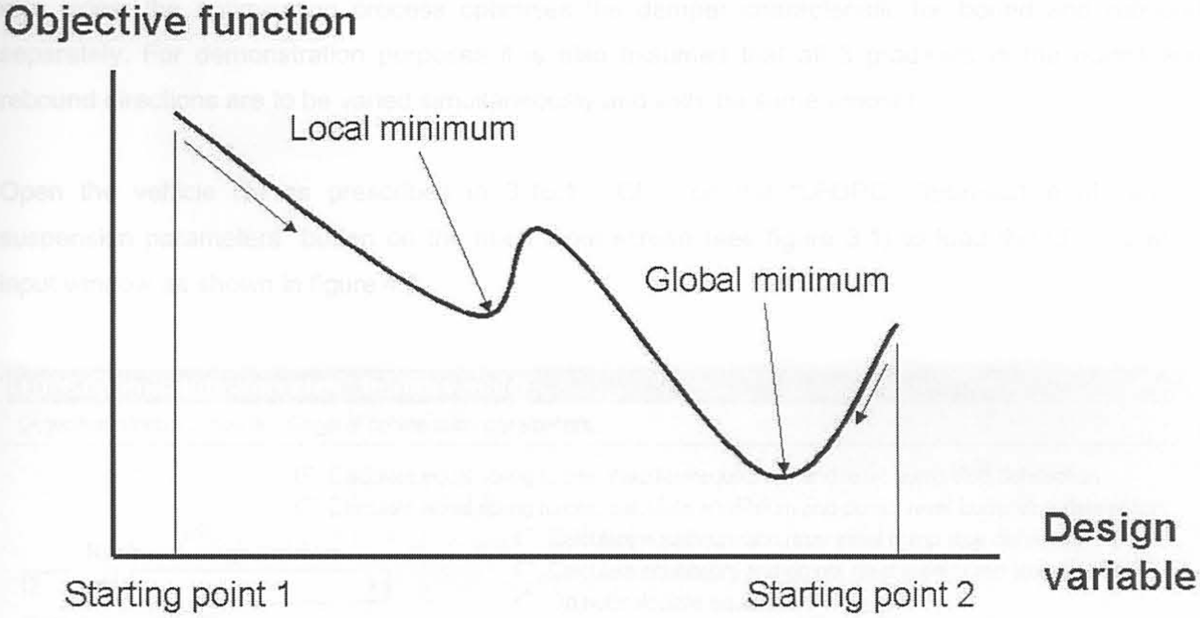
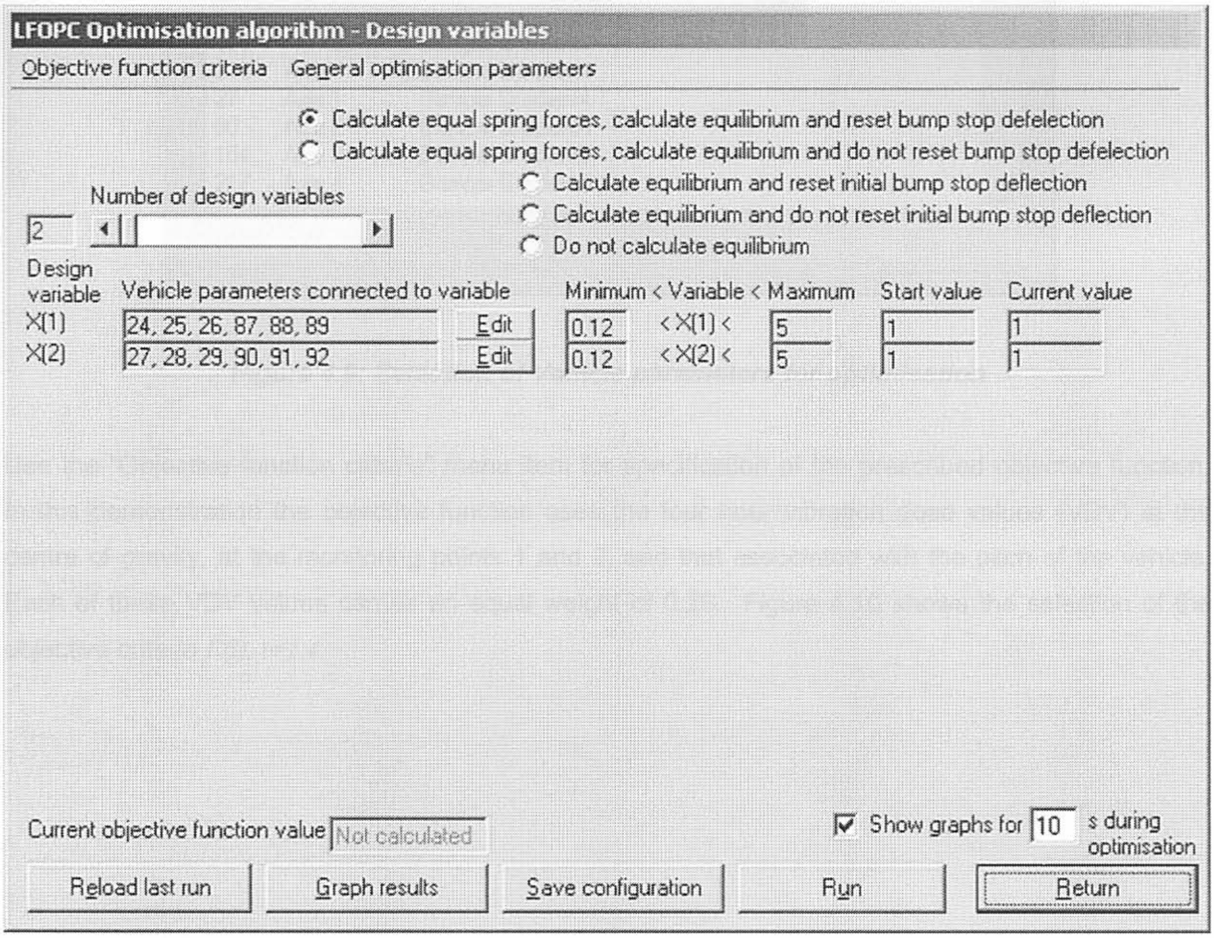


Figure 4.7: Schematic illustration of local and global minima

4.2 Optimisation example

The optimisation example described is that for the demo vehicle (see section 3.16) over a Belgian paving route profile at 30 km/h. Assuming that the same dampers are to be used on the front and rear axles, the optimisation process optimises the damper characteristic for bound and rebound separately. For demonstration purposes it is also assumed that all 3 gradients in the bound and rebound directions are to be varied simultaneously and with the same amount.

Open the vehicle file as prescribed in 3.16.1. Click on the "LFOPC: Optimisation of vehicle/ suspension parameters" button on the main input screen (see figure 3.1) to load the LFOPC Main input window as shown in figure 4.8.



