CHAPTER 5:

CASE STUDY

5. Case study

The problems experienced on the suspension of the Okapi vehicle (see figures 1.1 and 5.1) were described in section 1.1. This vehicle had gone through a series of design changes to improve mobility, fatigue life of the axles, and other general features of the vehicle [1, 2, 63, 64]. In spite of these improvements certain suspension failures remained and it was decided to perform a suspension optimisation on the vehicle using the simulation program Vehsim2d coupled to the LFOPC optimisation module.

Figure 5.1: Okapi vehicle as used in this case study

5.1 Introduction

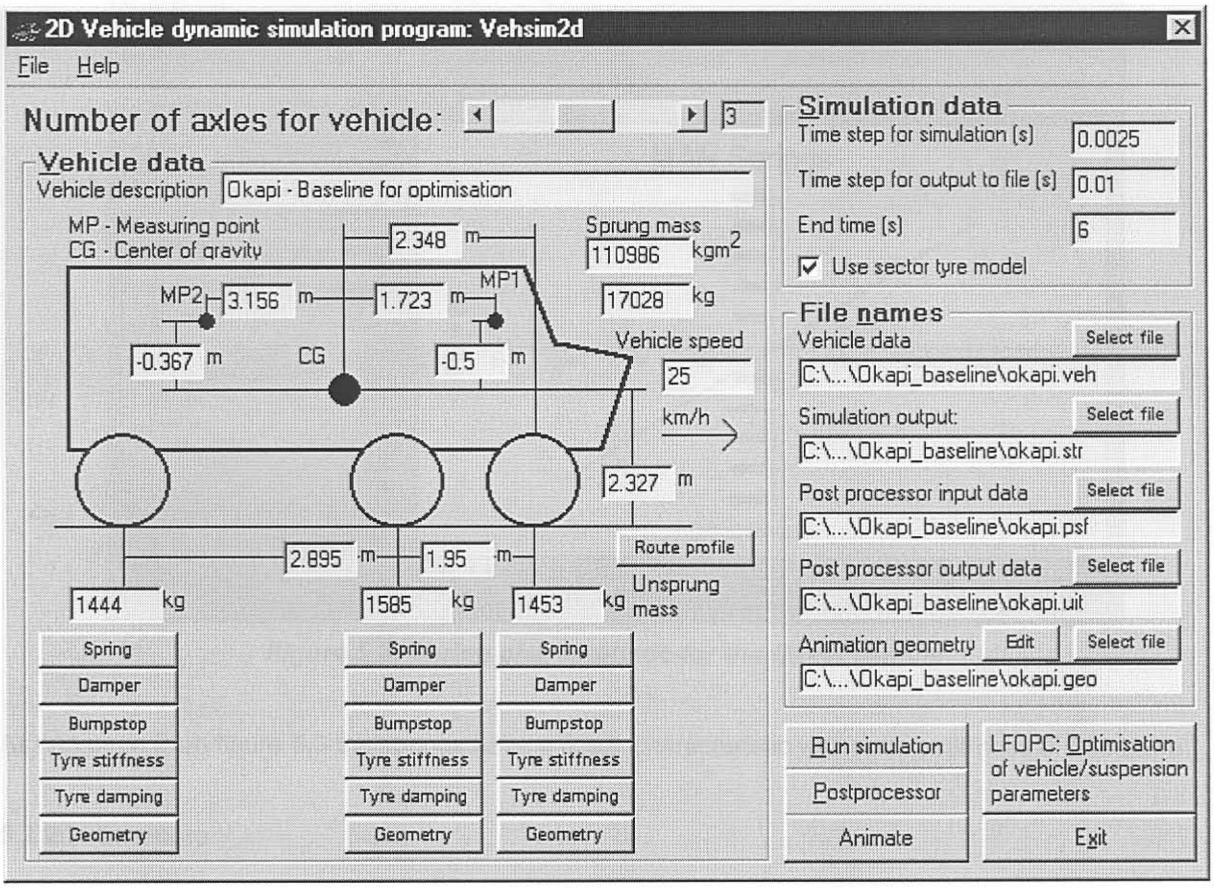
The purpose of this case study is to **find the optimum damper characteristic for the Okapi vehicle** using the suspension optimisation system developed in chapters 3 and 4. Section 5.2 describes the Okapi vehicle model developed for use in this case study. Section 5.3 describes the route profiles used and in section 5.4 the implementation of the optimisation process and the results obtained from the optimisation are presented. In section 5.5 suggestions arising from the optimisation study are made regarding specific damper characteristics.

5.2 Vehicle model

The vehicle model for the Okapi was based on data received from Reumech Ermetek [63] and Vickers OMC [64].

5.2.1 Vehicle geometry

Figure 5.2 shows the vehicle geometry, mass and inertia characteristics prescribed.



2D Vehicle dynamic simulation program: Vehsim2d

Number of axles for vehicle: 3

Vehicle data
Vehicle description: Okapi - Baseline for optimisation
MP - Measuring point
CG - Center of gravity
Sprung mass: 110986 kgm^2, 17028 kg
Vehicle speed: 25 km/h
Unsprung mass: 1444 kg, 1585 kg, 1453 kg

Simulation data
Time step for simulation (s): 0.0025
Time step for output to file (s): 0.01
End time (s): 6
☑ Use sector tyre model

File names
Vehicle data: C:\...\Okapi_baseline\okapi.veh
Simulation output: C:\...\Okapi_baseline\okapi.str
Post processor input data: C:\...\Okapi_baseline\okapi.psf
Post processor output data: C:\...\Okapi_baseline\okapi.uit
Animation geometry: C:\...\Okapi_baseline\okapi.geo

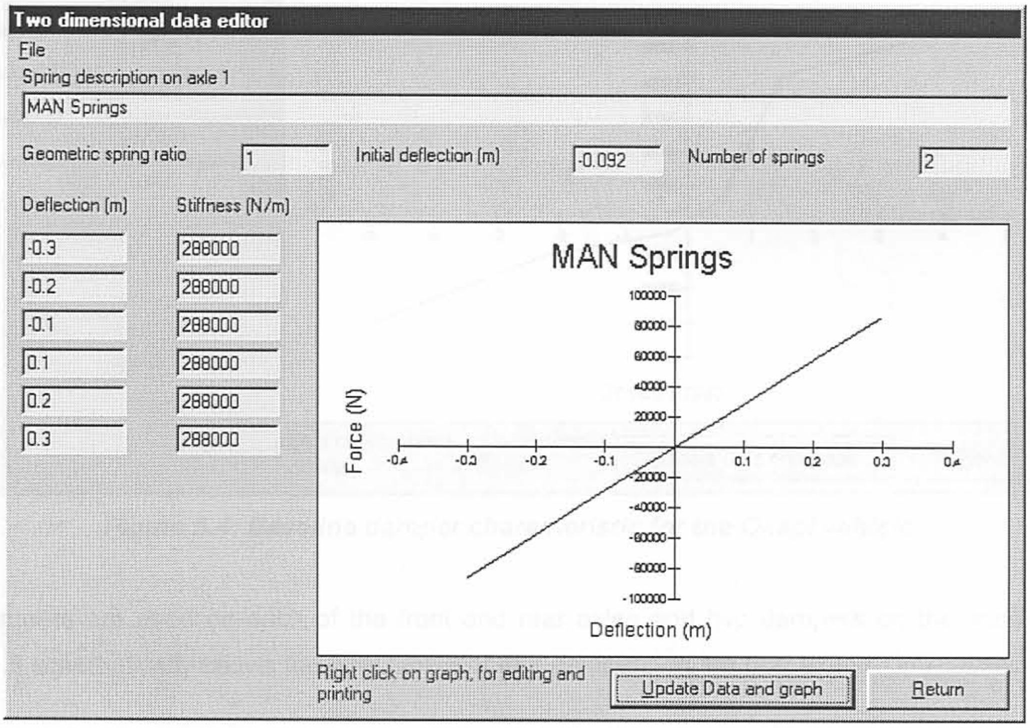
Figure 5.2: Simulation input for the Okapi vehicle

5.2.2 Suspension characteristics

The suspension characteristics are prescribed using a six piece-wise continuous linear approximation (see section 2.1 and figure 2.4 for more details).

5.2.2.1 Spring

Figure 5.3 shows the characteristic for the springs used on the Okapi vehicle. During the latest upgrade of the vehicle parabolic leaf springs, used by the truck manufacturer MAN on their new generation trucks, were fitted because they give minimum interleaf friction. This results in improved ride comfort and is an upgrade to the latest technology [64].



Spring description on axle 1: MAN Springs

Geometric spring ratio: 1
Initial deflection (m): -0.092
Number of springs: 2

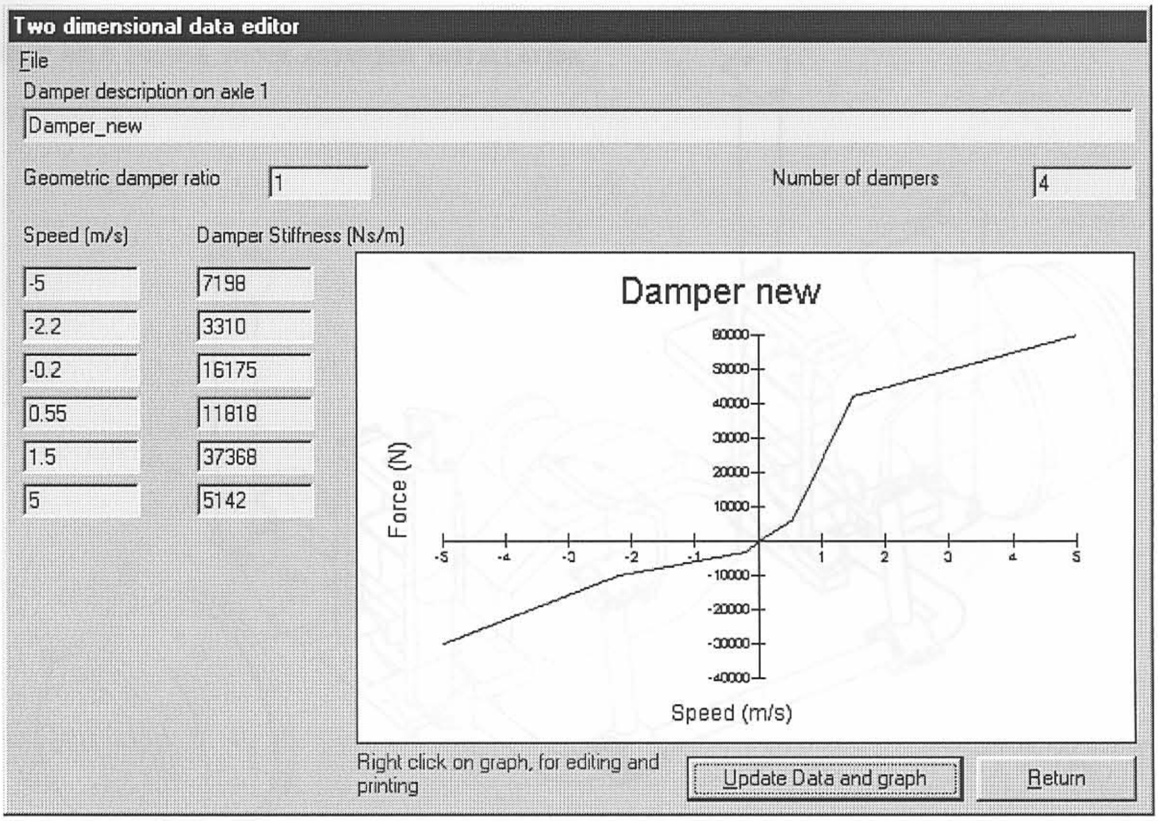
Deflection (m)	Stiffness (N/m)
-0.3	288000
-0.2	288000
-0.1	288000
0.1	288000
0.2	288000
0.3	288000

Figure 5.3: Spring characteristic for the Okapi vehicle

As can seen from figure 5.3 the springs have a linear characteristic with spring stiffness of 288 kN/m.

5.2.2.2 Dampers

The characteristics for the dampers were retrieved from the DADS model dated 24 July 1999 [63], and are shown in figure 5.4. The data for the dampers as used in the DADS model [63] were experimentally determined by testing the actual dampers as fitted on the Okapi [64]. A typical damper is referred to as Damper_new in figure 5.4 due to the fact that it is representative of the new dampers fitted to the vehicle during the 1999 upgrade project [64].



Two dimensional data editor

Damper description on axle 1: Damper_new

Geometric damper ratio: 1

Number of dampers: 4

Speed (m/s)	Damper Stiffness (Ns/m)
-5	7198
-2.2	3310
-0.2	16175
0.55	11818
1.5	37368
5	5142

Right click on graph, for editing and printing

Figure 5.4: Baseline damper characteristic for the Okapi vehicle

Four dampers are used on each of the front and rear axles and two dampers on the middle axle. Figure 5.5 schematically shows the attachment of four dampers on the rear axle.

Figure 5.6 compares the damper characteristic of the damper shown in figure 5.4 (Damper_new, now referred to as that of Vehsim2d) with that actually measured for two other similarly sized dampers, namely the Samil and Gabriel dampers. As can be seen from figure 5.6 the damper characteristic used for the damper of the Okapi vehicle (Vehsim2d) is similar to that obtained experimentally for the Samil damper, except in the high rebound deflections region where the damping force are smaller than that for the Samil damper. Uncertainties, however, exist in the measurements of the high rebound damping forces for the Samil and Gabriel dampers.

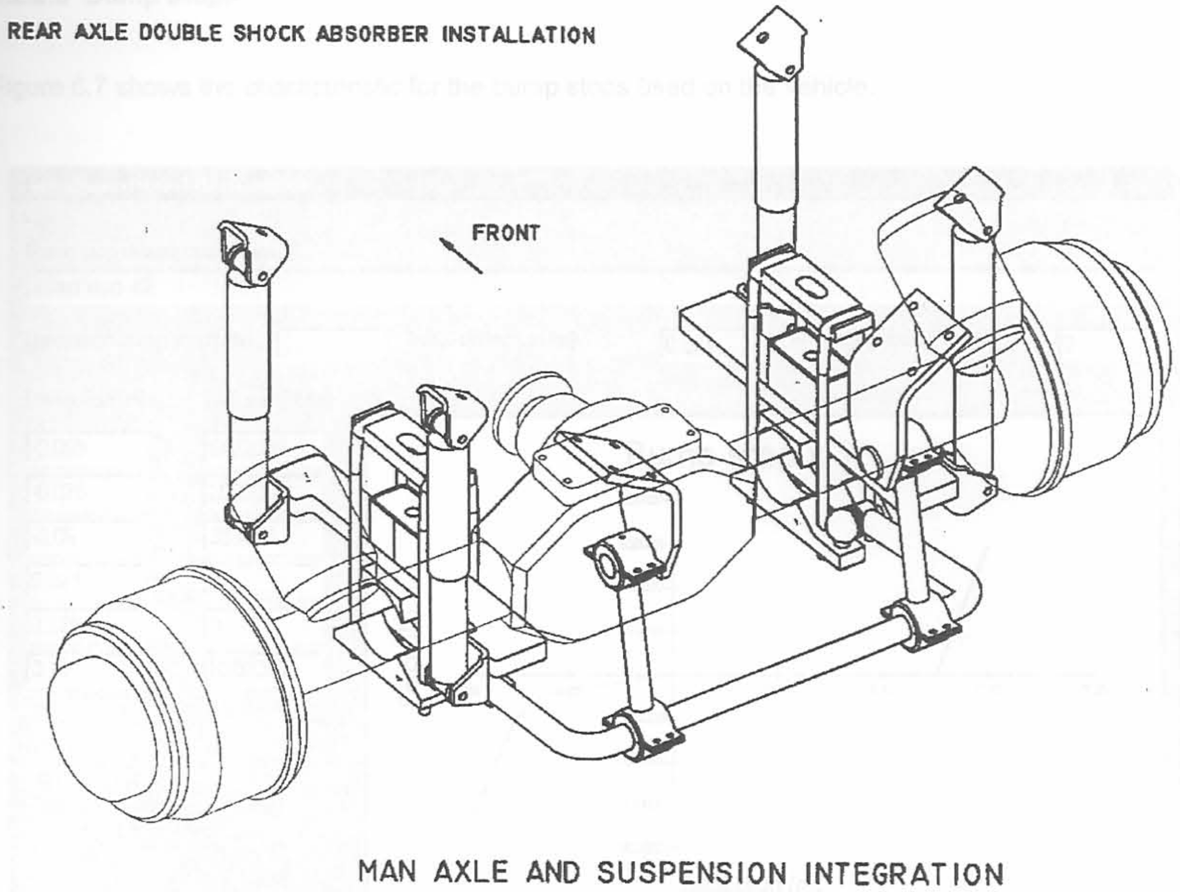


Figure 5.5: Drawing of the Okapi rear suspension showing the use of four dampers

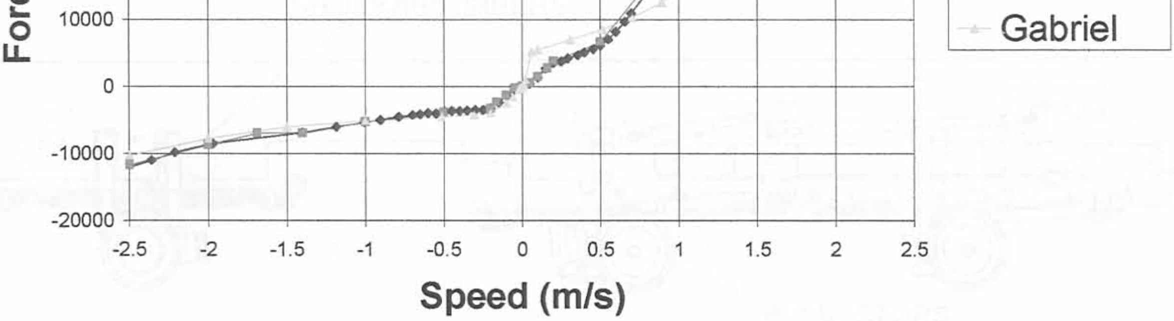
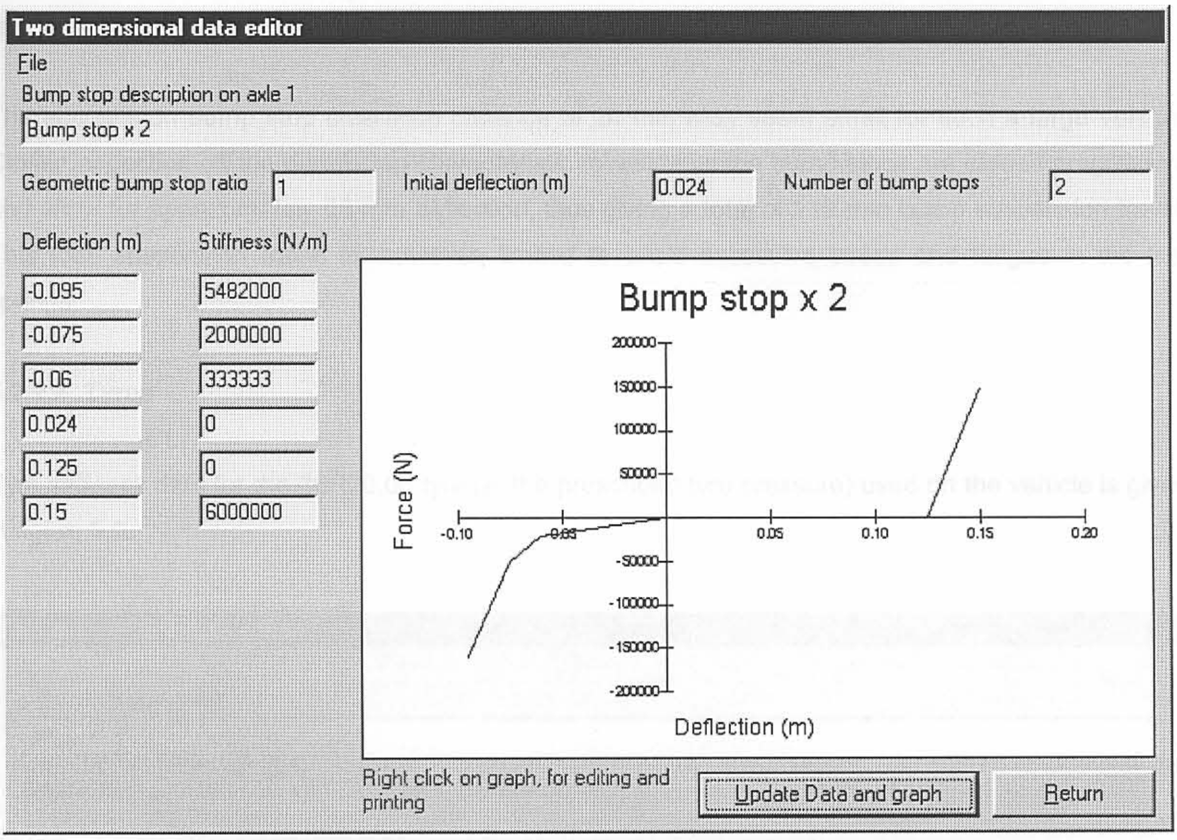