● Calculate equal spring forces, calculate equilibrium and reset bump stop defelection
○ Calculate equal spring forces, calculate equilibrium and do not reset bump stop defelection
○ Calculate equilibrium and reset initial bump stop deflection
○ Calculate equilibrium and do not reset initial bump stop deflection
○ Do not calculate equilibrium

Number of design variables: 2

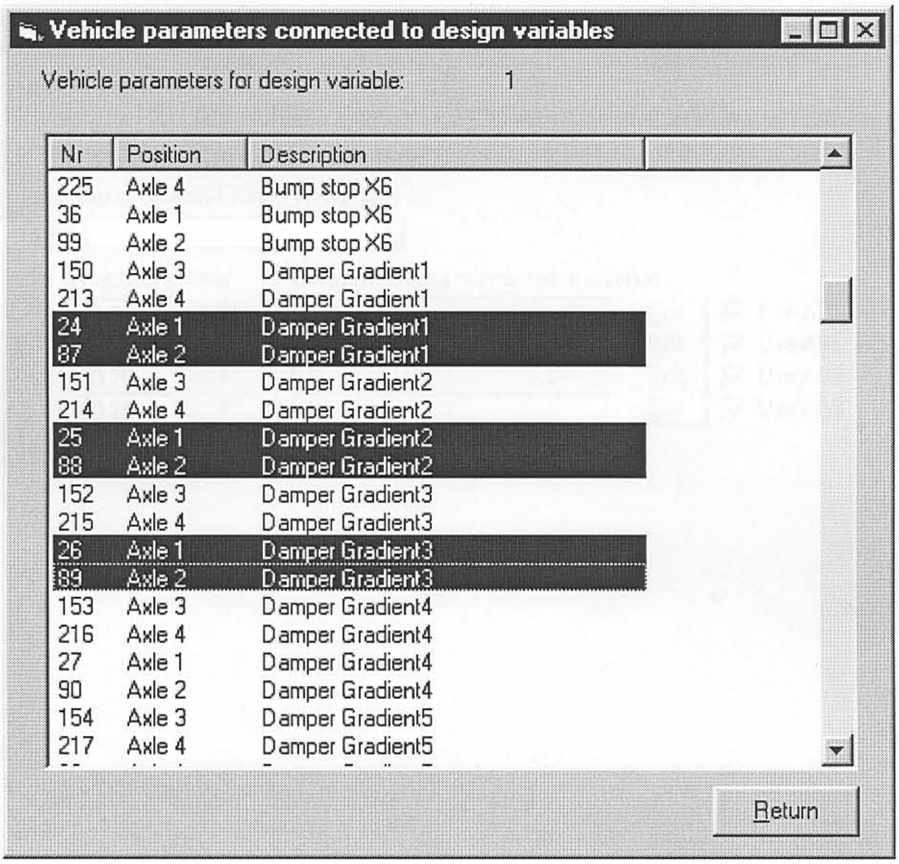
Design variable	Vehicle parameters connected to variable		Minimum	< Variable <	Maximum	Start value	Current value
X(1)	24, 25, 26, 87, 88, 89	Edit	0.12	< X(1) <	5	1	1
X(2)	27, 28, 29, 90, 91, 92	Edit	0.12	< X(2) <	5	1	1

Current objective function value: Not calculated

☑ Show graphs for 10 s during optimisation

Figure 4.8: Optimisation input

In this example it is assumed that the design variables can lie between 0.12 and 5 (i.e. the characteristics linked to the design variable can change between 12% and 500% of that for the baseline vehicle) and will start from 1 (i.e. the baseline). Check the prescribed input for the design parameters by clicking on the "Edit" button. For example, the design parameters linked to variable *X(1)* are as shown in figure 4.9.

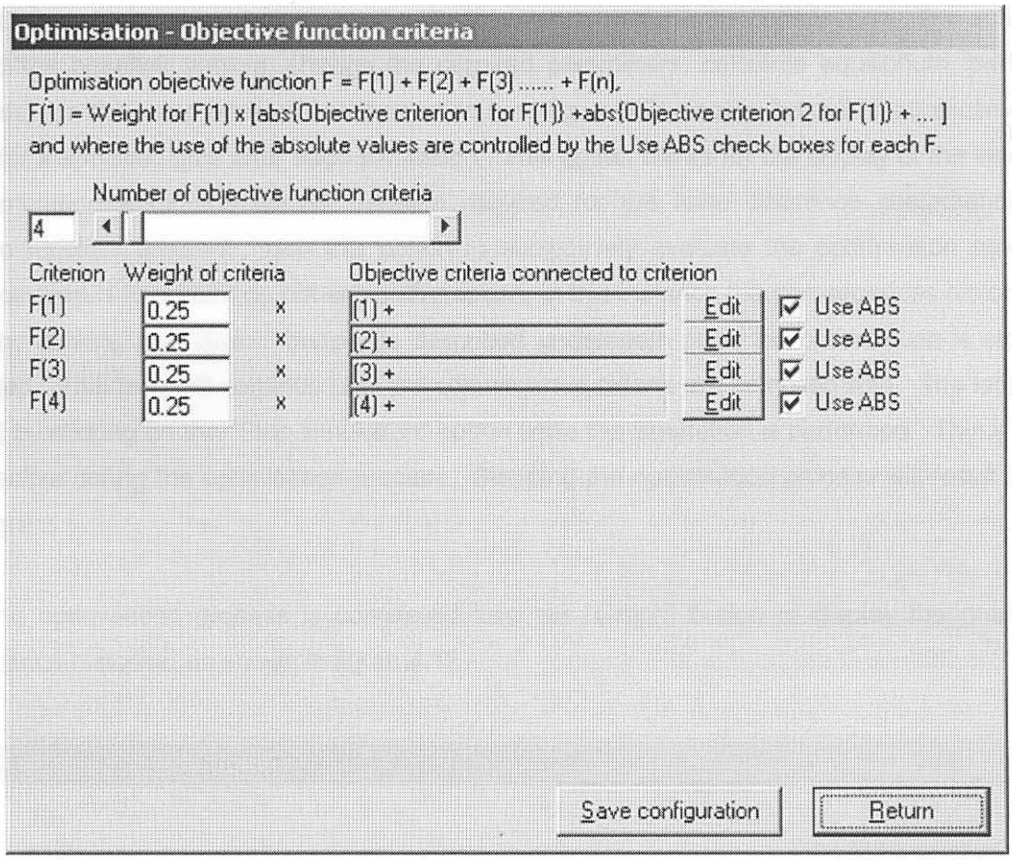


Vehicle parameters for design variable: 1

Nr	Position	Description
225	Axle 4	Bump stop X6
36	Axle 1	Bump stop X6
99	Axle 2	Bump stop X6
150	Axle 3	Damper Gradient1
213	Axle 4	Damper Gradient1
24	Axle 1	Damper Gradient1
87	Axle 2	Damper Gradient1
151	Axle 3	Damper Gradient2
214	Axle 4	Damper Gradient2
25	Axle 1	Damper Gradient2
88	Axle 2	Damper Gradient2
152	Axle 3	Damper Gradient3
215	Axle 4	Damper Gradient3
26	Axle 1	Damper Gradient3
89	Axle 2	Damper Gradient3
153	Axle 3	Damper Gradient4
216	Axle 4	Damper Gradient4
27	Axle 1	Damper Gradient4
90	Axle 2	Damper Gradient4
154	Axle 3	Damper Gradient5
217	Axle 4	Damper Gradient5

Figure 4.9: Selection of Vehicle parameters for optimisation

Use the "Objective function criteria" menu item for specification of the prescribed objective function. In this demonstration the objective function uses the four hour vibration dose values (VDV) at the centre of gravity, at the monitoring points 1 and 2, and that associated with the pitch of the vehicle. Each of these VDV values carries an equal weight of 0.25. Figure 4.10 shows the selection of the objective criteria $F(i),\ i=1,4$.



Optimisation - Objective function criteria

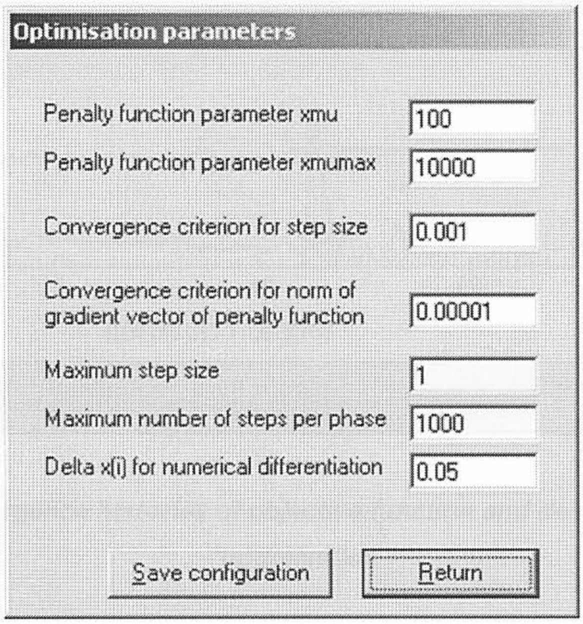
Optimisation objective function F = F(1) + F(2) + F(3) ...... + F(n),
F(1) = Weight for F(1) x [abs{Objective criterion 1 for F(1)} +abs{Objective criterion 2 for F(1)} + ...]
and where the use of the absolute values are controlled by the Use ABS check boxes for each F.