Figure 5.6: Comparison of damper characteristics for the Okapi vehicle (Vehsim2d) compared to similar dampers (Samil and Gabriel)

5.2.2.3 Bump stops

Figure 5.7 shows the characteristic for the bump stops used on the vehicle.



Two dimensional data editor

File

Bump stop description on axle 1: Bump stop x 2

Geometric bump stop ratio: 1

Initial deflection (m): 0.024

Number of bump stops: 2

Deflection (m)	Stiffness (N/m)
-0.095	5482000
-0.075	2000000
-0.06	333333
0.024	0
0.125	0
0.15	6000000

Right click on graph, for editing and printing

Figure 5.7: Bump stop characteristic for the Okapi vehicle

As can be seen from figure 5.8, four bump stops are used on each axle. The characteristic shown in figure 5.7 is a combination of the bump stop characteristic at the front and rear of the axle. An artificial bump stop is introduced in the rebound direction to model the restriction of the axle in the rebound direction, which is physically done by cables on the vehicle.

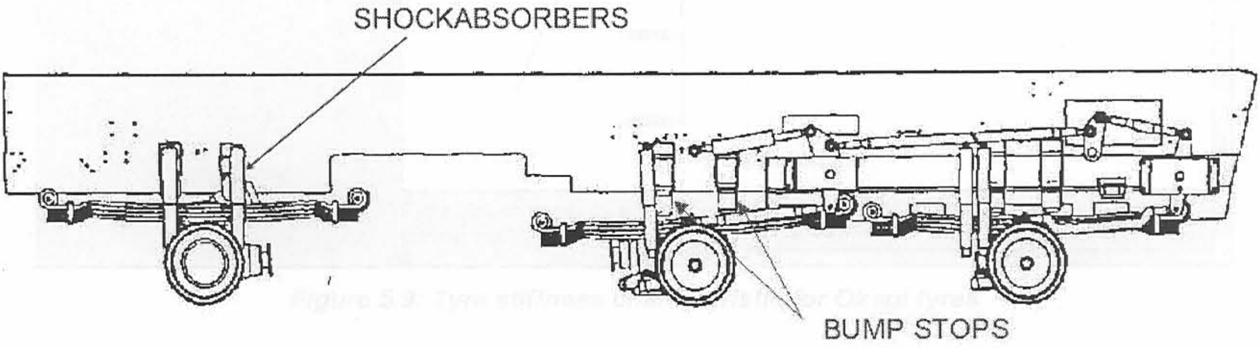


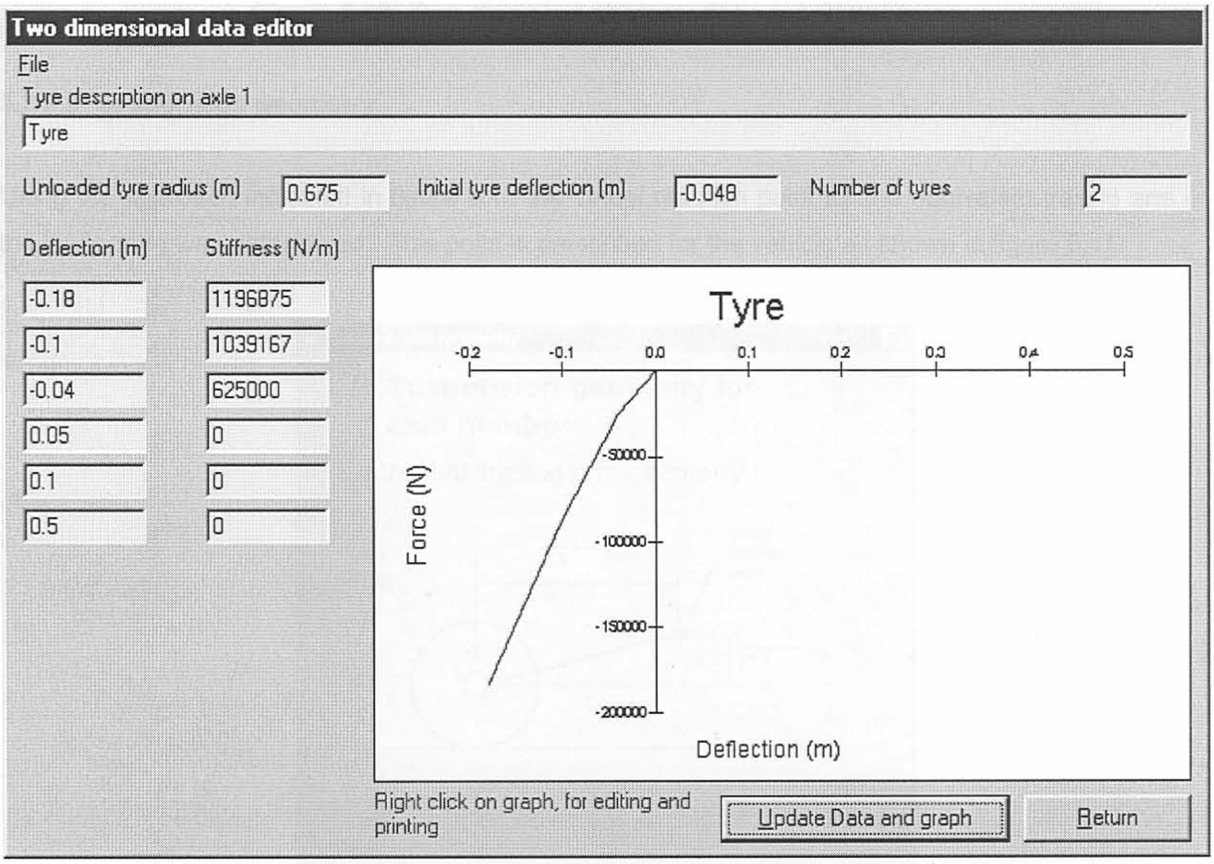
Figure 5.8: Bump stops used on the Okapi vehicle

The bump stops used are placed in such a manner that a suspension travel in the bump direction of 24 mm is available before the leaf spring makes contact with the bump stops. From figure 5.7 it can be seen that this suspension travel is taken into consideration by prescribing an initial deflection of 0.024 m. From this initial point 101 mm travel is allowed in the rebound direction before the cables limit the rebound travel of the suspension.

The suspension bump stop clearance distance of 24 mm may seem small for such a large vehicle. Closer inspection off the bump stop characteristic reveals that the bump stops are indeed progressive and allow for approximately 95 mm deflection, thus giving a total of 119 mm bump suspension travel. This total suspension travel is, however, limited to avoid excessive stress and fatigue in the leaf springs.

5.2.2.4 Tyres

Tyre stiffness data for the 16R20.00 tyre (at the prescribed tyre pressure) used on the vehicle is given in figure 5.9.



Tyre description on axle 1: Tyre

Unloaded tyre radius (m): 0.675

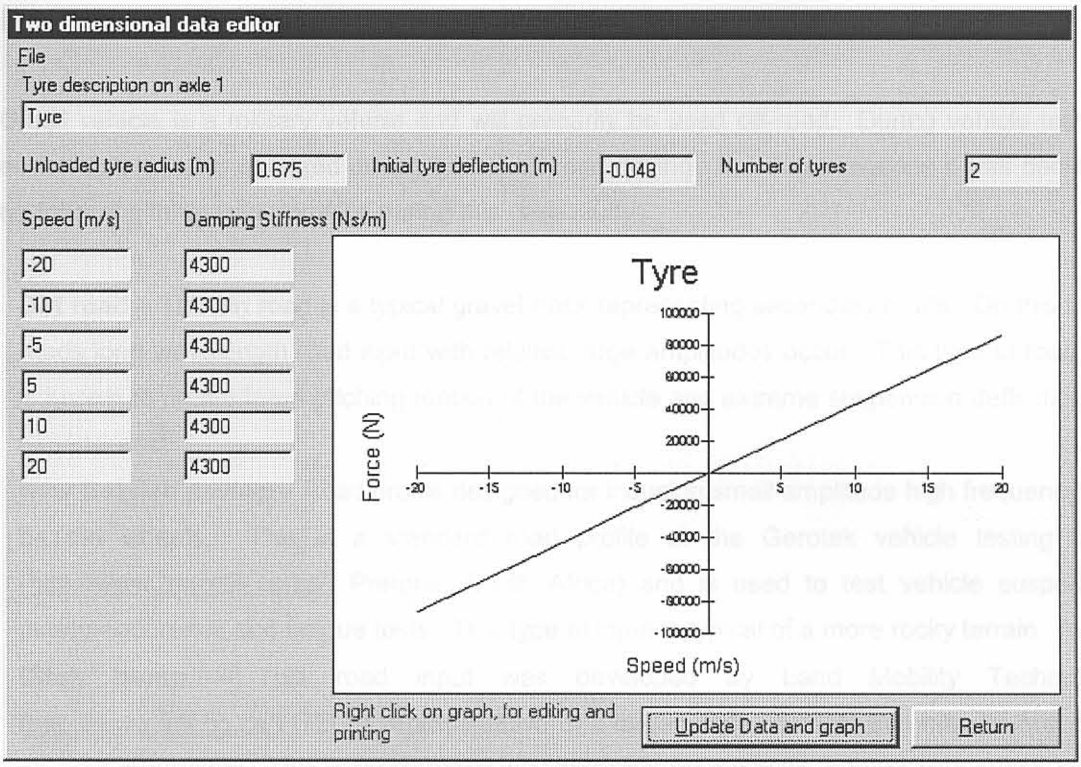
Initial tyre deflection (m): -0.048

Number of tyres: 2

Deflection (m)	Stiffness (N/m)
-0.18	1196875
-0.1	1039167
-0.04	625000
0.05	0
0.1	0
0.5	0

Figure 5.9: Tyre stiffness characteristic for Okapi tyres

The damping characteristic of the tyre is given in figure 5.10



Tyre description on axle 1: Tyre

Unloaded tyre radius (m): 0.675

Initial tyre deflection (m): -0.048

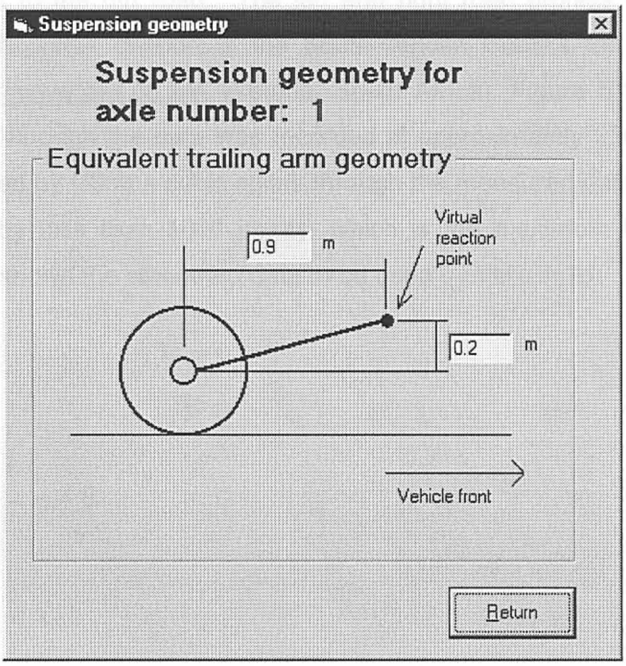
Number of tyres: 2

Speed (m/s)	Damping Stiffness (Ns/m)
-20	4300
-10	4300
-5	4300
5	4300
10	4300
20	4300

Figure 5.10: Tyre damping characteristic for Okapi tyres

5.2.2.5 Suspension geometry

Using the approach indicated in figure 3.13 the virtual reaction point for the equivalent trailing arm of the leaf spring was determined. This point is prescribed for the vehicle as shown in figure 5.11.



0.9 m

0.2 m

Figure 5.11: Virtual reaction point for Okapi vehicle

5.3 Route profiles

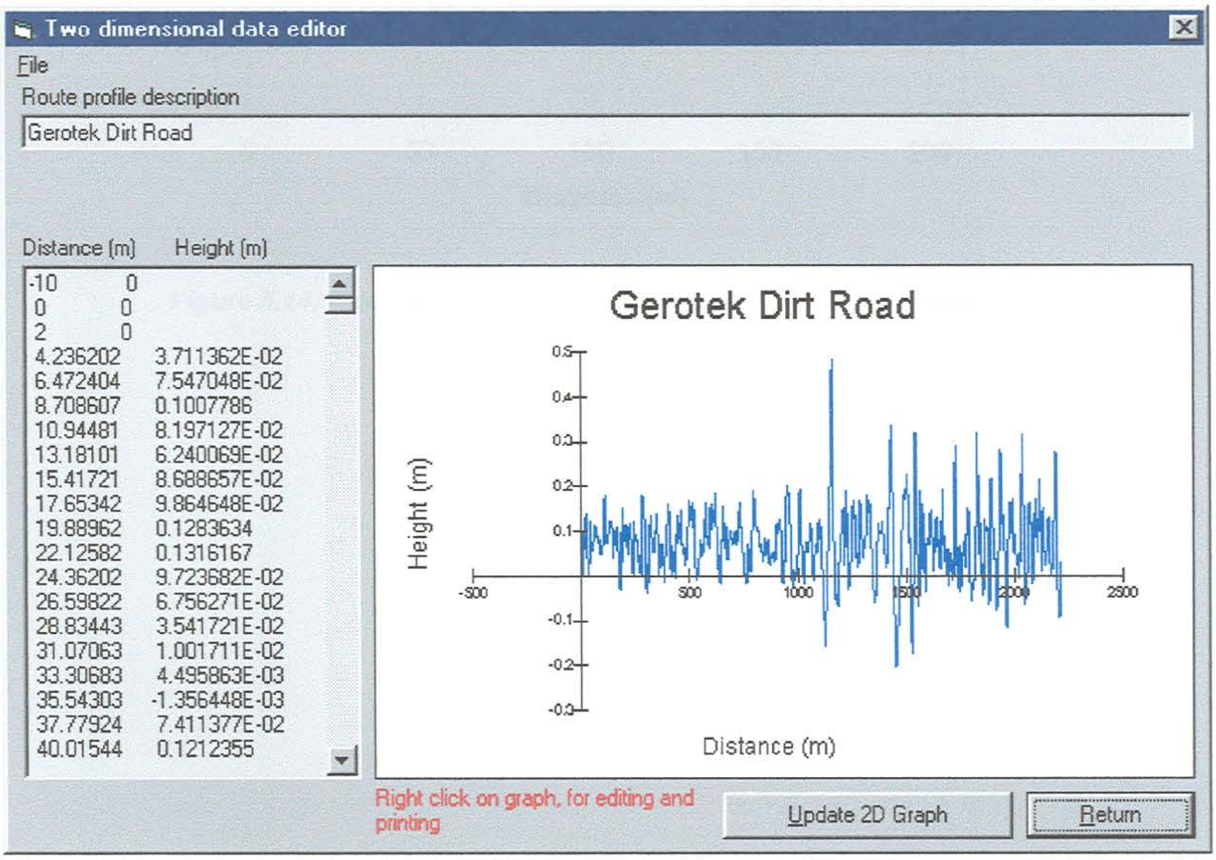
The Okapi vehicle is a military vehicle and will primarily be used off-road. During vehicle tests the suspension failures also occurred during typical off-road driving. For these reasons it was decided to use the following three route profiles during this case study:

- **Dirt road** – The dirt road is a typical gravel track representing secondary roads. On this type of roads long wavelength road input with relative large amplitudes occur. This type of road input is known to create large pitching motion of the vehicle and extreme suspension deflections are experienced.
- **New Belgian paving –** Road profile designed for inducing small amplitude high frequency input on the wheels. This is a standard road profile at the Gerotek vehicle testing facility (http://www.gerotek.co.za/, Pretoria, South Africa) and is used to test vehicle suspensions during endurance and fatigue tests. This type of input is typical of a more rocky terrain.
- **Ditch bump –** This road input was developed by Land Mobility Technologies (http://www.lmt.co.za/) [72] as representative of a large single obstacle that may be met during off-road movement. This is representative of crossing, for example, a fallen tree during off-road movement.