Number of objective function criteria: 4

Criterion	Weight of criteria		Objective criteria connected to criterion		
F(1)	0.25	x	[1] +	Edit	☑ Use ABS
F(2)	0.25	x	[2] +	Edit	☑ Use ABS
F(3)	0.25	x	[3] +	Edit	☑ Use ABS
F(4)	0.25	x	[4] +	Edit	☑ Use ABS

Figure 4.10: Objective function input

The general optimisation parameters are prescribed by using the "General optimisation parameters" menu item on the LFOPC Main input window. The general parameters selected here are as shown in figure 4.11.



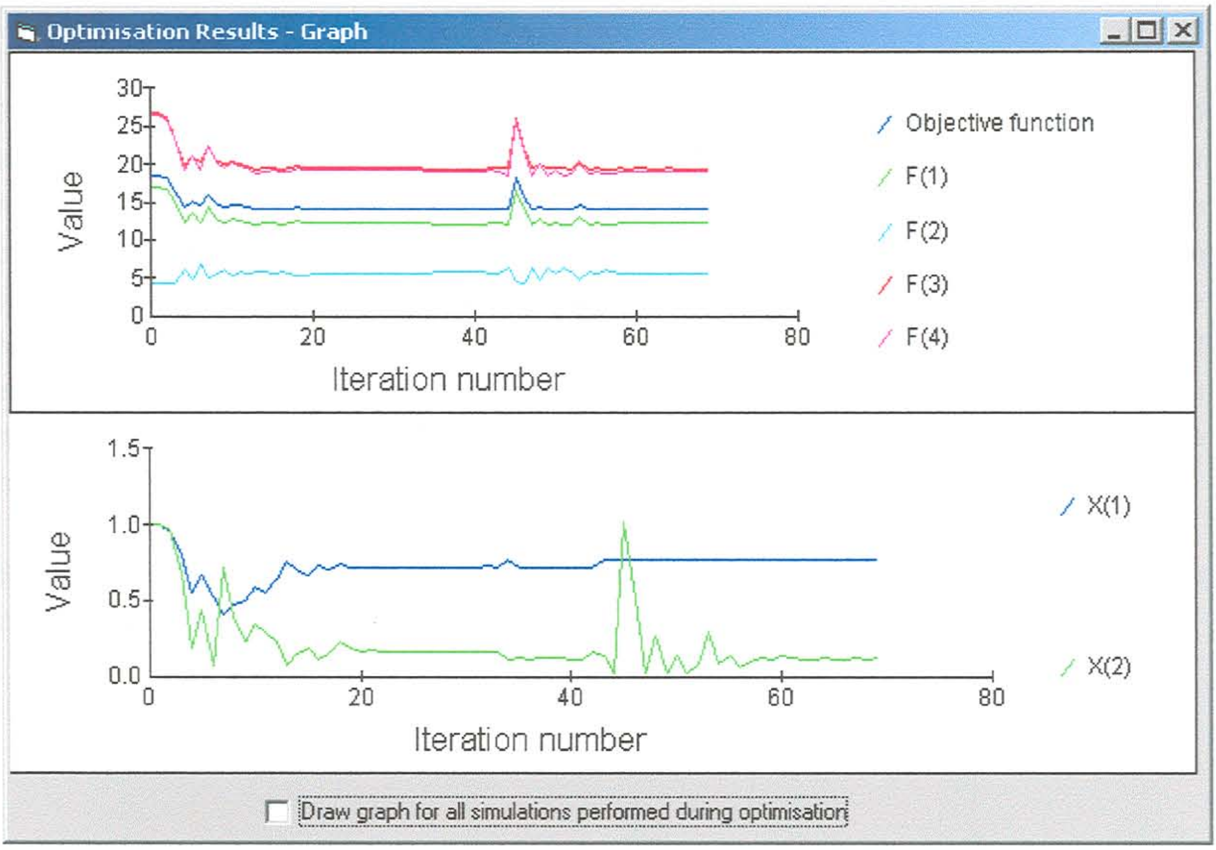
Optimisation parameters

Penalty function parameter xmu	100
Penalty function parameter xmumax	10000
Convergence criterion for step size	0.001
Convergence criterion for norm of gradient vector of penalty function	0.00001
Maximum step size	1
Maximum number of steps per phase	1000
Delta x(i) for numerical differentiation	0.05

Figure 4.11: General parameters for optimisation algorithm

On the LFOPC Main input window use the "Run" button to perform the optimisation. The optimisation will load the baseline vehicle, change the required parameters, calculate equilibrium, perform the simulation, run the postprocessor and if selected (see figure 4.8) display the optimisation convergence graphs for a specified time after each simulation. This option allows for the display of the values after each simulation within the current iteration required for the finite difference computation of the objective function gradient. Use this option to subjectively evaluate the optimisation process. If simulation time is important do not select this option, in this instance the convergences history can be shown by clicking the "Graph" button as described underneath once the optimisation is stopped or completed. This loop will continue until the convergence criteria are complied with. The loop can be stopped by clicking on the "Stop simulation" button while the simulation is performed. This is the only button active during the optimisation process. Stopping the optimisation process will result in exiting the program.

Once the optimisation process is completed, use the "Graph" button to display the graph of the convergence histories, as shown in figure 4.12.



☐ Draw graph for all simulations performed during optimisation

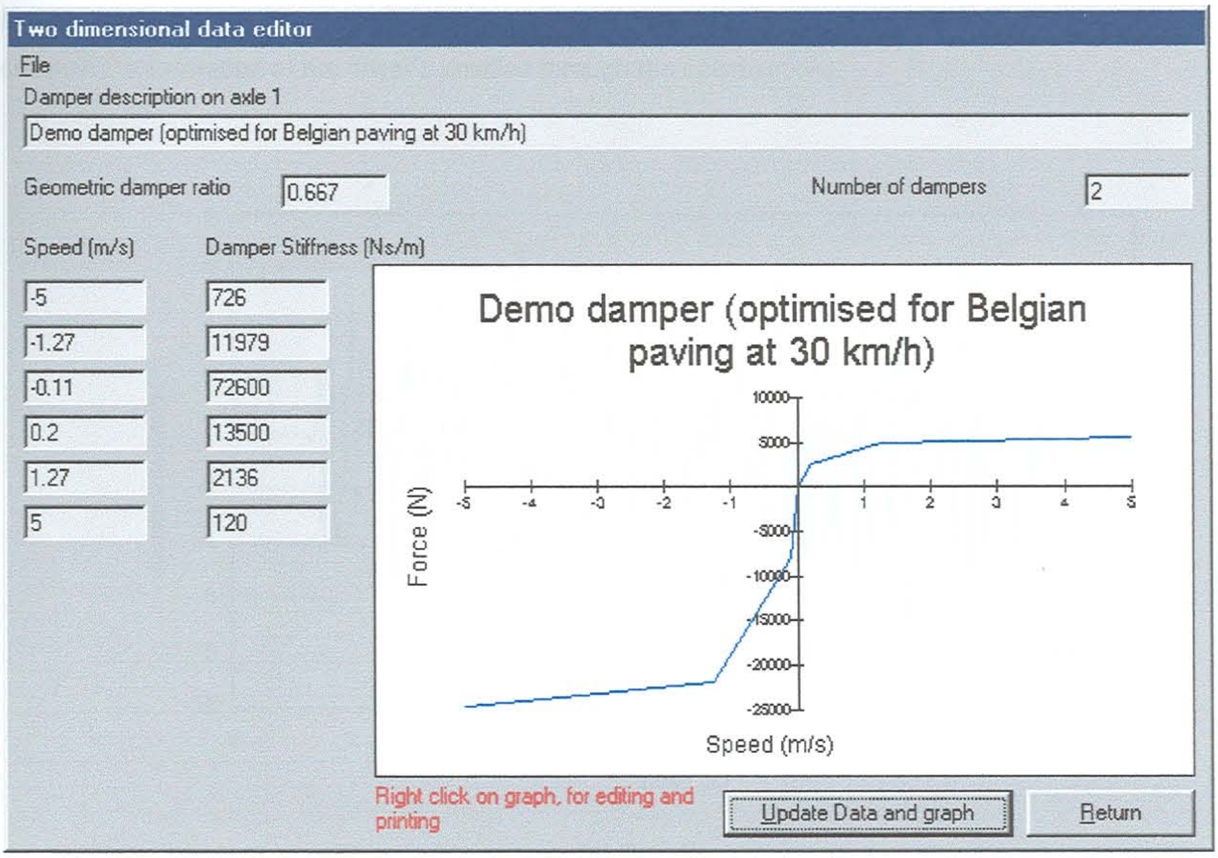
Figure 4.12: Convergence histories of objective function and design variables during optimisation

In figure 4.12 the objective function value and that for the individual objective criteria used are shown on the top graph. The bottom graph displays the values for design variables $X(1)$ and $X(2)$. From the convergence history, as shown in figure 4.12, the reduction in the objective function value from a starting value of 18.60 (for the baseline vehicle) to a minimum value of 14.07 (for the optimum configuration) can be seen. Thus a reduction of 24.4 % in the objective function value is obtained. The corresponding optimum design variable values obtained are $X(1) = 0.726$ and $X(2) = 0.12$. This means that the damper characteristic in the bump direction must be decreased to 0.726 of its baseline value and that in rebound to 0.12 of its baseline value to obtain the best ride comfort according to the specified objective function computed over the Belgian paving at 30 km/h.

At first glance it appears from the graphs shown in figure 4.12 that convergence has already been obtained at iteration number 22. Closer inspection of the design variables in this region, however, reveals that the value for $X(2)$ is slightly lower than the minimum constraint value of 0.12 and, because of the relative tight tolerances set, the algorithm continues to iterate. At approximately iteration number 45, phase 2 (see section A.5 of Appendix A) of the LFOPC algorithm is entered and a trajectory is initiated to a point on the nearest active constraint. Due to the flat gradient of the objective function in this region, big steps are initially taken for the design variable $X(2)$ but the algorithm recovers quickly and it finally converges to an optimum that exactly satisfies the constraints (see discussions in section 4.1.4 and 4.1.6).

For convergence to within the tolerances set a total number of 70 iteration steps, equivalent to, 210 simulations, were performed during the optimisation. On a Pentium III, 800 MHz personal computer the optimisation took 18 minutes. It can clearly be seen from figure 4.12, that an acceptable accurate optimum solution is already achieved during phase 1 after about 22 iterations (66 simulations), which requires only about 5.65 minutes computational time! Thus for this case looser tolerances could have been set. Allowance is also made for the user to interactively terminate the iteration process if effective convergence has obviously been reached. The tyre model used during the optimisation was the point follower model. Using the sector tyre model approximately doubles the simulation time required.

Selecting the "Optimise_vehicle.veh" file, the damper characteristic for the optimised damper is displayed as shown in figure 4.13.



Damper description on axle 1

Demo damper (optimised for Belgian paving at 30 km/h)

Geometric damper ratio: 0.667

Number of dampers: 2

Speed (m/s)	Damper Stiffness (Ns/m)
-5	726
-1.27	11979
-0.11	72600
0.2	13500
1.27	2136
5	120

Right click on graph, for editing and printing

Figure 4.13: Optimised damper

Figure 4.14 shows a comparison between the baseline (see also figure 3.23) and optimum damper characteristics.

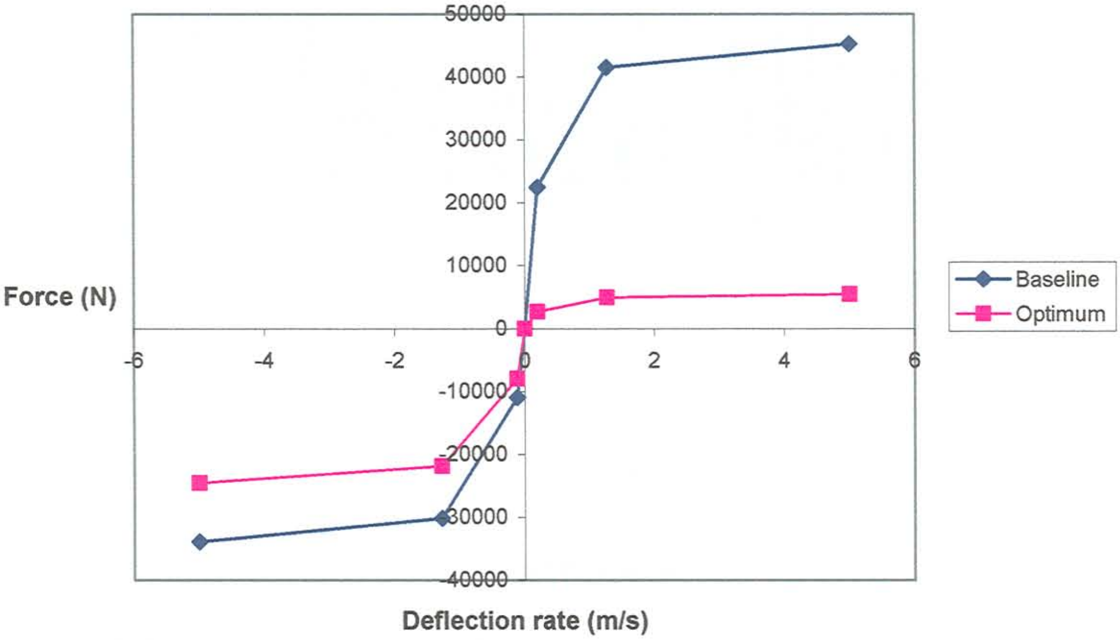
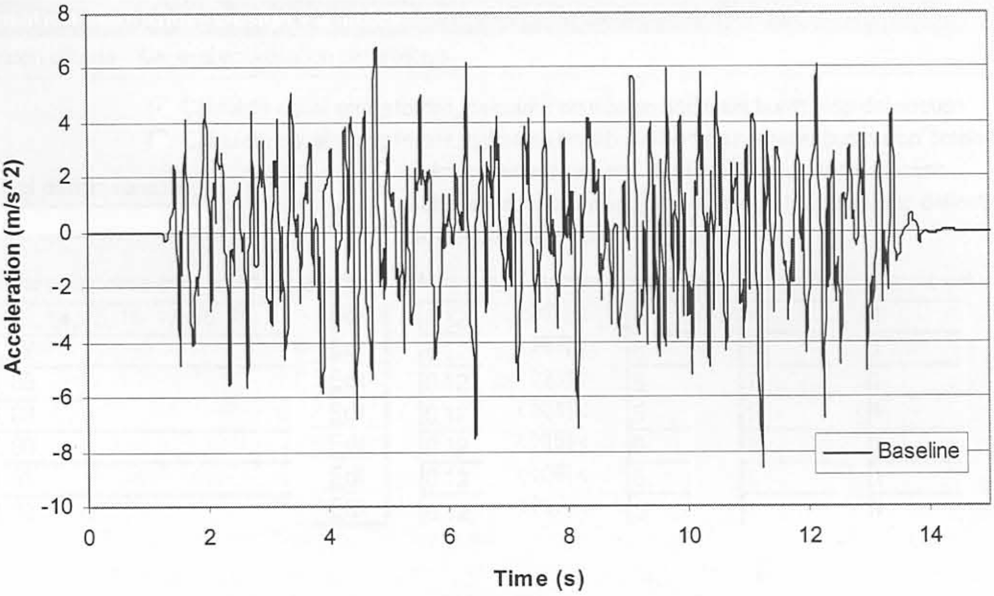
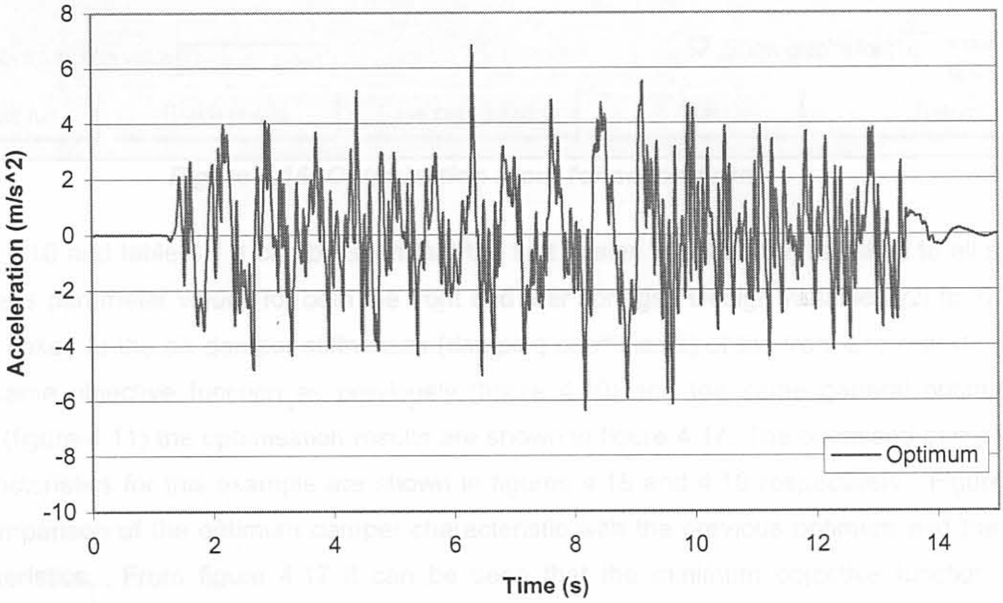