5.3.1 Dirt road

The dirt road data used here were obtained as the mean of the left and right profiles of the gravel track at Gerotek. The data is for a 2.2 km section of the road in an anti clockwise direction starting from the workshop next to the dirt road. The left and right road profiles were measured using a profilometer of the Transportek division of the South African Council for Scientific and Industrial Research (CSIR), (http://www.csir.co.za/, Pretoria, South Africa). Figure 5.12 shows the measured data for the dirt road. Although the data was recorded at approximately 250 mm intervals, the data used here were smoothed by fitting a cubic spline through the measured data to enable the 2.2 km of data to be prescribed by less than 1000 points, which is the maximum that can be handled by Vehsim2d. Figure 5.13 shows the smoothed data to be used by Vehsim2d.

Figure 5.12: Dirt road profile as measured with profilometer



Route profile description

Gerotek Dirt Road

Distance (m)	Height (m)
-10	0
0	0
2	0
4.236202	3.711362E-02
6.472404	7.547048E-02
8.708607	0.1007786
10.94481	8.197127E-02
13.18101	6.240069E-02
15.41721	8.688657E-02
17.65342	9.864648E-02
19.88962	0.1283634
22.12582	0.1316167
24.36202	9.723682E-02
26.59822	6.756271E-02
28.83443	3.541721E-02
31.07063	1.001711E-02
33.30683	4.495863E-03
35.54303	-1.356448E-03
37.77924	7.411377E-02
40.01544	0.1212355

Right click on graph, for editing and printing

Figure 5.13: Dirt road profile as prescribed for Vehsim2d

5.3.2 New Belgian paving

Data for the new Belgian paving were also obtained using the CSIR profilometer. The data used in the simulation were obtained by combining the east to west data with west to east data as measured on the new Belgian paving to obtain approximately 200 m of route profile. Figure 5.14 shows the measured data and figure 5.15 the data prescribed for Vehsim2d.

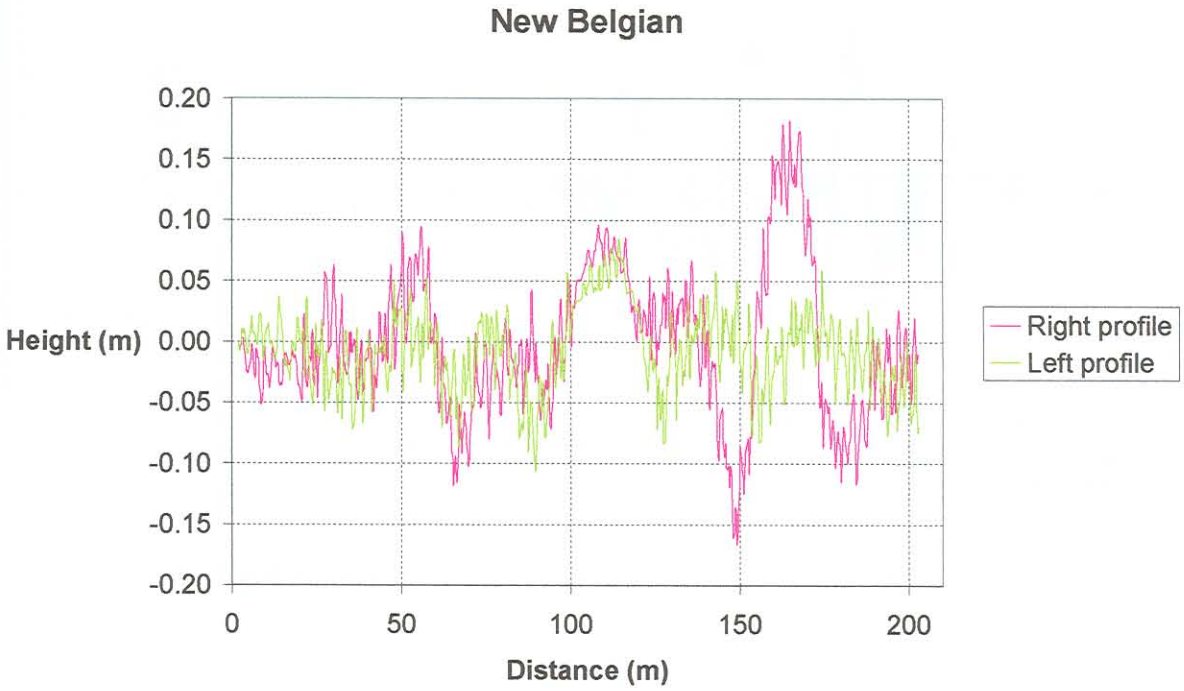
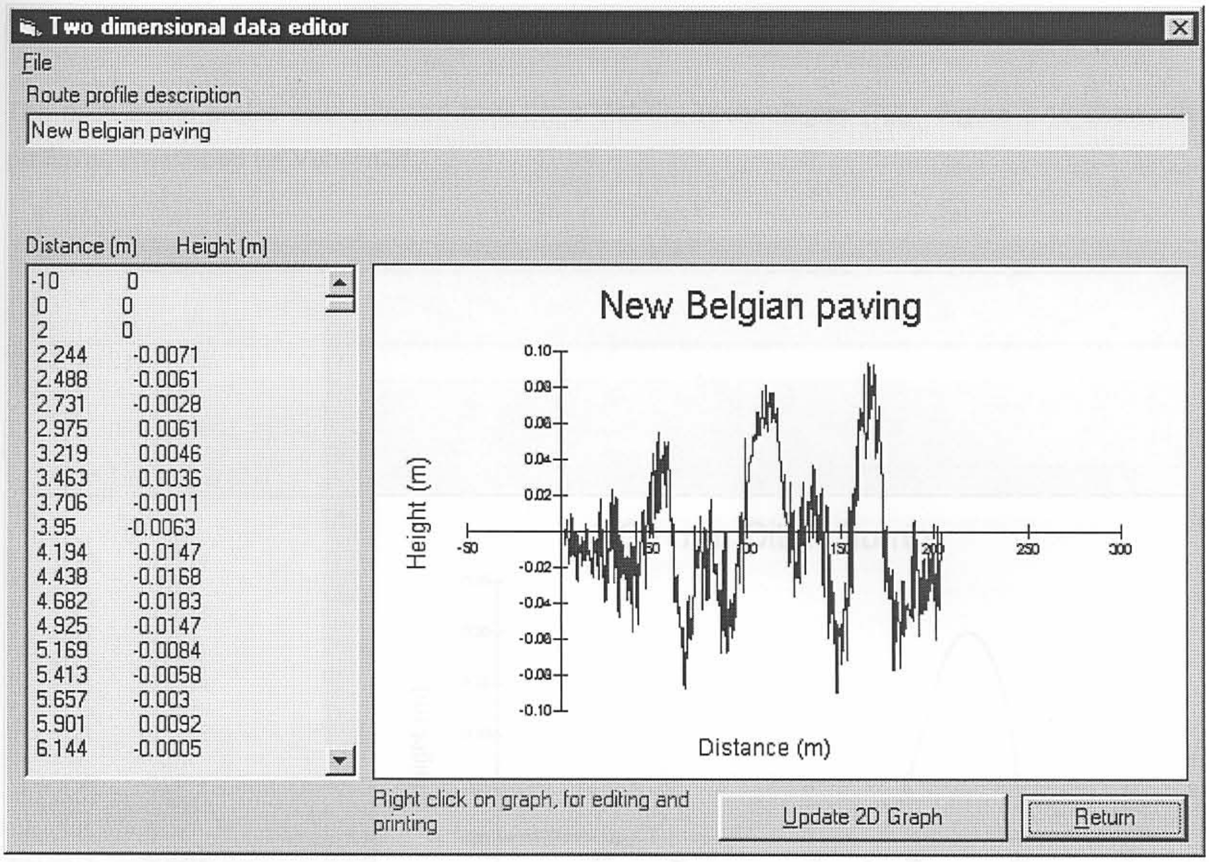


Figure 5.14: New Belgian road profile as measured with profilometer



Route profile description

New Belgian paving

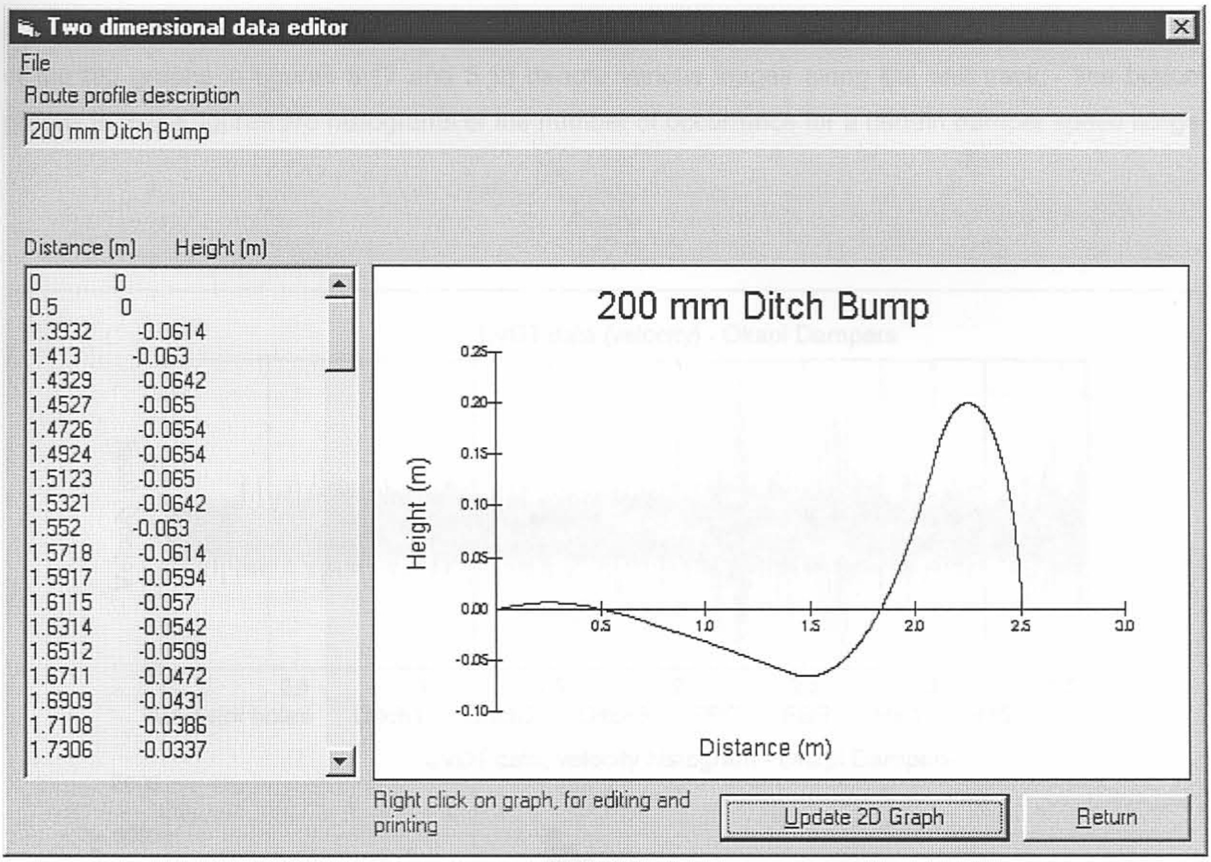
Distance (m)	Height (m)
-10	0
0	0
2	0
2.244	-0.0071
2.488	-0.0061
2.731	-0.0028
2.975	0.0061
3.219	0.0046
3.463	0.0036
3.706	-0.0011
3.95	-0.0063
4.194	-0.0147
4.438	-0.0168
4.682	-0.0183
4.925	-0.0147
5.169	-0.0084
5.413	-0.0058
5.657	-0.003
5.901	0.0092
6.144	-0.0005

Right click on graph, for editing and printing

Figure 5.15: New Belgian road profile as prescribed for Vehsim2d

5.3.3 Ditch bump

The ditch bump profile was obtained from Land Mobility Technologies [72]. Figure 5.16 shows the profile as prescribed for Vehsim2d.



Two dimensional data editor

File

Route profile description: 200 mm Ditch Bump

Distance (m)	Height (m)
0	0
0.5	0
1.3932	-0.0614
1.413	-0.063
1.4329	-0.0642
1.4527	-0.065
1.4726	-0.0654
1.4924	-0.0654
1.5123	-0.065
1.5321	-0.0642
1.552	-0.063
1.5718	-0.0614
1.5917	-0.0594
1.6115	-0.057
1.6314	-0.0542
1.6512	-0.0509
1.6711	-0.0472
1.6909	-0.0431
1.7108	-0.0386
1.7306	-0.0337

Right click on graph, for editing and printing

Figure 5.16: Ditch bump road profile as prescribed for Vehsim2d

5.4 Optimisation input

Inspection of the experimental data, in figures 5.17 and 5.18, for the Okapi vehicle driven over a certain test track, shows that damper deflection rates obtained were typically below 1.5 m/s. Figure 5.17 shows test data for the Okapi vehicle fitted with Okapi (Gabriel as shown in figure 5.6) dampers. Figure 5.18 displays the data for the Okapi fitted with Samil dampers. The annotations at the bottom of the top graphs in figures 5.17 and 5.18 denote various stages along the test track. The bottom graphs in these figures are histograms of the number of occurrence for a certain damper speed range.

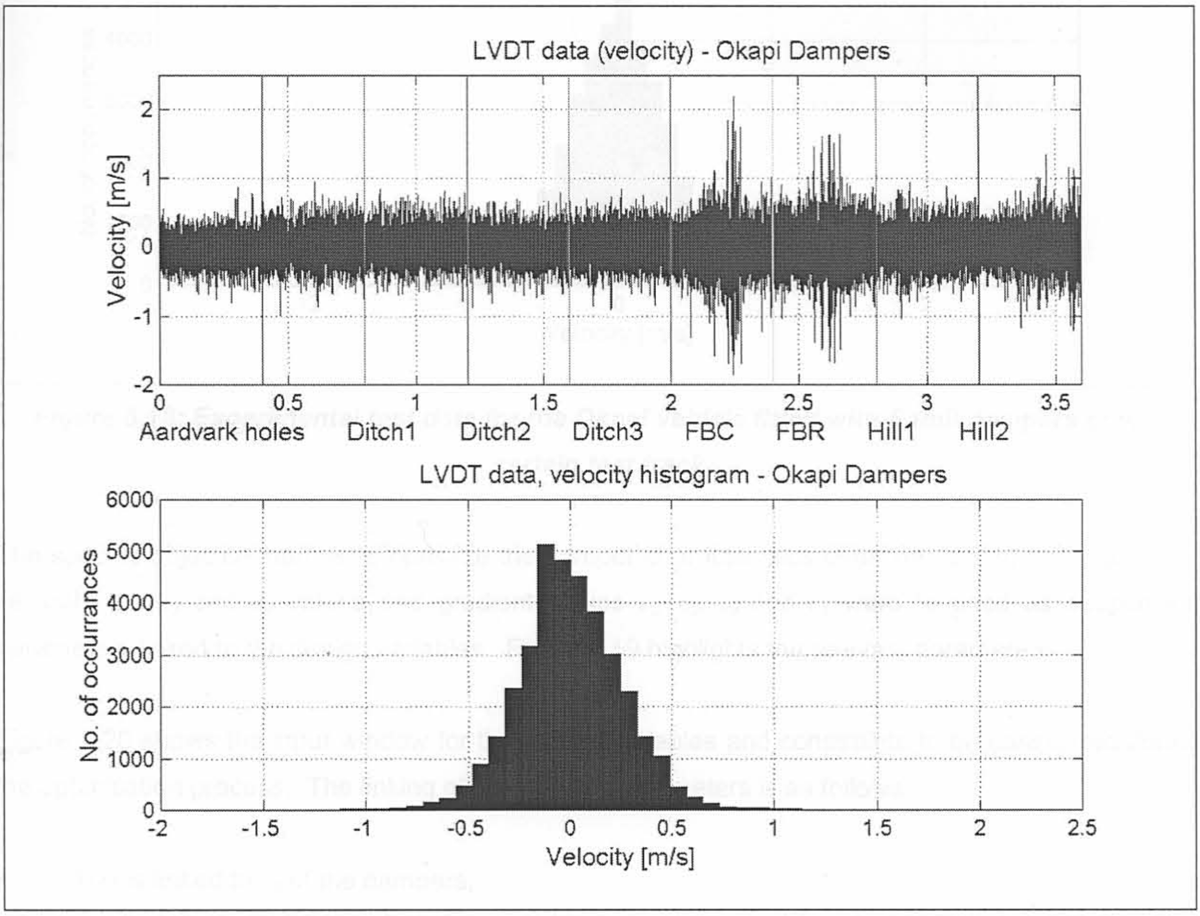


Figure 5.17: Experimental test data for the Okapi vehicle fitted with Okapi (Gabriel dampers) over a certain test track

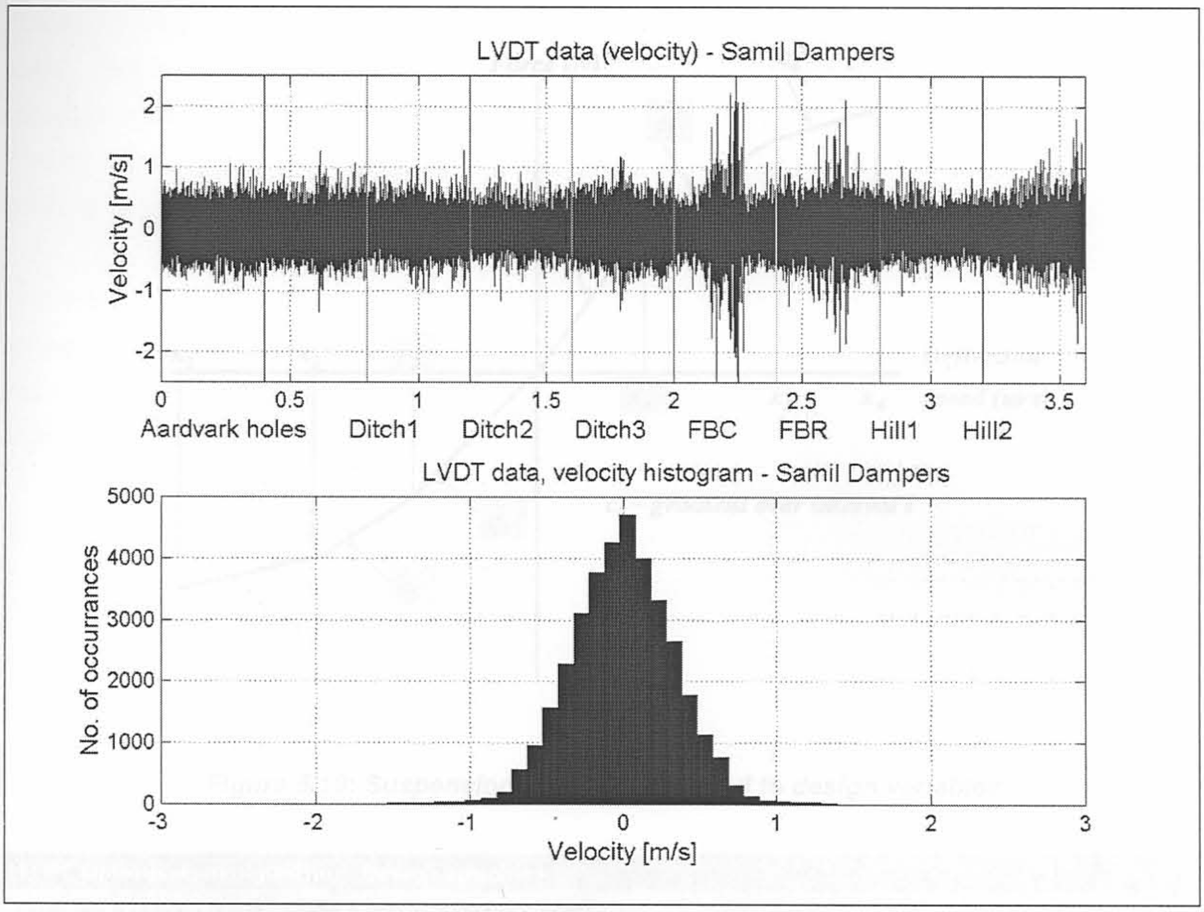


Figure 5.18: Experimental test data for the Okapi vehicle fitted with Samil dampers over a certain test track

The specific objective here is to optimise the damper characteristics over the –2.5 to 2.5 m/s range, i.e. only the x_3 and x_4 values and gradient values c_2, c_3, c_4 and c_5 were to used as suspension parameters linked to the design variables. Figure 5.19 highlights the relevant parameters.