Figure 4.14: Comparison between baseline and optimised damper

Comparing figure 4.15(b) with 4.15(a) indicates the reduction obtained over the whole route, in the simulated acceleration at the driver's position through the optimisation.



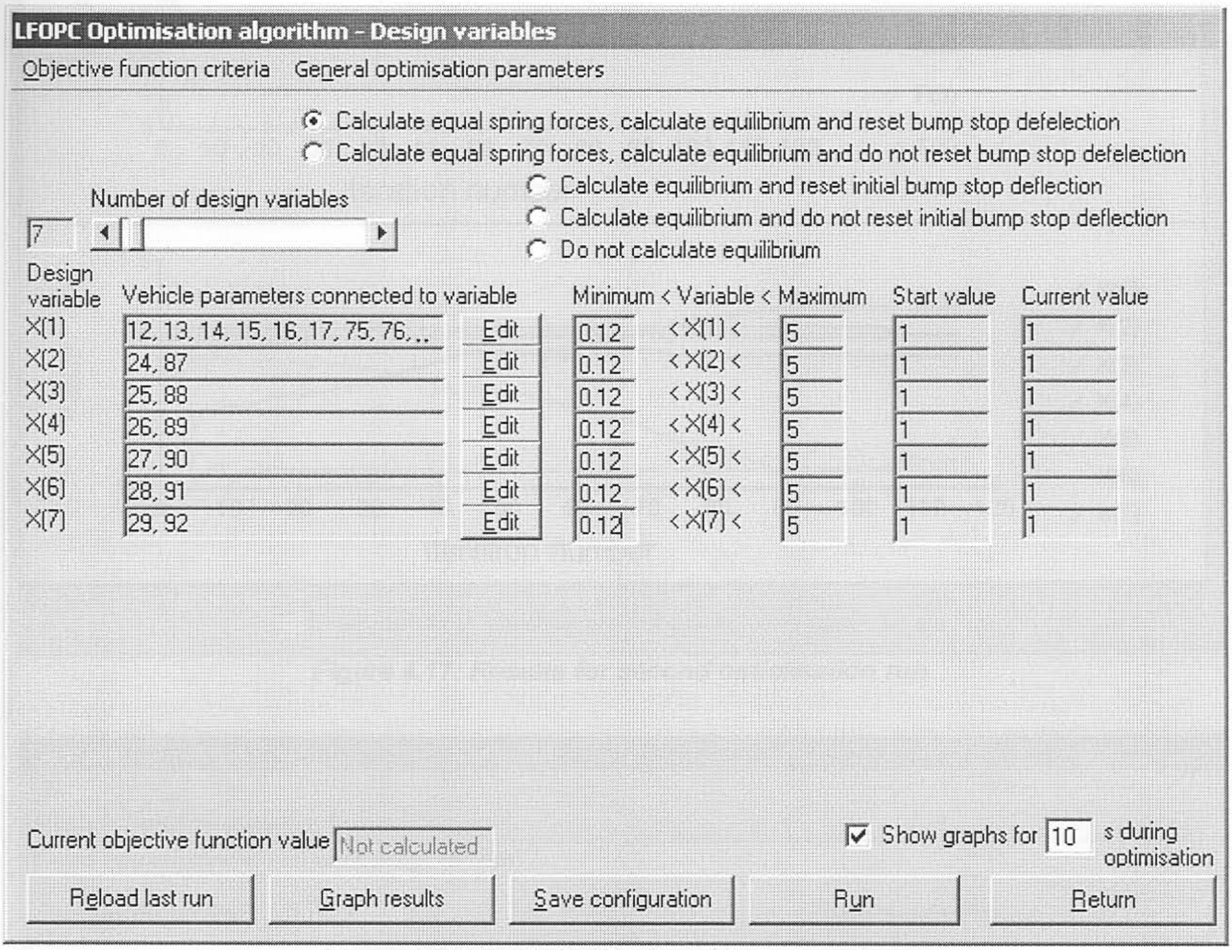
(a) Baseline



(b) Optimum

Figure 4.15: Comparison between simulated driver's position vertical acceleration for the baseline and the optimised damper

For the example described above only two design variables were used. To investigate if a further reduction in the objective function can be obtained, an optimisation was run with 7 design variables. The selection of the 7 design variables is shown in figure 4.16.