Figure 5.20 shows the input window for the design variables and constraints to be considered during the optimisation process. The linking of variables to parameters is as follows:

- $X(1)$ is linked to x_3 of the dampers,
- $X(2)$ is linked to x_4 of the dampers,
- $X(3)$ is linked to c_2 of the dampers,
- $X(4)$ is linked to c_3 of the dampers,
- $X(5)$ is linked to c_4 of the dampers and
- $X(6)$ is linked to c_5 of the dampers.

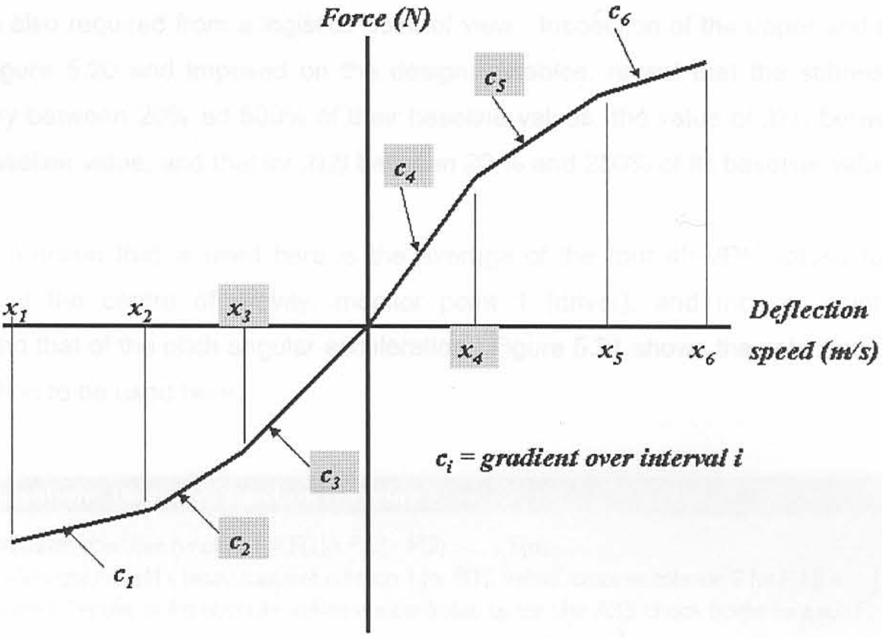
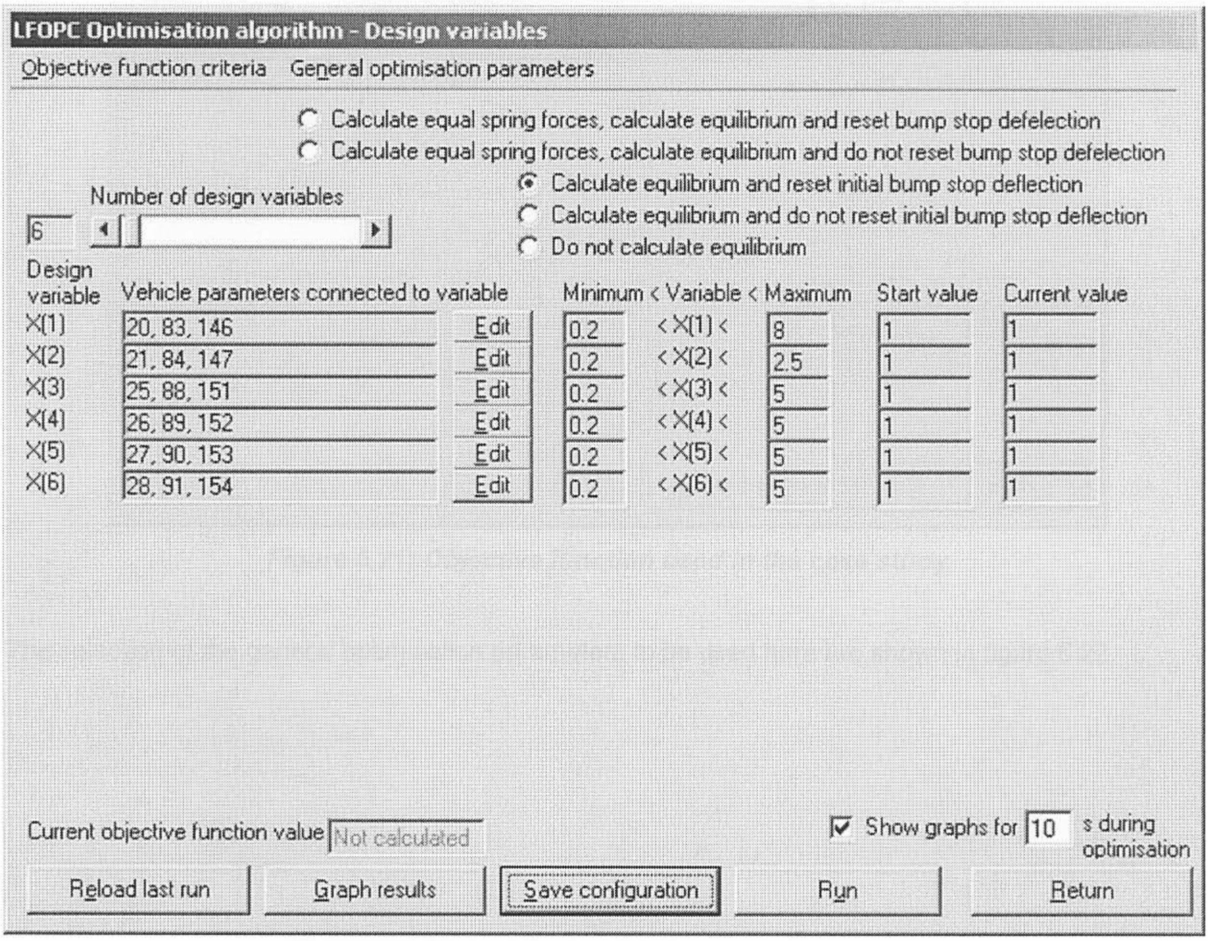


Figure 5.19: Suspension parameters linked to design variables



○ 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: 6

Design variable	Vehicle parameters connected to variable		Minimum	< Variable <	Maximum	Start value	Current value
X(1)	20, 83, 146	Edit	0.2	< X(1) <	8	1	1
X(2)	21, 84, 147	Edit	0.2	< X(2) <	2.5	1	1
X(3)	25, 88, 151	Edit	0.2	< X(3) <	5	1	1
X(4)	26, 89, 152	Edit	0.2	< X(4) <	5	1	1
X(5)	27, 90, 153	Edit	0.2	< X(5) <	5	1	1
X(6)	28, 91, 154	Edit	0.2	< X(6) <	5	1	1

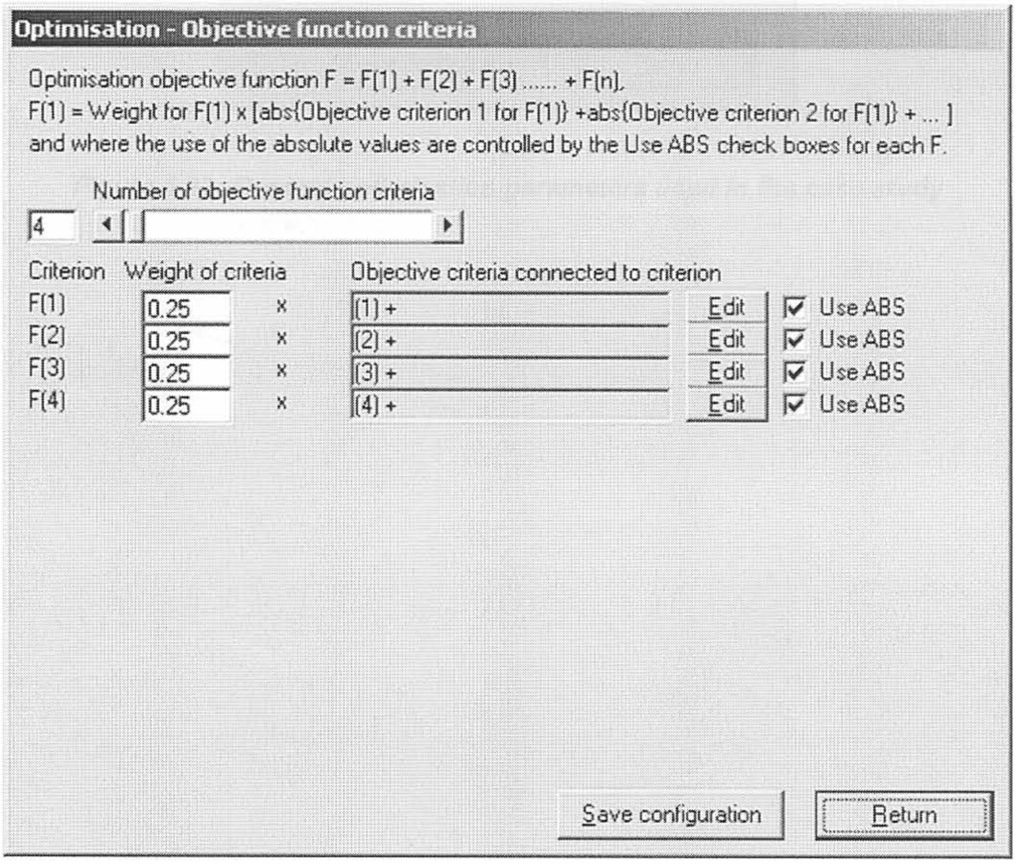
Current objective function value: Not calculated

☑ Show graphs for 10 s during optimisation

Figure 5.20: Design variable input for case study

According to this selection of parameters the same dampers are used on the front, middle and rear axles. This is also required from a logistics point of view. Inspection of the upper and lower bounds specified in figure 5.20 and imposed on the design variables, reveal that the stiffness values are allowed to vary between 20% ad 500% of their baseline values, the value of *X(1)* between 20% and 800% of its baseline value, and that for *X(2)* between 20 % and 250% of its baseline value.

The objective function that is used here is the average of the four 4h-VDV values for the vertical accelerations at the centre of gravity, monitor point 1 (driver), and monitor point 2 (left rear passenger), and that of the pitch angular acceleration. Figure 5.21 shows the selection of the specific objective function to be used here.



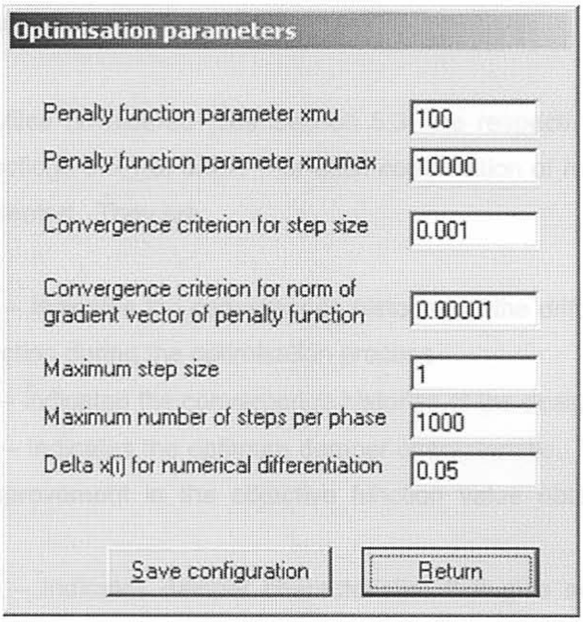
Optimisation objective function F = F(1) + F(2) + F(3) ...... + F(n),
F(1) = Weight for F(1) x [abs{Objective criterion 1 for F(1)} +abs{Objective criterion 2 for F(1)} + ...]
and where the use of the absolute values are controlled by the Use ABS check boxes for each F.

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 5.21: Objective function used in the case study

The selection of the general optimisation parameters to be used here are shown in figure 5.22.



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 5.22: General optimisation parameters used in the case study

5.5 Optimisation results

For each of the route profiles considered (see Section 5.3) the respective optimisation results are displayed graphically in sections 5.5.1 to 5.5.7. For each combination of route profile and speed four graphical displays are presented. They are:

* Graphical display 1 – Indicates the convergence histories of the different objective criteria and overall objective function during the optimisation process.
* Graphical display 2 – Indicated the convergence histories of the design variables.
* Graphical display 3 – Indicates the optimum damper characteristic. The % value in the legend indicates the % improvement in the objective function value obtained with respect to the baseline value.
* Graphical display 4 – Indicates damper characteristics that give an objective function value within 5% of that of the optimum configuration.

A discussion of the results for the different optimisation runs is presented in section 5.5.8.

5.5.1 Dirt road 40 km/h

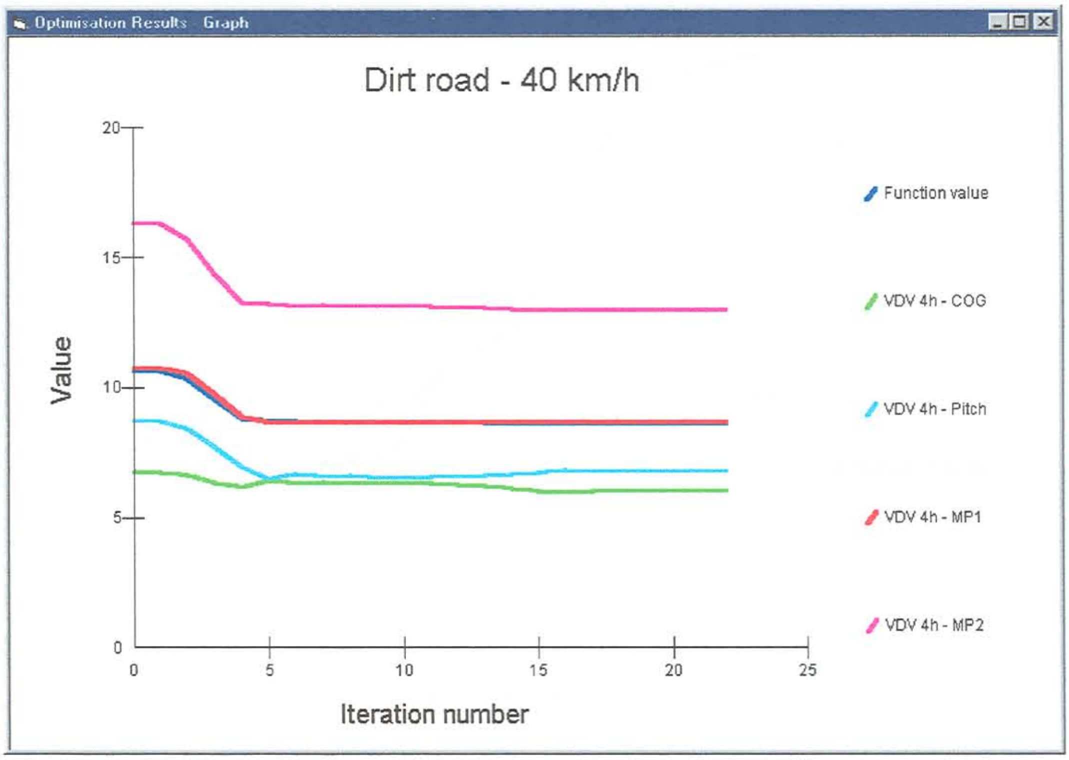


Figure 5.23: Objective function

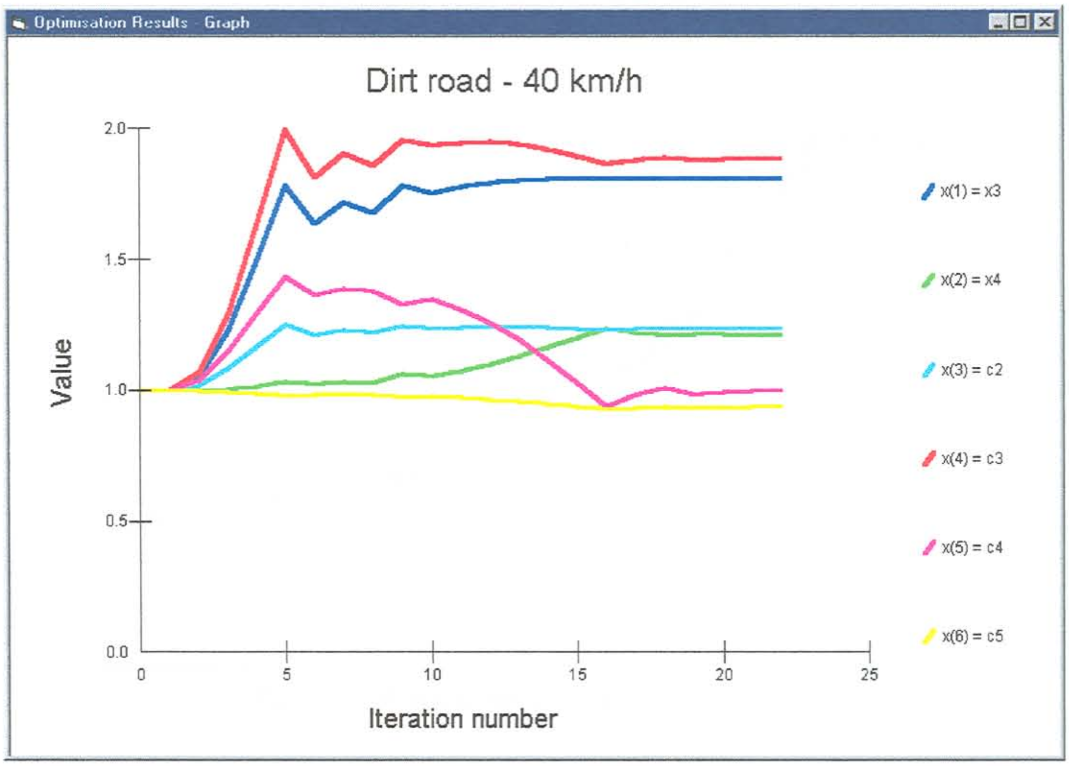


Figure 5.24: Design variables

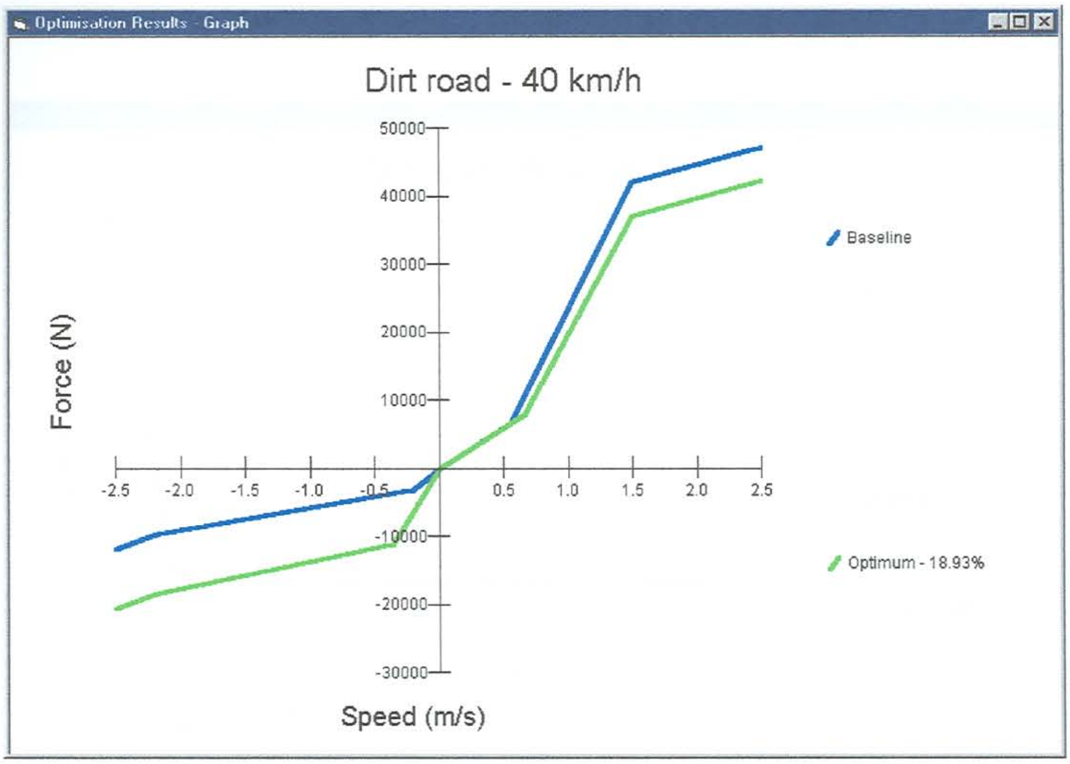


Figure 5.25: Optimum damper characteristics

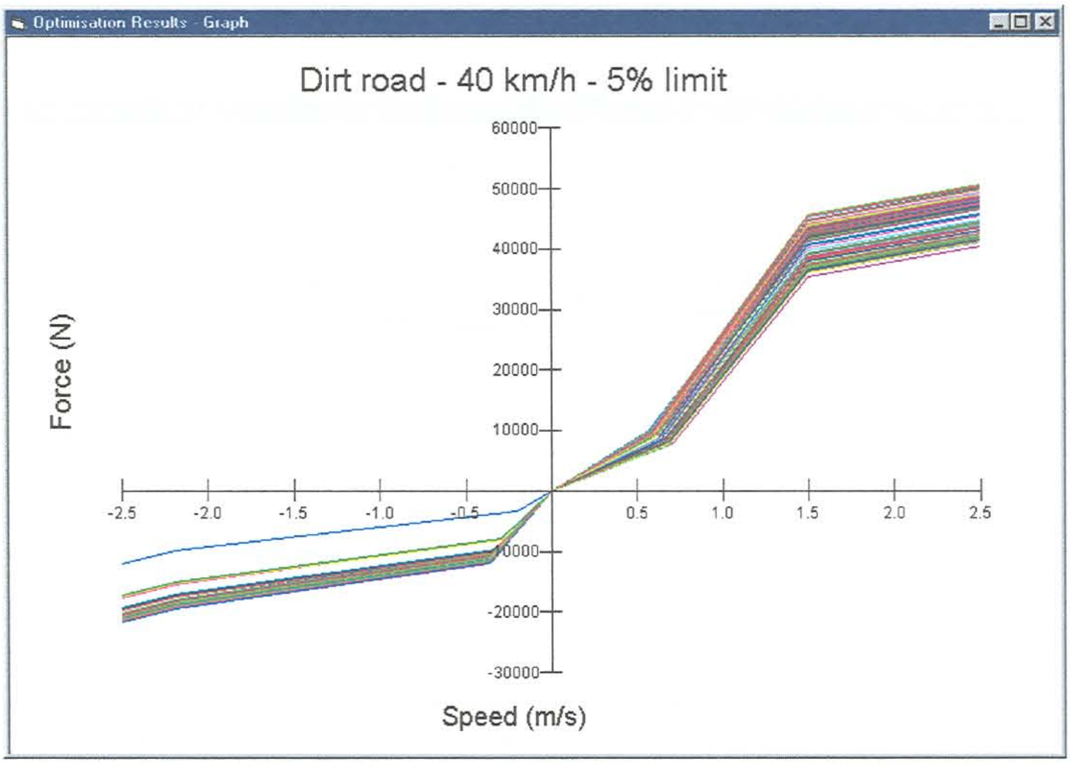


Figure 5.26: 5% Limit damper characteristics

5.5.2 Dirt road 60 km/h

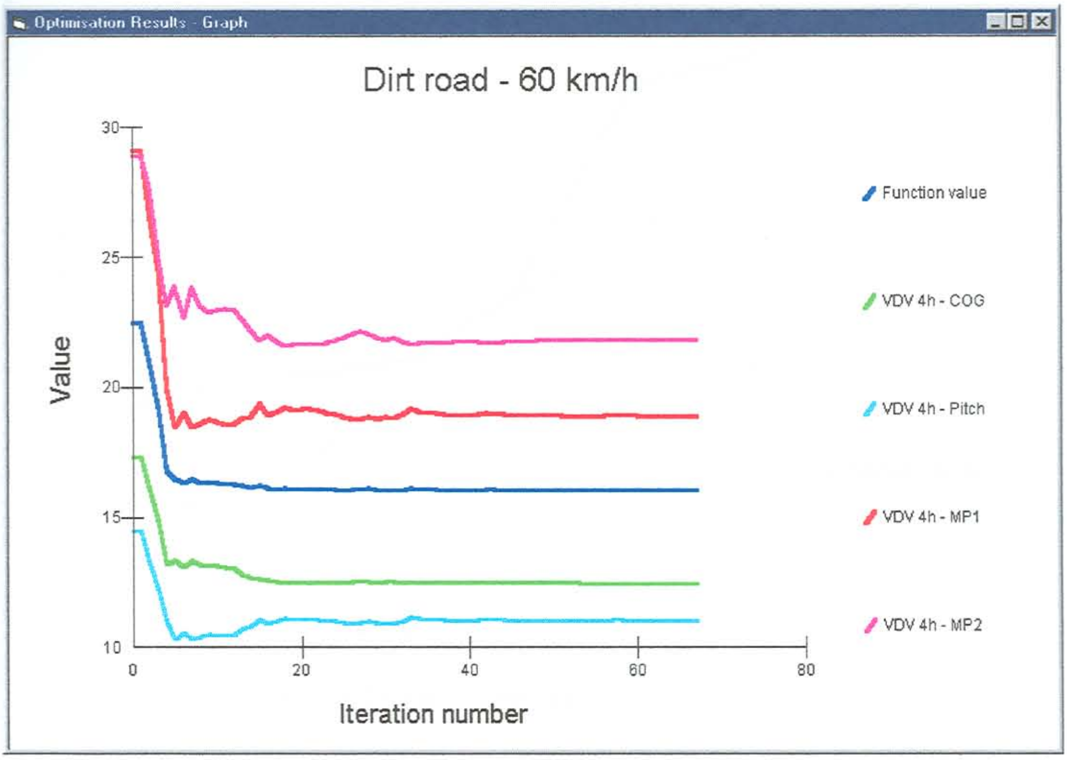


Figure 5.27: Objective function

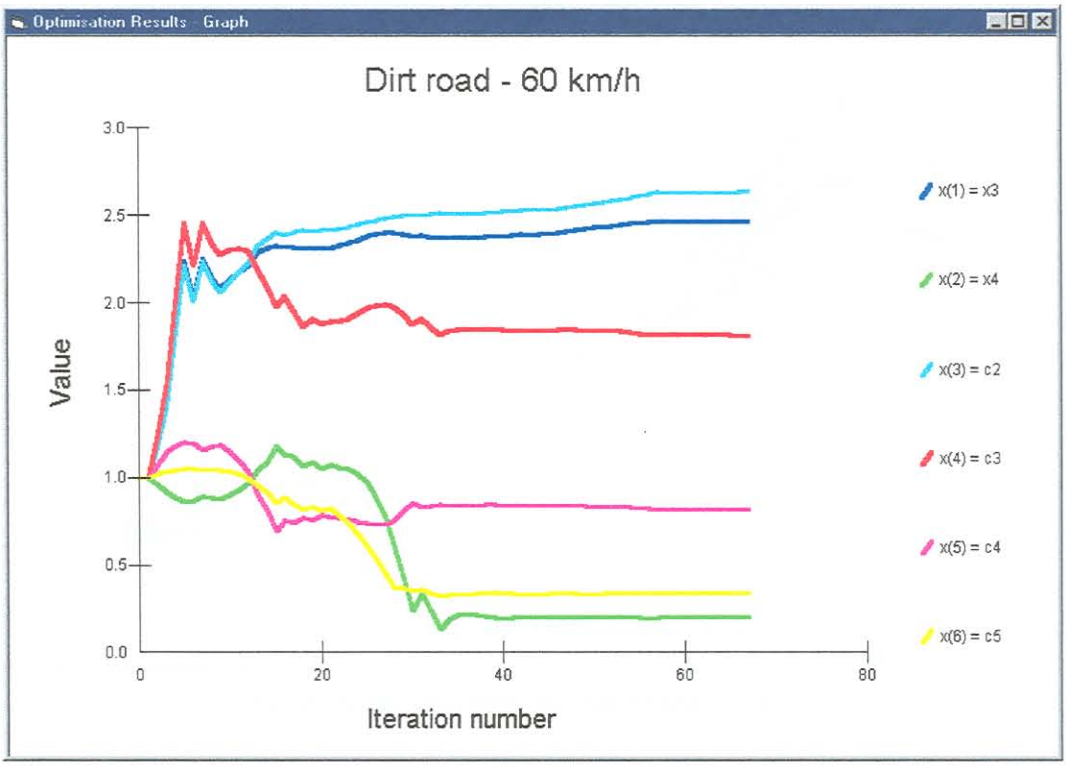


Figure 5.28: Design variables

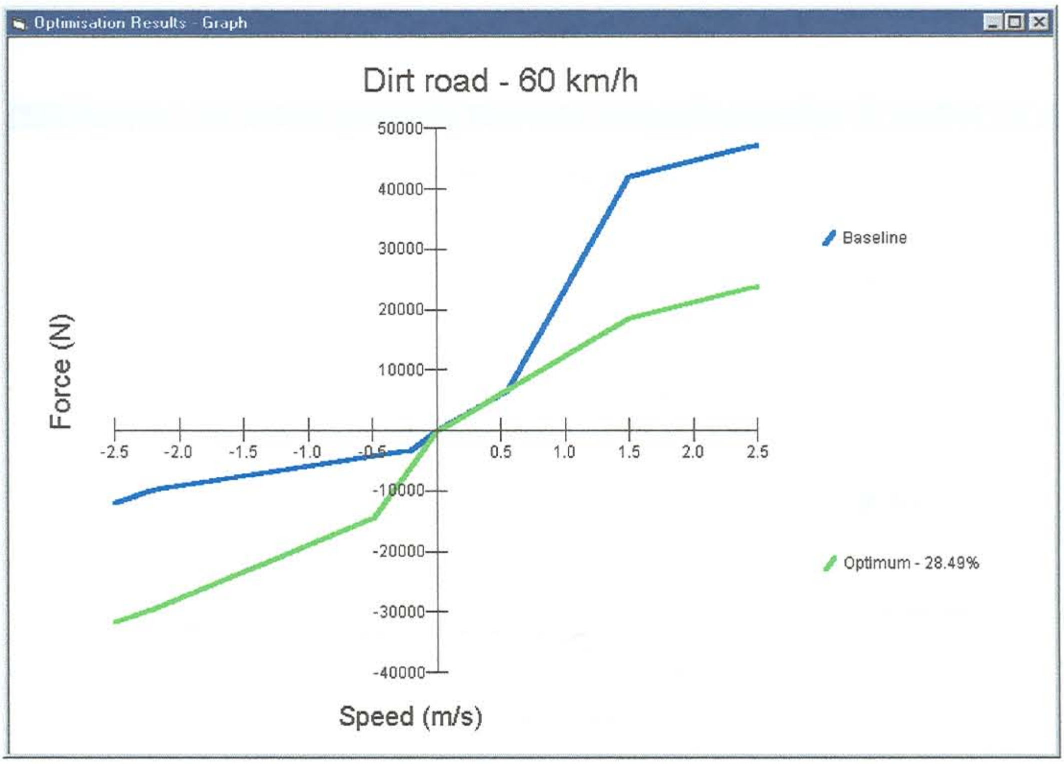


Figure 5.29: Optimum damper characteristics

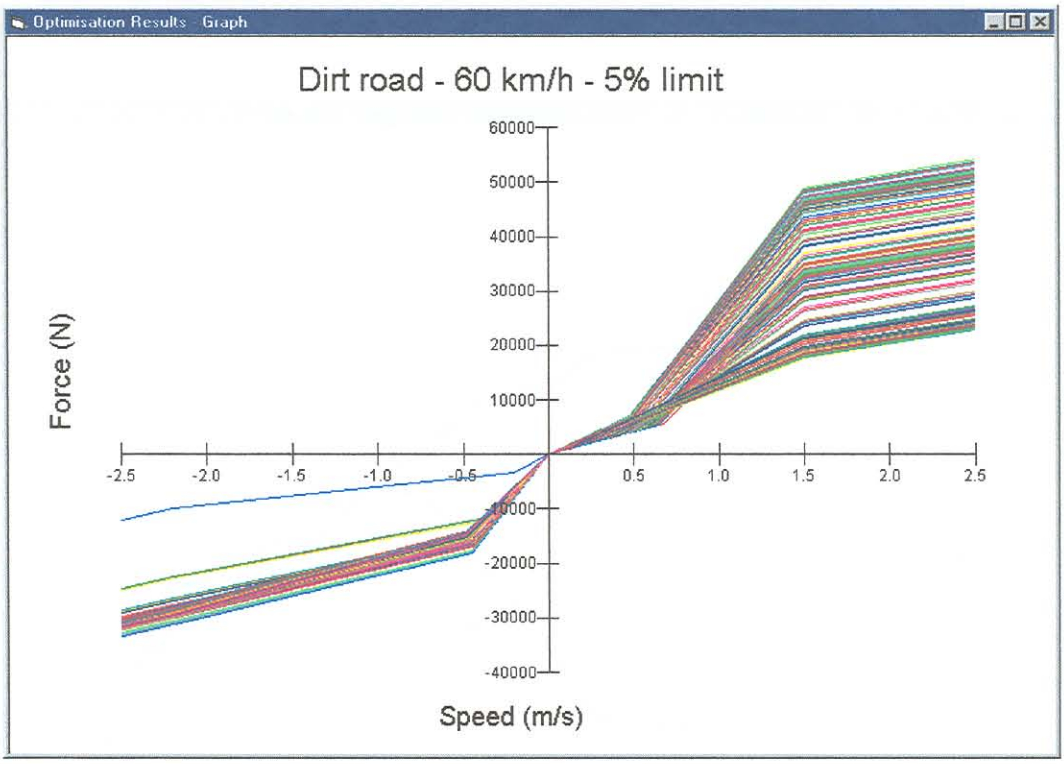


Figure 5.30: 5% Limit damper characteristics

5.5.3 Dirt road 70 km/h

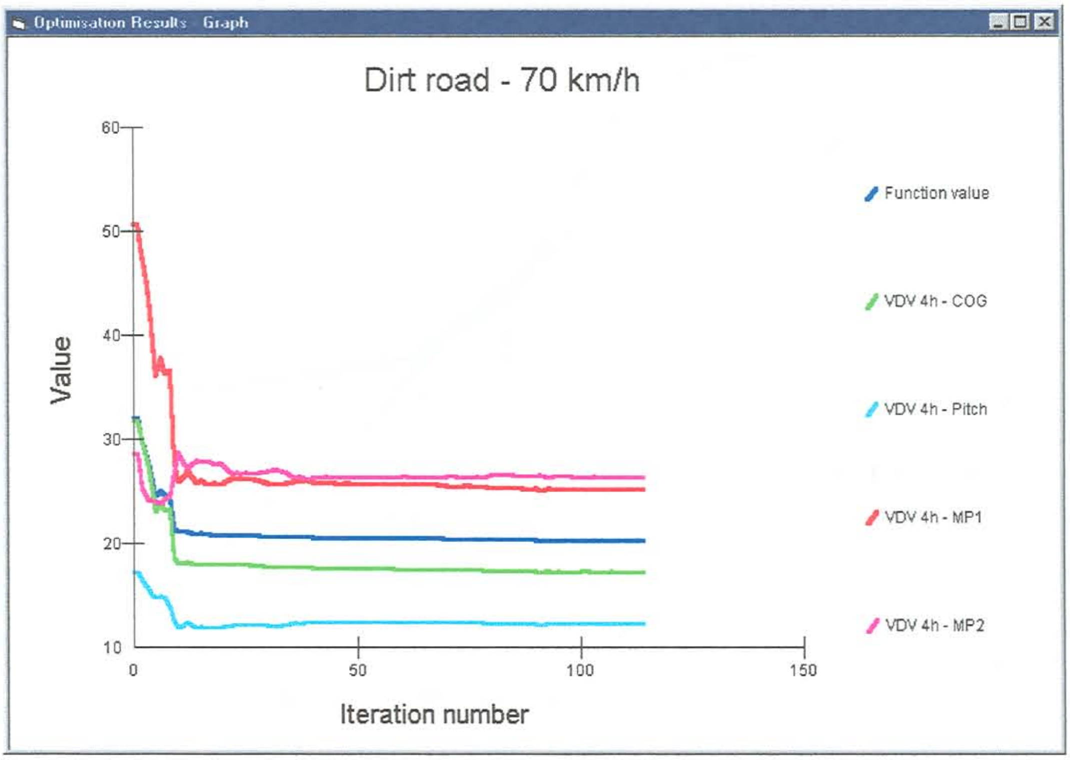


Figure 5.31: Objective function

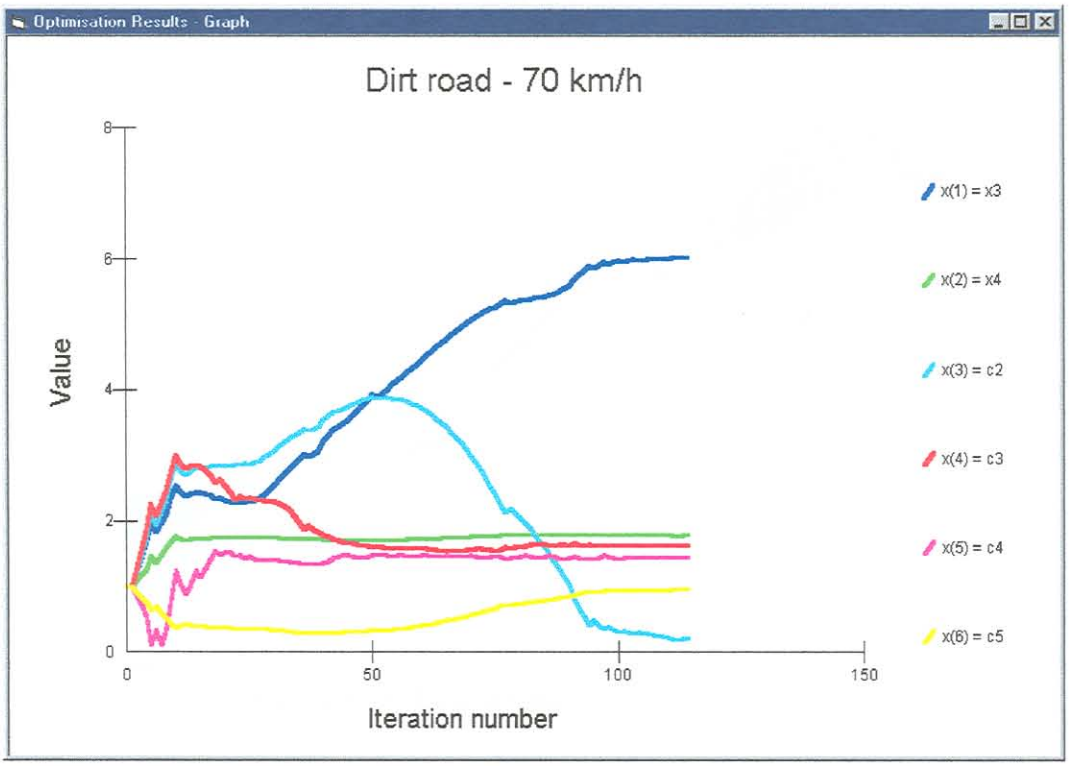


Figure 5.32: Design variables

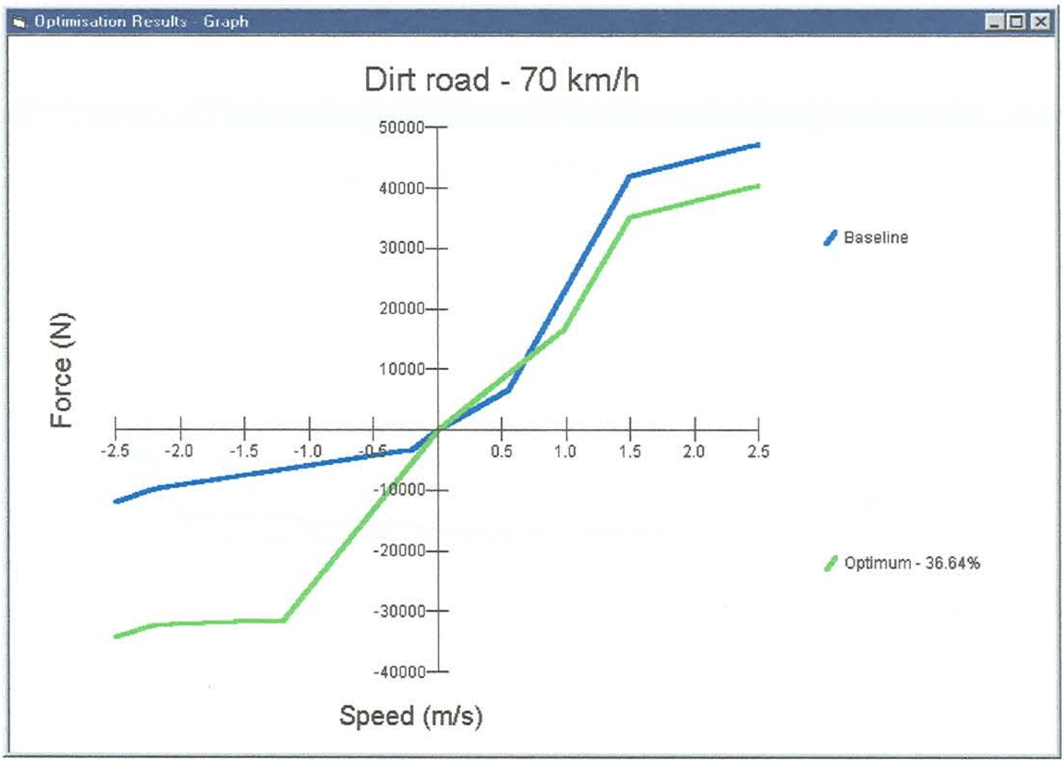


Figure 5.33: Optimum damper characteristics

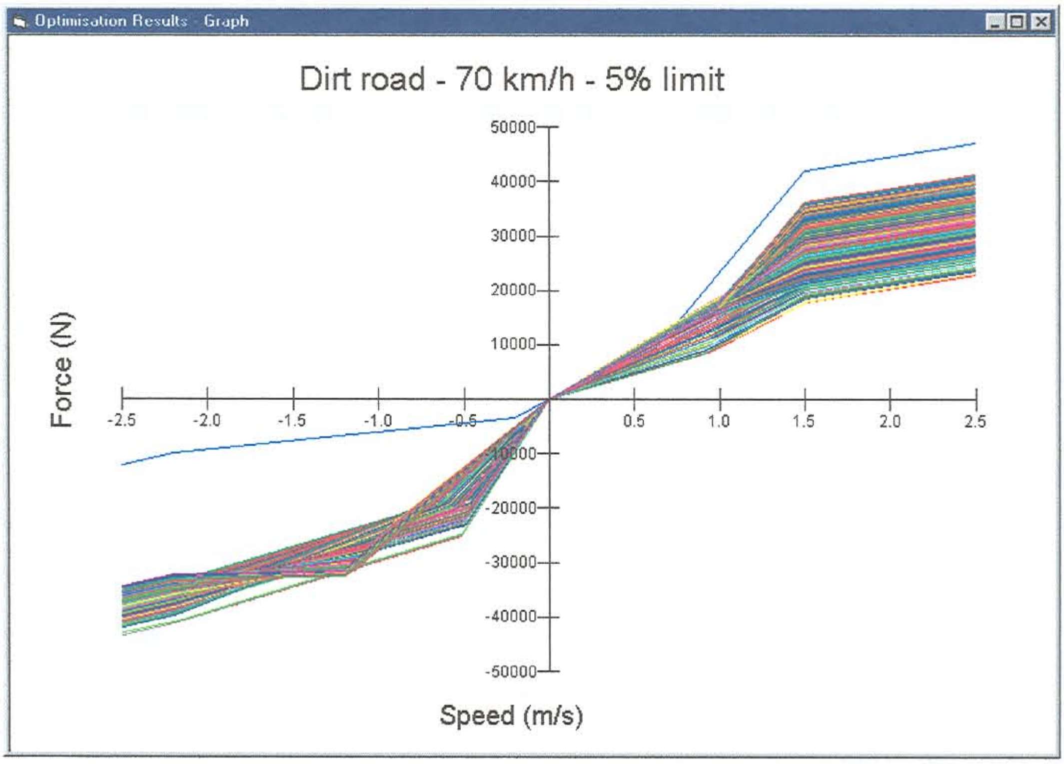


Figure 5.34: 5% Limit damper characteristics

5.5.4 Ditch bump 20 km/h

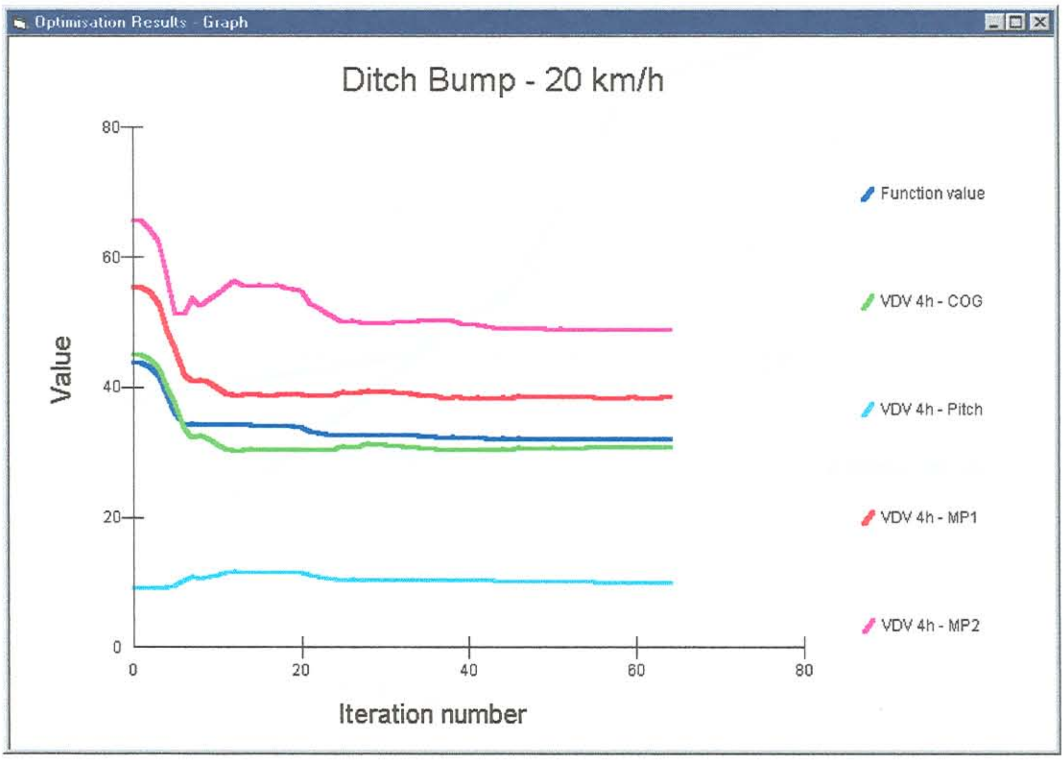


Figure 5.35: Objective function

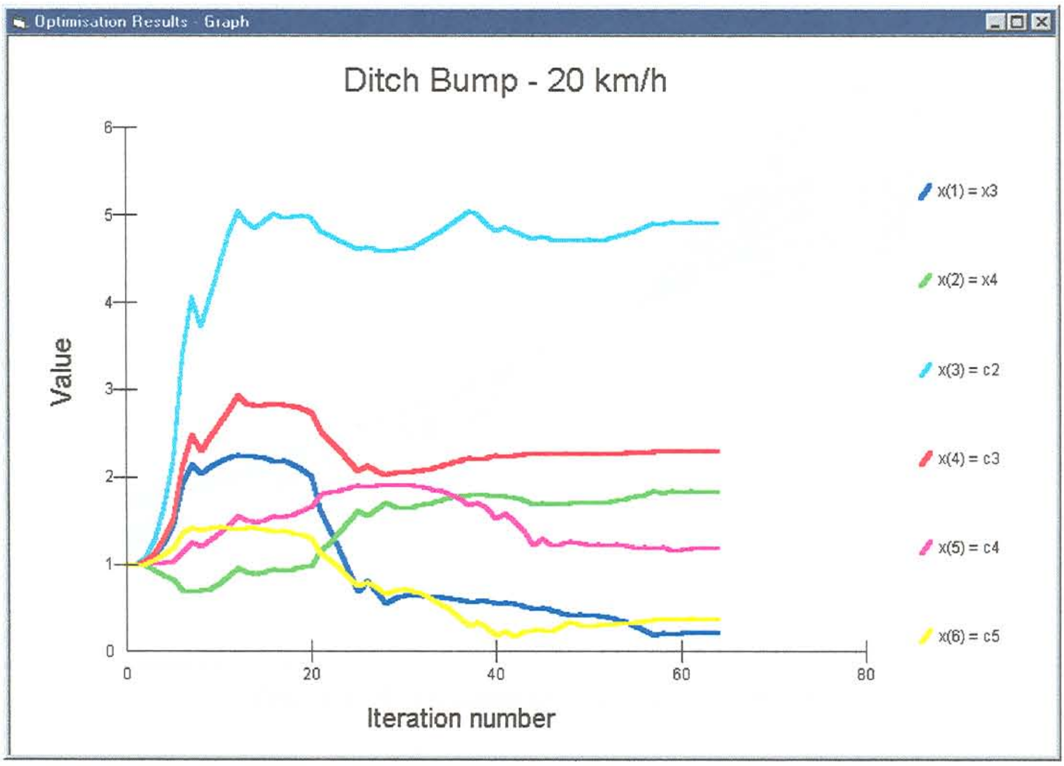


Figure 5.36: Design variables

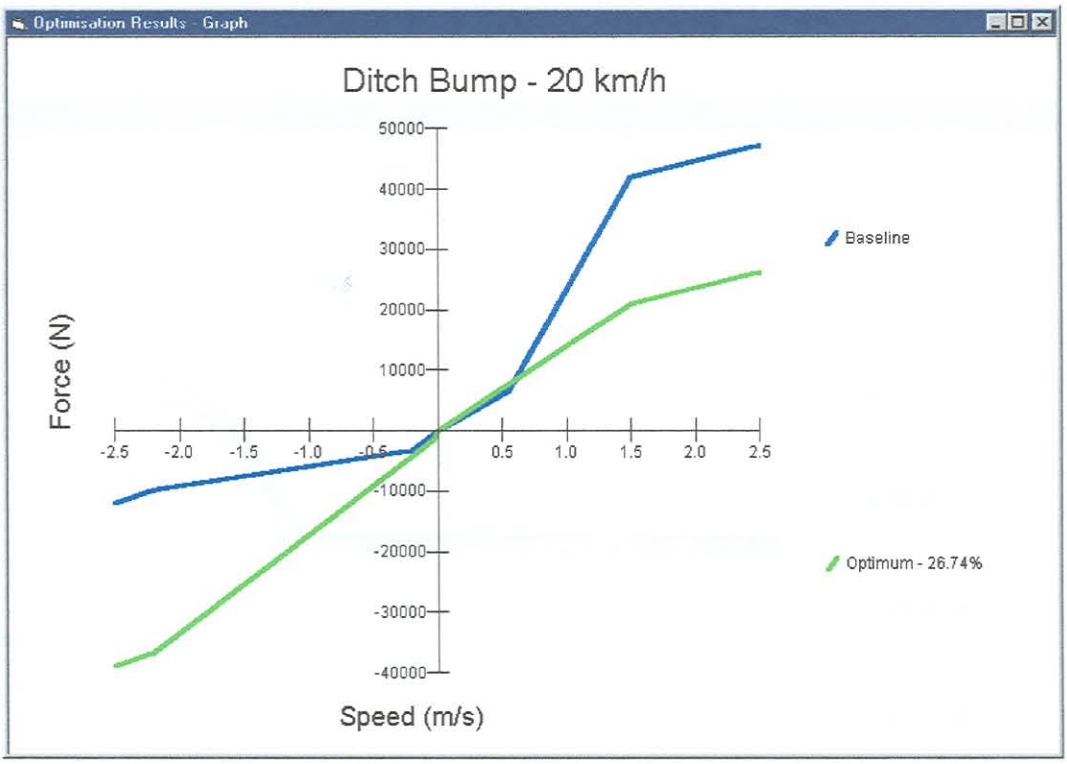


Figure 5.37: Optimum damper characteristics

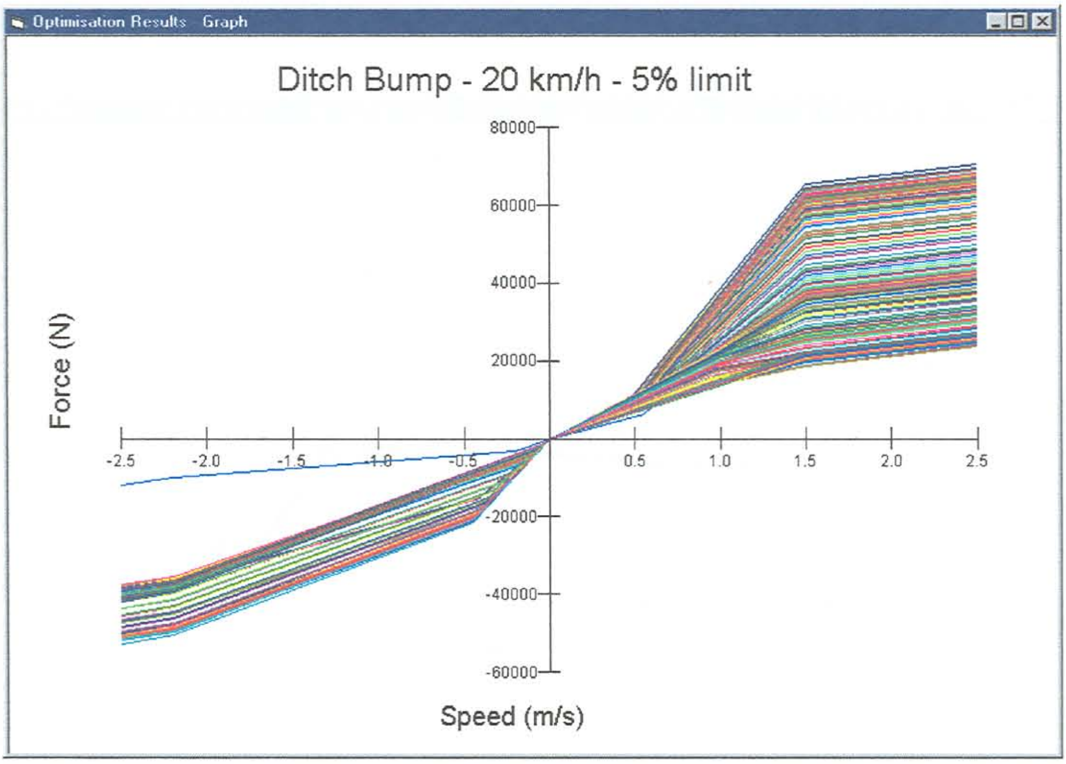