● Calculate equal spring forces, calculate equilibrium and reset bump stop defelection
○ Calculate equal spring forces, calculate equilibrium and do not reset bump stop defelection
○ Calculate equilibrium and reset initial bump stop deflection
○ Calculate equilibrium and do not reset initial bump stop deflection
○ Do not calculate equilibrium

Number of design variables: 7

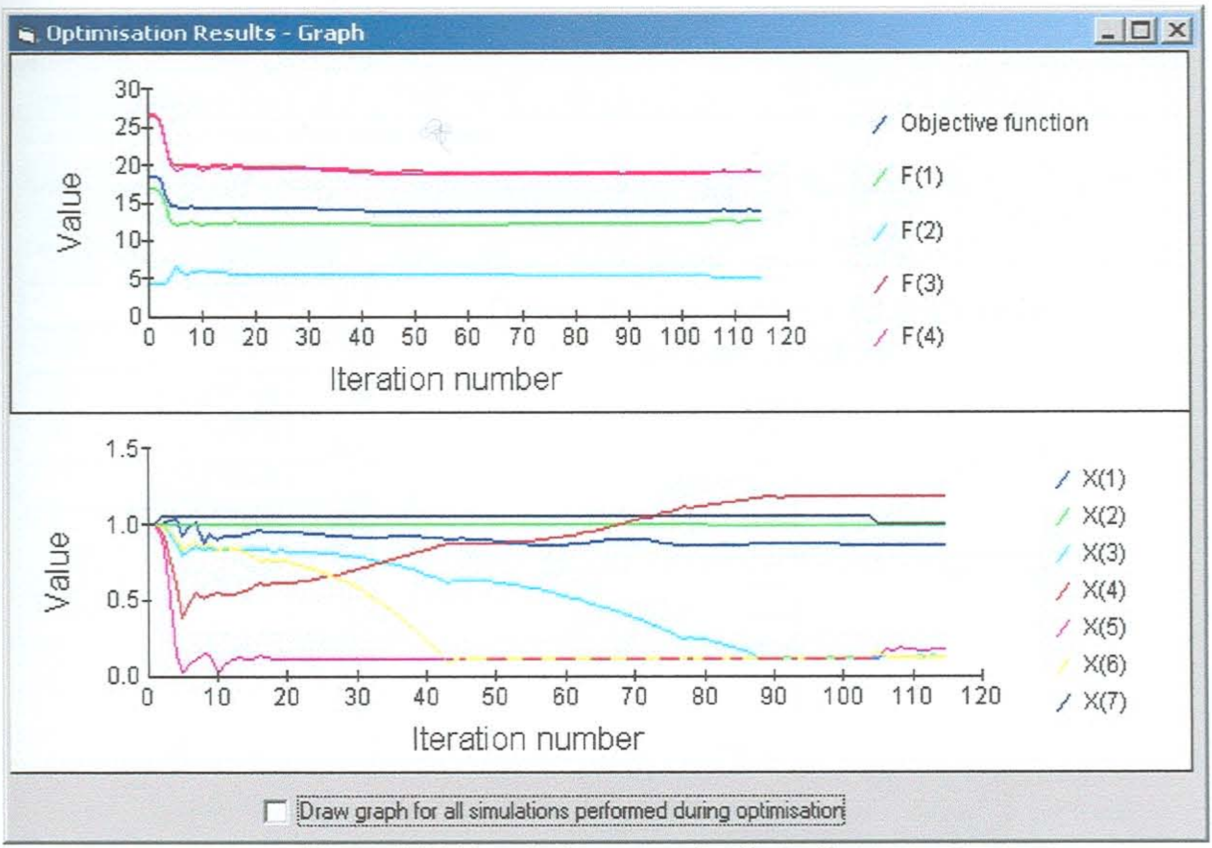
Design variable	Vehicle parameters connected to variable	Minimum	< Variable <	Maximum	Start value	Current value
X(1)	12, 13, 14, 15, 16, 17, 75, 76, ..	0.12	< X(1) <	5	1	1
X(2)	24, 87	0.12	< X(2) <	5	1	1
X(3)	25, 88	0.12	< X(3) <	5	1	1
X(4)	26, 89	0.12	< X(4) <	5	1	1
X(5)	27, 90	0.12	< X(5) <	5	1	1
X(6)	28, 91	0.12	< X(6) <	5	1	1
X(7)	29, 92	0.12	< X(7) <	5	1	1

Current objective function value: Not calculated

☑ Show graphs for 10 s during optimisation

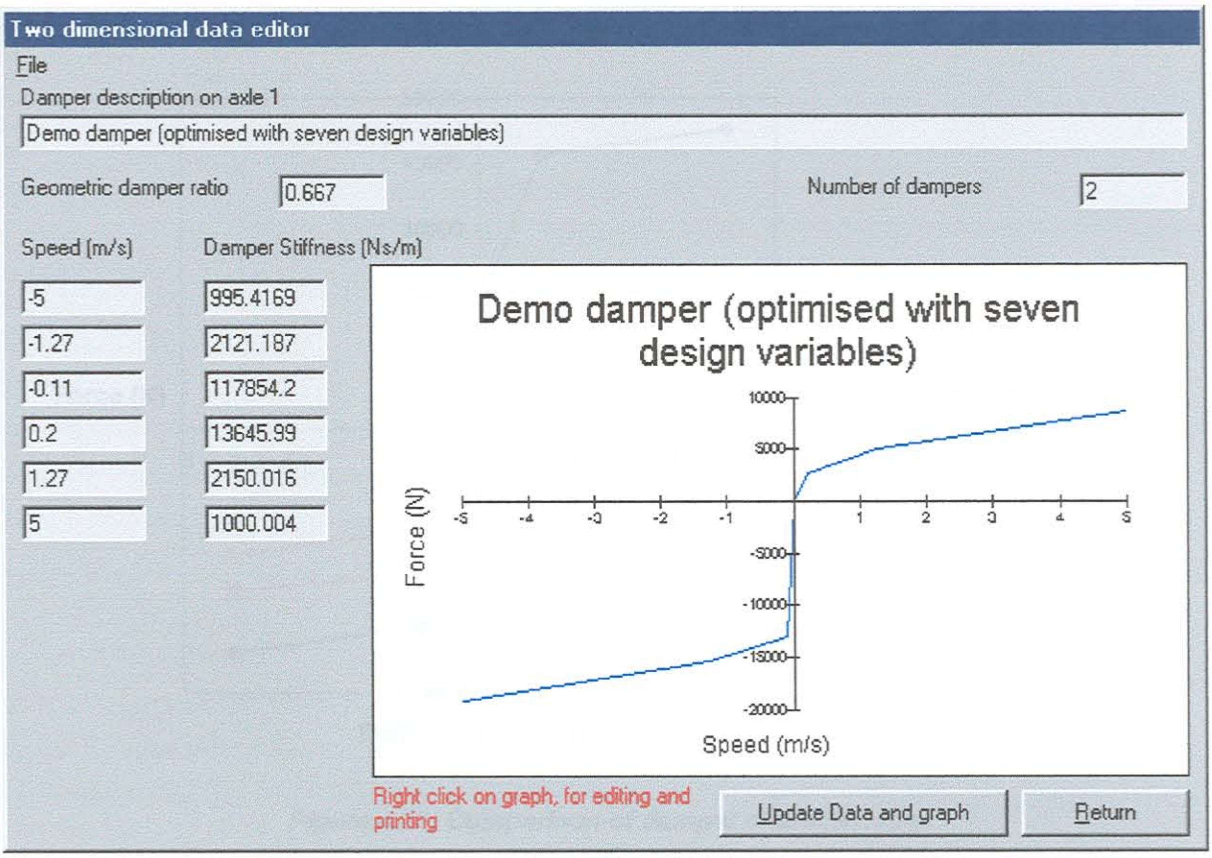
Figure 4.16: Optimisation input for second run

From figure 4.16 and table 4.1 it can be seen that the first design variable *X(1)* is linked to all six the spring stiffness parameter values for both the front and rear springs. Design variable *X(2)* to *X(7)* are respectively linked to the six damper stiffnesses (damping coefficients) of the front and rear dampers. Using the same objective function as previously (figure 4.10) and the same general optimisation parameters (figure 4.11) the optimisation results are shown in figure 4.17. The optimised damper and spring characteristics for this example are shown in figures 4.18 and 4.19 respectively. Figure 4.20 shows a comparison of the optimum damper characteristic with the previous optimum and the base line characteristics. From figure 4.17 it can be seen that the minimum objective function value obtained with this optimisation run is 13.85 (25.5 % reduction) compared to the baseline value of 18.60 and the previous optimum of 14.07 (24.4%) reduction. Thus in this case, increasing the number of variables results in only a marginal improvement in the optimum objective function value. The converged optimum values for *X(1)* to *X(7)*, as shown in figure 4.17, are respectively: 0.865, 0.995, 0.129, 1.179, 0.121, 0.121 and 1.00. From these values it is clear that the spring stiffness for the optimum configuration must be reduced to 86.5% of that for the baseline vehicle.