Figure 5.38: 5% Limit damper characteristics

5.5.5 Ditch bump – 30 km/h

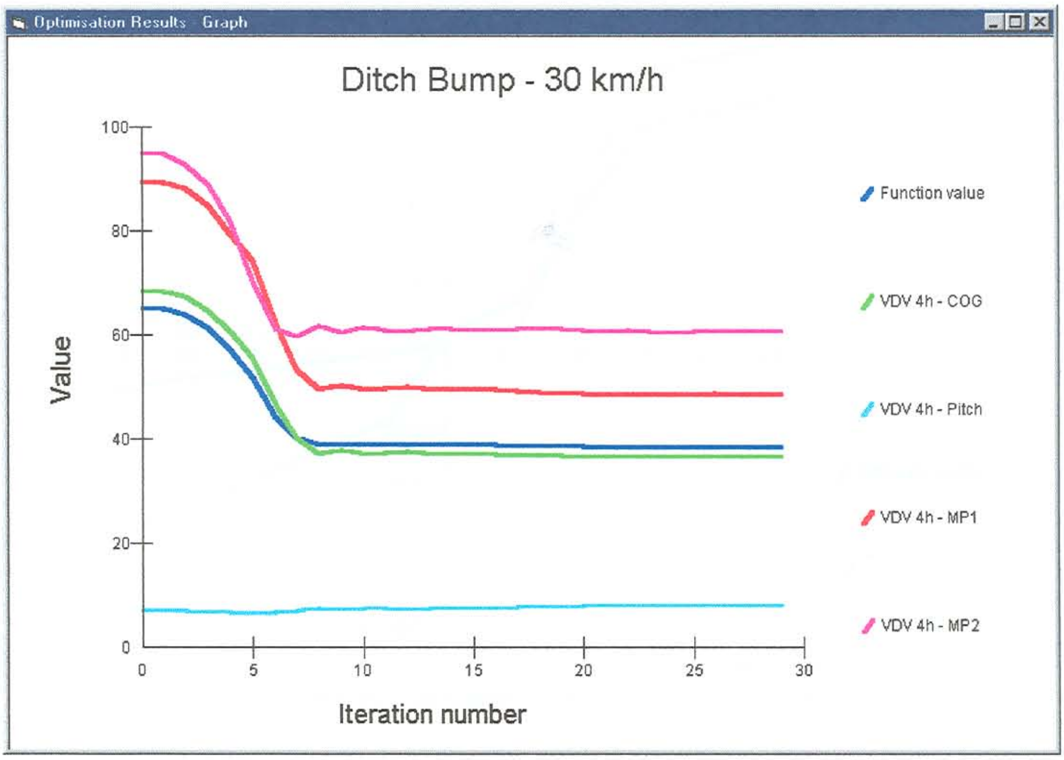


Figure 5.39: Objective function

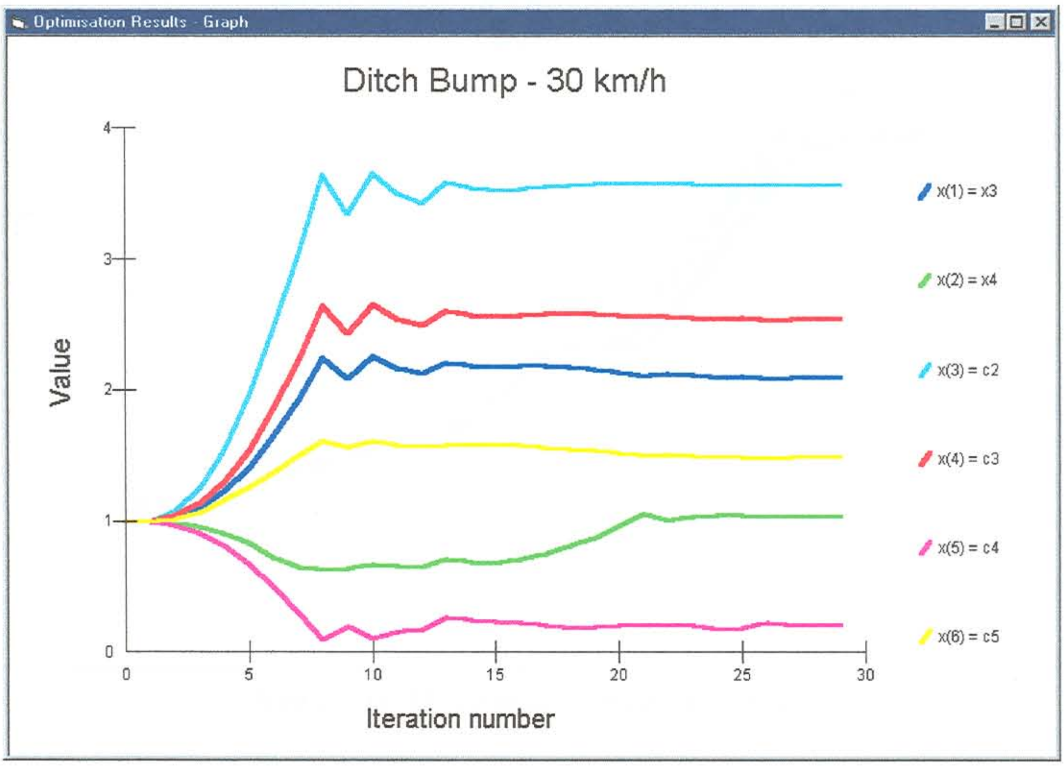


Figure 5.40: Design variables

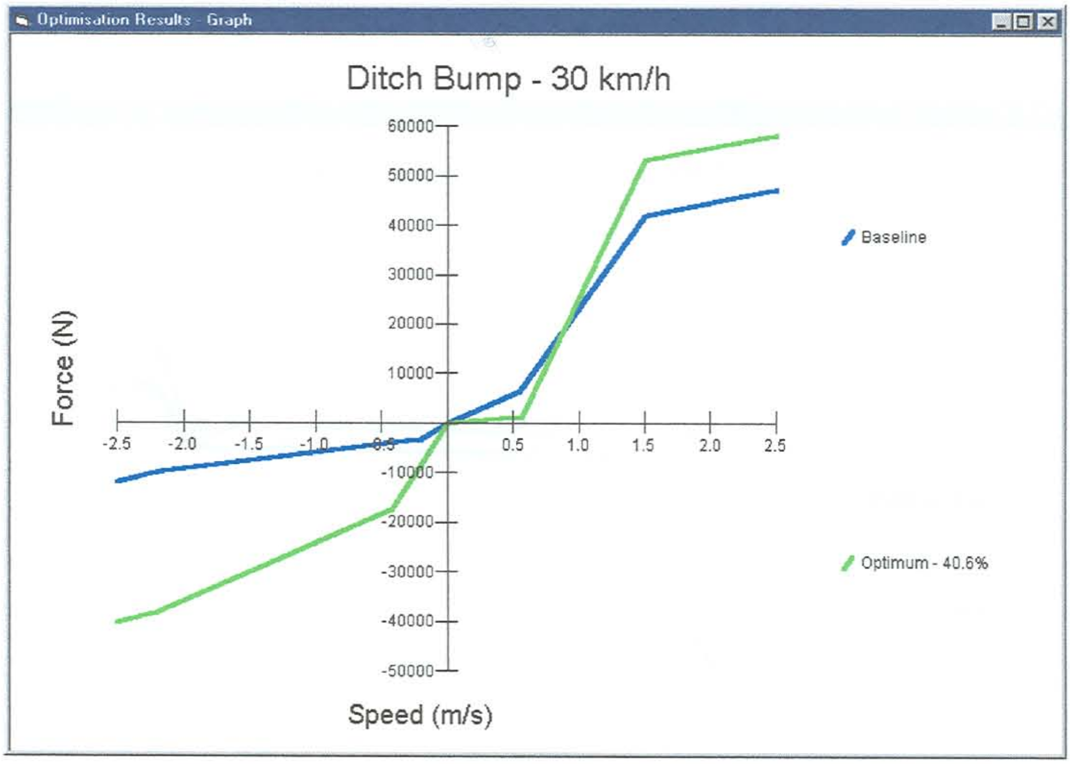


Figure 5.41: Optimum damper characteristics

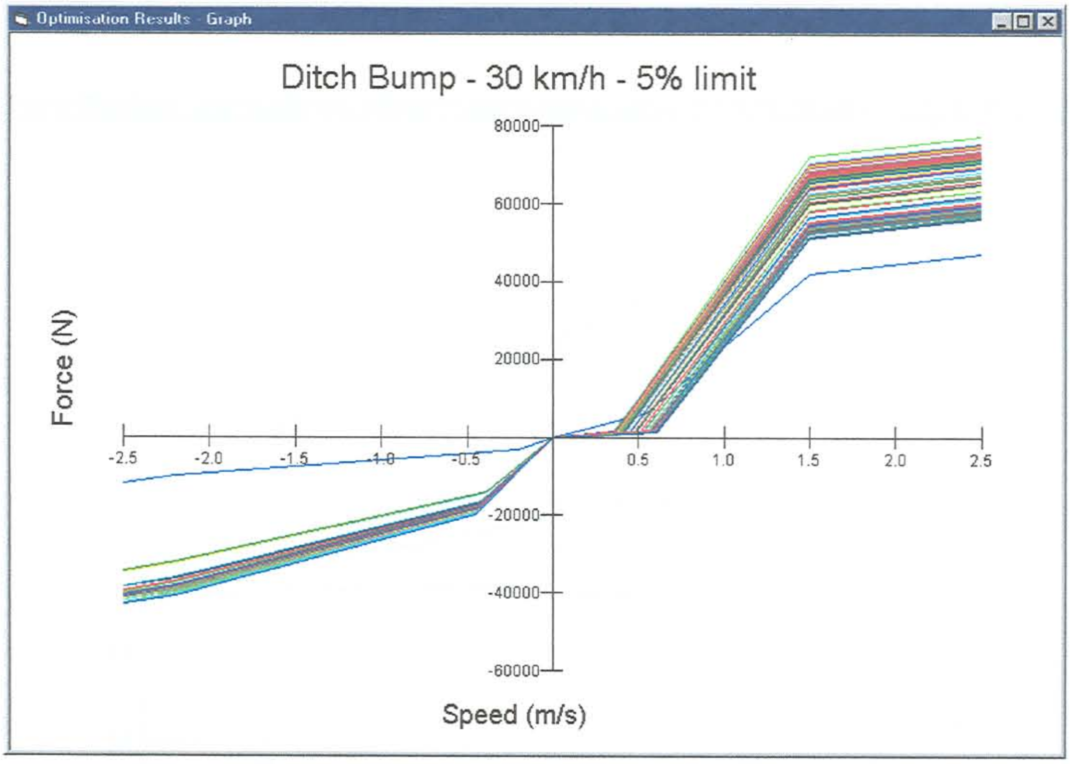


Figure 5.42: 5% Limit damper characteristics

5.5.6 New Belgian 30 km/h

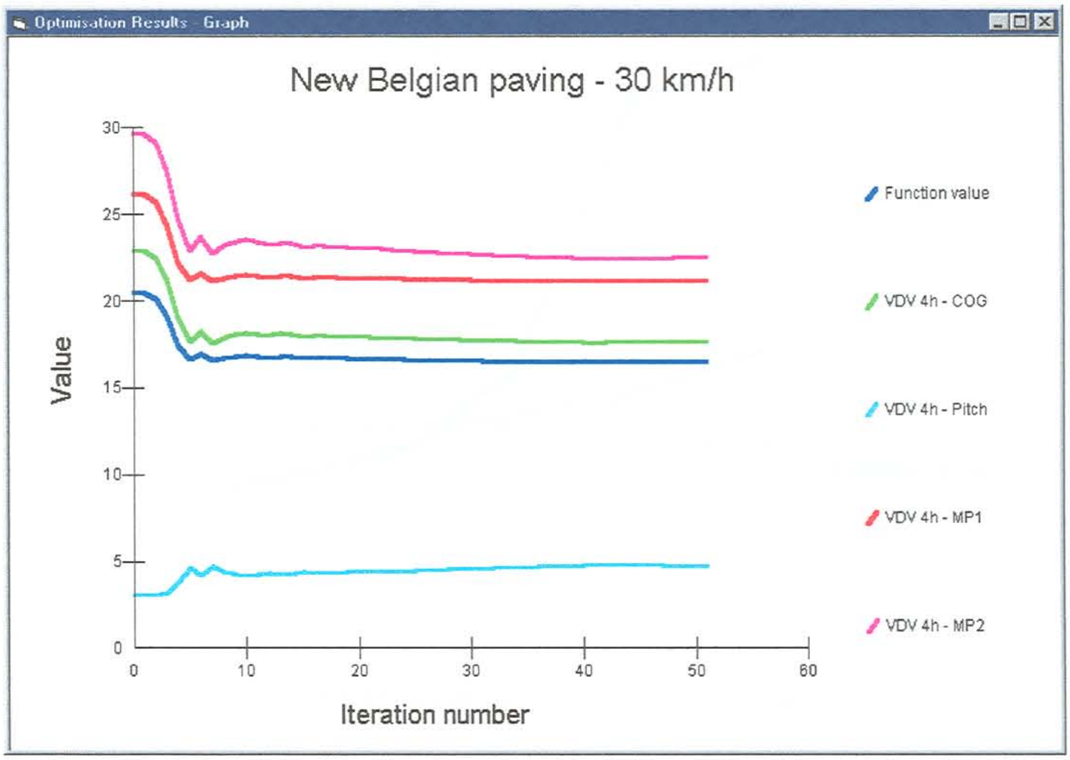


Figure 5.43: Objective function

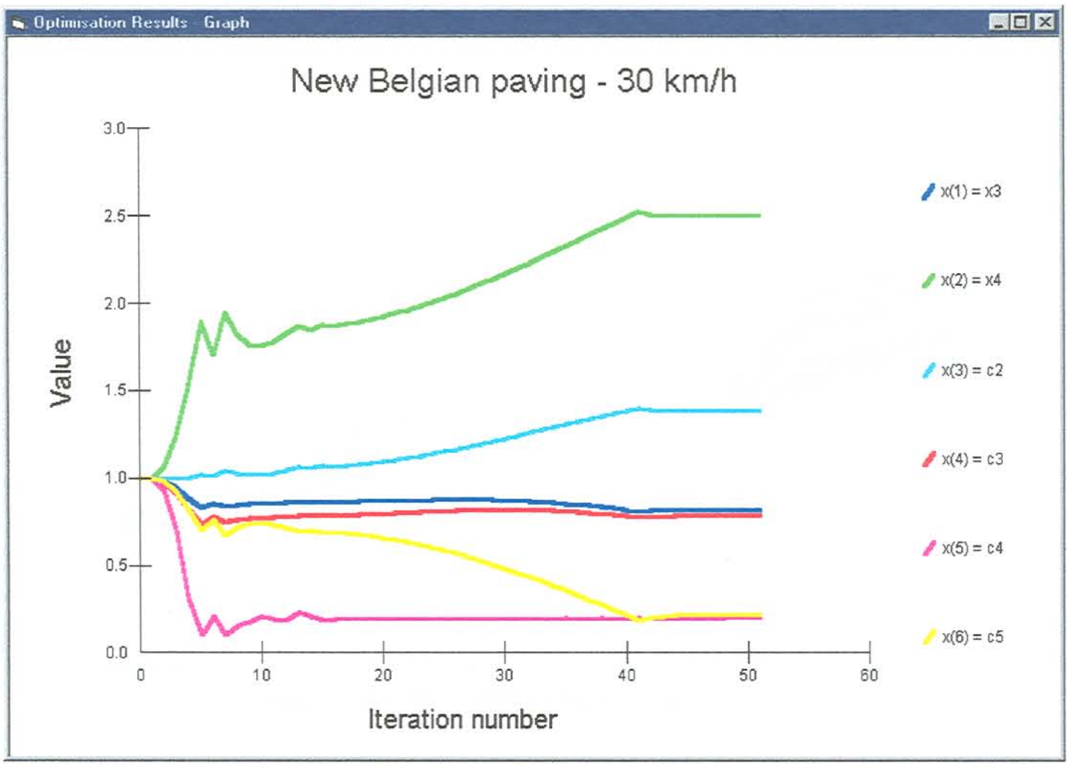


Figure 5.44: Design variables

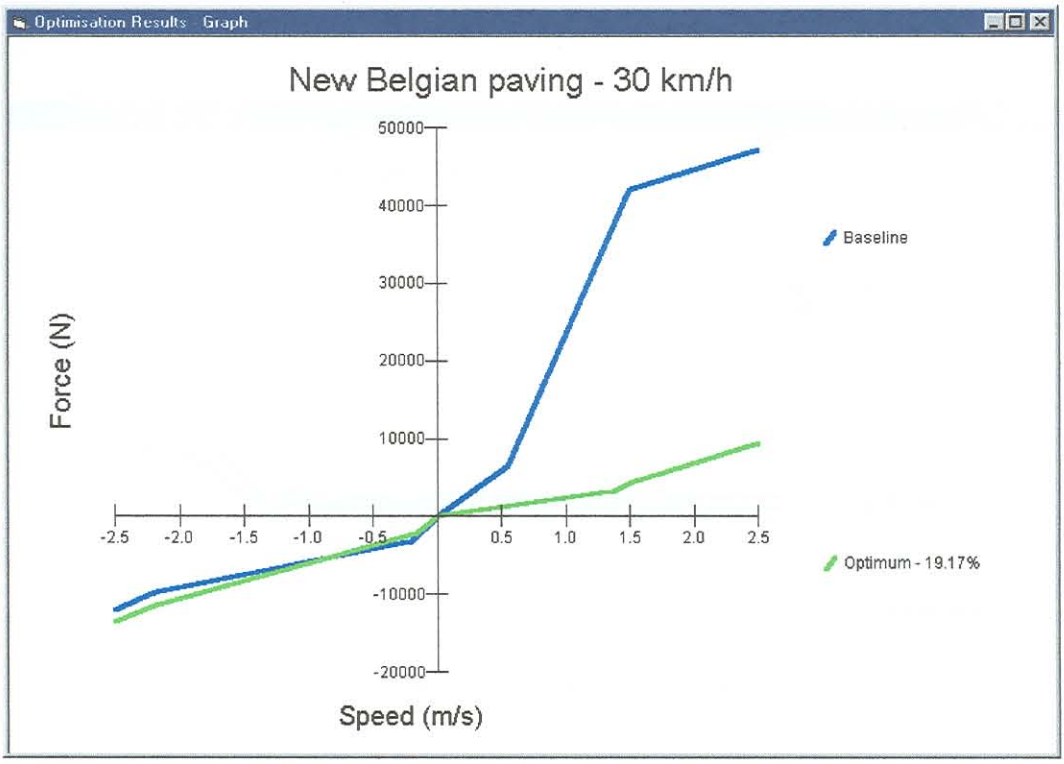


Figure 5.45: Optimum damper characteristics

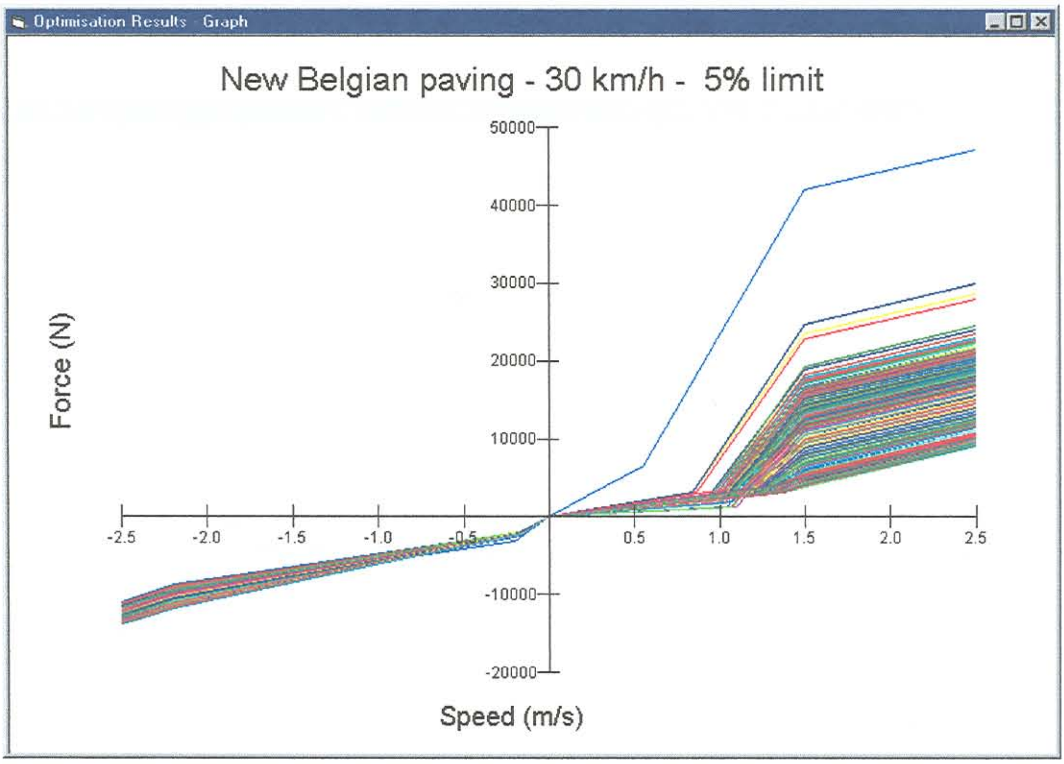


Figure 5.46: 5% Limit damper characteristics

5.5.7 New Belgian 40 km/h

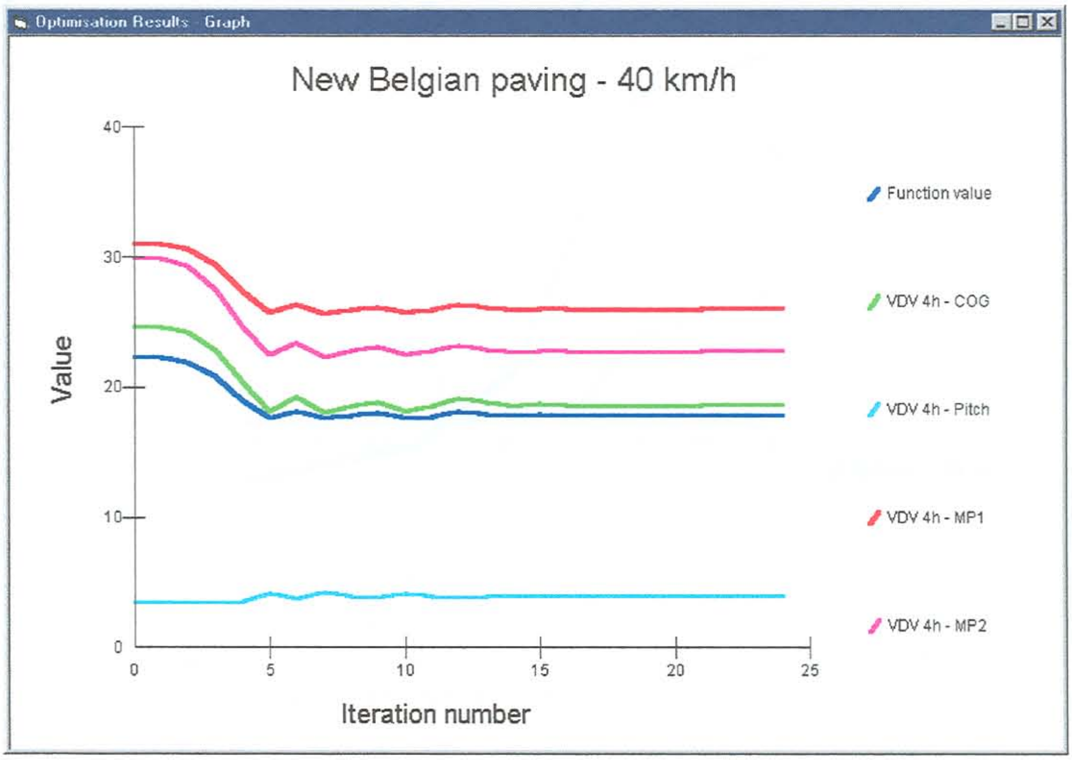


Figure 5.47: Objective function

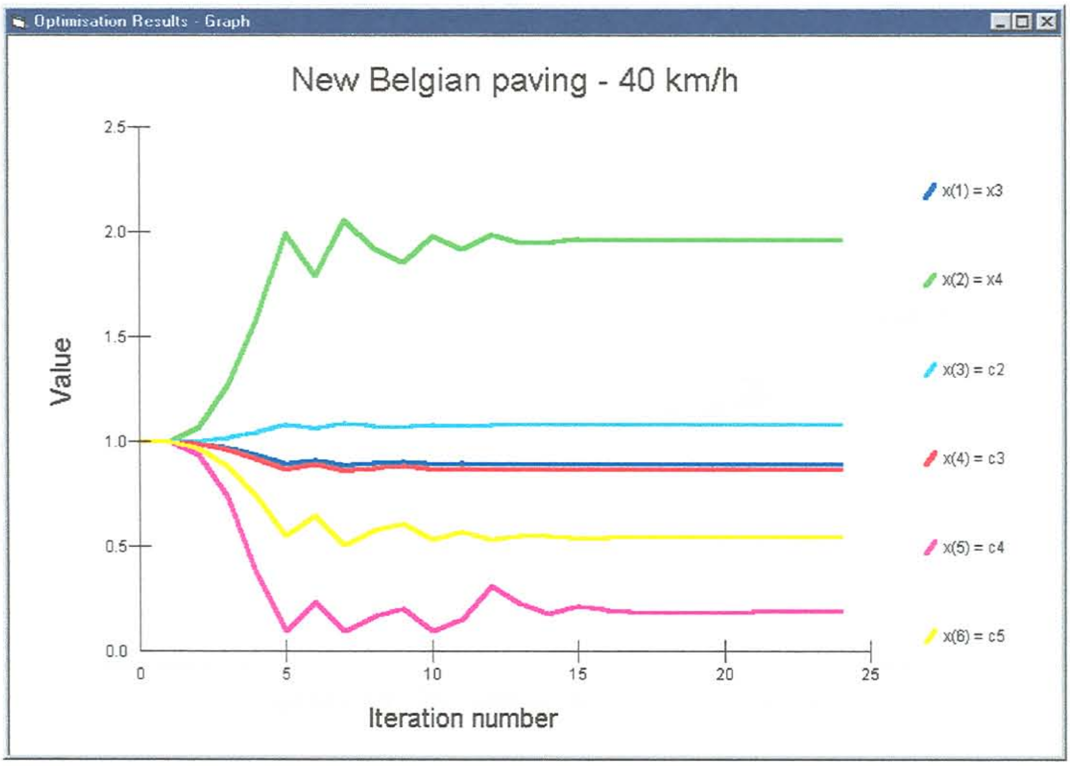


Figure 5.48: Design variables

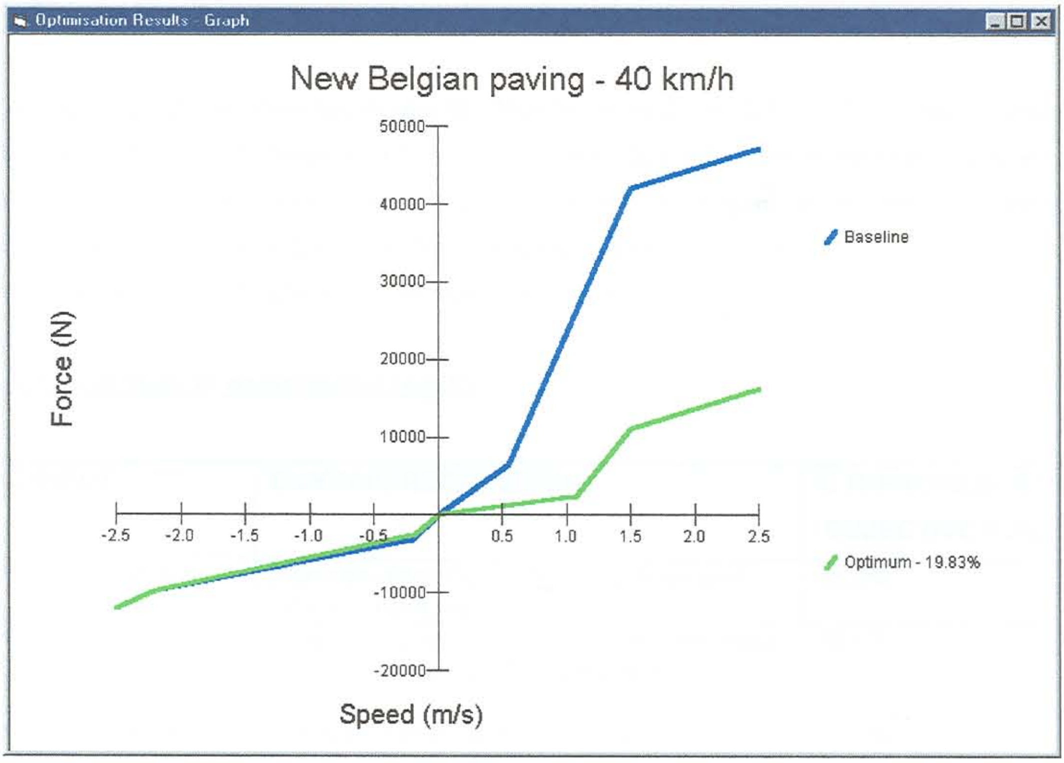


Figure 5.49: Optimum damper characteristics

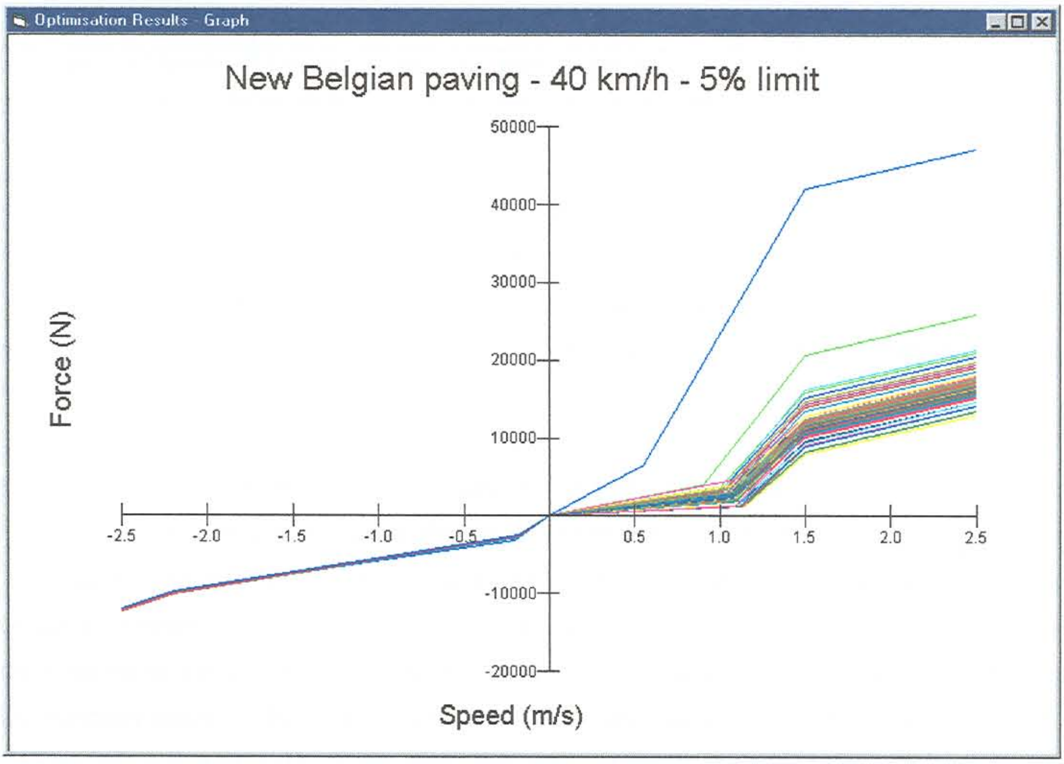


Figure 5.50: 5% Limit damper characteristics

5.5.8 Discussion of optimisation results

The main features of the optimisation results, depicted in sections, 5.5.1 to 5.5.7 are summarised in table 5.1. Reductions of between 40.6% and 18.9% are obtained in the respective objective function values for the different ride conditions. Critical requirements in damping are evident from the 5% limit graphs that indicate narrow bands in the damping region within which it is imperative that the characteristic fall in order to obtain appreciable improvement.

Table 5.1: Summary of optimisation results

ROAD INPUT	DAMPING REQUIREMENT	% IMPROVEMENT IN OBJECTIVE FUNCTION
Dirt road – 40 km/h	Increase damping for bump (critical) and rebound damping	18.9%
Dirt road – 60 km/h	Increase bump damping (critical), decrease rebound damping. Rebound damping not critical	28.5%
Dirt road – 70 km/h	Increase bump damping (critical)	36.5%
Ditch Bump – 20 km/h	Increase bump damping (critical)	26.7%
Ditch Bump – 30 km/h	Bump damping must be increased (critical)	40.6%
New Belgian – 30 km/h	Decrease rebound damping (critical)	19.2%
New Belgian – 40 km/h	Decrease rebound damping (critical)	19.8%

From table 5.1 it can be seen that on the average the damping in the bump direction must be increased and the damping in the rebound direction must decreased for improvement in the objective function. For every combination of speed and road input a different optimum damper characteristic is obtained. The specific mobility requirements for the vehicle will finally determine the suitable damper characteristics to be used.