☐ Draw graph for all simulations performed during optimisation

Figure 4.17: Results for second optimisation run



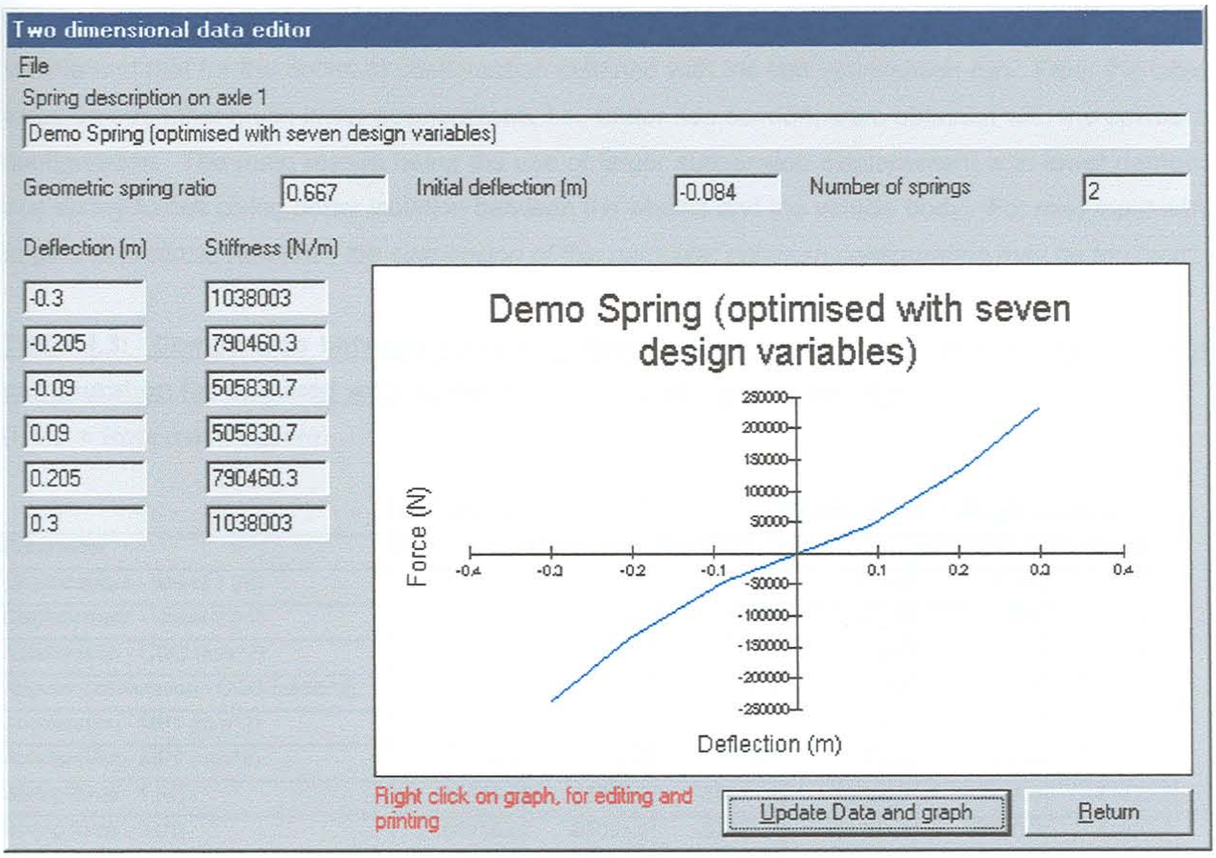
Damper description on axle 1: Demo damper (optimised with seven design variables)

Geometric damper ratio: 0.667

Number of dampers: 2

Speed (m/s)	Damper Stiffness (Ns/m)
-5	995.4169
-1.27	2121.187
-0.11	117854.2
0.2	13645.99
1.27	2150.016
5	1000.004

Figure 4.18: Optimised damper from second run



Spring description on axle 1: Demo Spring (optimised with seven design variables)

Geometric spring ratio: 0.667

Initial deflection (m): -0.084

Number of springs: 2

Deflection (m)	Stiffness (N/m)
-0.3	1038003
-0.205	790460.3
-0.09	505830.7
0.09	505830.7
0.205	790460.3
0.3	1038003

Right click on graph, for editing and printing

Figure 4.19: Optimised spring from second run

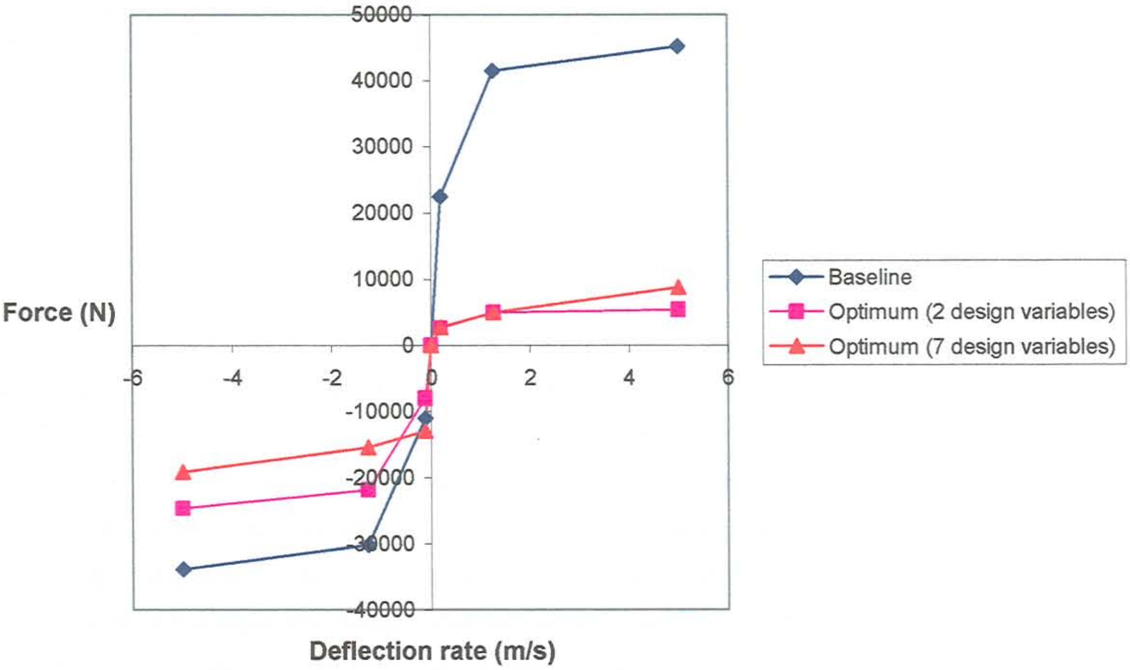


Figure 4.20: Comparison of damper characteristics

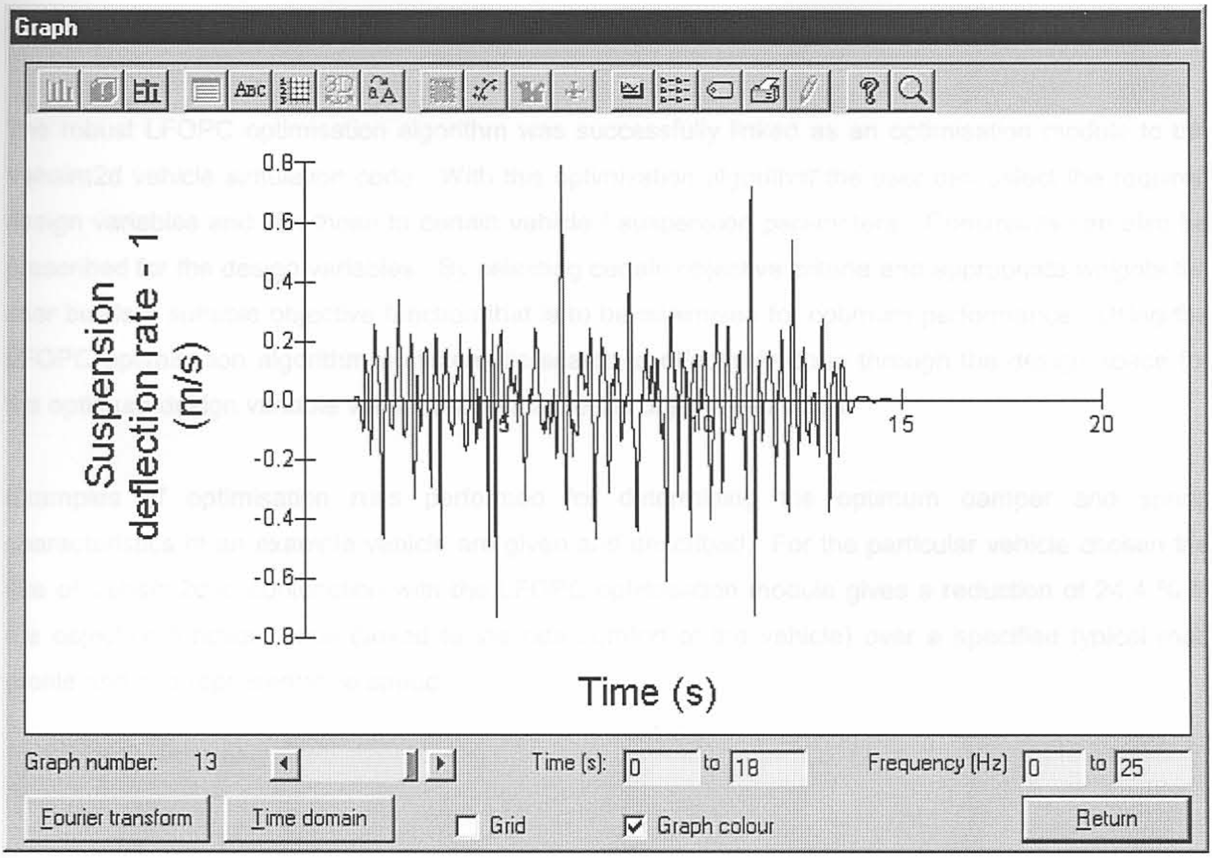
Table 4.3 shows a comparison for several objective criteria between the values for the baseline vehicle and that for the optimum configuration obtained with the last optimisation run. From the table it can be seen that much lower accelerations, i.e., better ride comfort, were obtained with the optimum configuration. The main reason being the use of larger suspension displacement with lower damper and spring forces giving better isolation between the wheels and the vehicle body. *For road input with larger fluctuations, however, the suspension of this particular optimum configuration may be too "soft".*

Table 4.3: Comparison between objective criteria values for base line vehicle and optimum configuration (as obtained with optimisation with seven design variables)

(RMS = Root mean square)

	Baseline vehicle			**Optimum with 7 design variables**		
Parameter	**RMS**	**Minimum**	**Maximum**	**RMS**	**Minimum**	**Maximum**
Displacement - wheel 1 (m)	0.016	-0.072	0.040	0.015	-0.066	0.039
Displacement - wheel 2 (m)	0.015	-0.072	0.040	0.015	-0.065	0.040
Acceleration - COG (m/s^2)	1.132	-4.507	2.874	0.800	-2.512	2.630
Angular acceleration - COG (rad/s^2)	0.755	-2.252	2.416	0.555	-1.914	1.705
Acceleration - MP1 (m/s^2)	1.854	-7.574	5.771	1.370	-4.628	4.474
Acceleration - MP2 (m/s^2)	1.858	-6.939	5.841	1.320	-4.149	4.141
Spring force - 1 (N)	66875.0	-86019.6	-50941.1	62026.3	-78845.9	-41430.0
Spring force - 2 (N)	66716.0	-85001.0	-52583.7	61854.1	-77760.3	-41637.9
Damper force - 1 (N)	10670.7	-22931.0	37783.2	7837.2	-19183.9	5072.5
Damper force - 2 (N)	10511.5	-24280.8	37377.7	7806.2	-19115.6	4932.4
Bump stop force - 1 (N)	0.000	0.000	0.000	0.000	0.000	0.000
Bump stop force - 2 (N)	0.000	0.000	0.000	0.000	0.000	0.000
Suspension deflection - 1 (m)	0.008	-0.029	0.028	0.015	-0.019	0.050
Suspension deflection - 2 (m)	0.008	-0.027	0.025	0.014	-0.018	0.049
Suspension deflection rate - 1 (m/s)	0.146	-0.727	0.790	0.215	-1.166	1.048
Suspension deflection rate - 2 (m/s)	0.142	-0.819	0.765	0.207	-1.130	0.975
Tyre deflection - 1 (m)	0.060	-0.085	-0.018	0.060	-0.087	-0.038
Tyre deflection - 2 (m)	0.060	-0.087	-0.018	0.060	-0.088	-0.036
Wheel force - 1 (N)	70493.2	-104290.4	-24405.2	70055.0	-94395.9	-46850.4
Wheel force - 2 (N)	70320.7	-101295.6	-23763.1	69883.6	-93166.1	-47088.5

For full convergence to the strict convergence tolerances set, the optimisation with the seven design variables required 115 iterations corresponding to 920 simulation runs (compared to the previous 210). The computational time was 79 minutes (compared to 18 minutes previously) on the same computer. For this particular example the use of more than the two design variables to optimise the suspension is probably not justified. This conclusion is, however, not generally true. One reason for the small improvement obtained in this case for the complete damper optimisation, is that the range of damper speeds of the base line design obtained on the specific road input, was already relatively low as can be seen from figure 4.21. It is again apparent from figure 4.17 that, if looser tolerances are set for convergence, an effective optimum objective function value may be achieved in a quarter of the time required for full convergence. Of course the user may interactively, by inspection of the displayed convergence graphs, terminate the optimisation process at any point if sufficient reduction in objective function has been achieved.



Graph number: 13

Time (s): 0 to 18

Frequency (Hz) 0 to 25

Figure 4.21: Damper speeds obtained (for the base line damper) during the simulation

4.3 Summary

The robust LFOPC optimisation algorithm was successfully linked as an optimisation module to the Vehsim2d vehicle simulation code. With this optimisation algorithm the user can select the required design variables and link these to certain vehicle / suspension parameters. Constraints can also be prescribed for the design variables. By selecting certain objective criteria and appropriate weights the user builds a suitable objective function that is to be minimised for optimum performance. Using the LFOPC optimisation algorithm a systematic search is effectively done through the design space for the optimum design variable values that minimise the objective function.

Examples of optimisation runs performed for determining the optimum damper and spring characteristics of an example vehicle are given and described. For the particular vehicle chosen the use of Vehsim2d in conjunction with the LFOPC optimisation module gives a reduction of 24.4 % in the objective function value (linked to the ride comfort of the vehicle) over a specified typical road profile and at a representative speed.