Interesting results are obtained for the dirt road profile at 70 km/h (see section 5.5.3). Inspection of the behaviour of objective function value (figure 5.31) indicates that an optimum solution is effectively found after approximately 40 simulations, after which the objective function value remains more of less constant. Inspection of figure 5.32, however, shows that after simulation 40 there are large changes in some of the design variables (*X(1)* and *X(3)*), although this only marginally improves the objective function value. This indicates that for this particular profile and speed, there are many combinations of *X(1)* and *X(3)* values that yield near optimum objective function values. Similar tendencies are also observed for some of the other profile and speed combinations.

5.6 Damper characteristics suggested by optimisation results

The optimum design variable values for the different road profiles and speeds are summarised in table 5.2.

Table 5.2: Summary of design variables for the damper characteristics.

Terrain & Speed	$X(1)$	$X(2)$	$X(3)$	$X(4)$	$X(5)$	$X(6)$
Dirt road 40 km/h	1.81	1.21	1.24	1.89	1.00	0.94
Dirt road 60 km/h	2.46	0.20	2.69	1.81	0.82	0.34
Dirt road 70 km/h	6.02	1.78	0.21	1.62	1.44	0.96
Ditch bump 20 km/h	0.21	1.83	4.91	2.30	1.19	0.38
Ditch bump 30 km/h	2.10	1.04	3.57	2.55	0.20	1.49
New Belgian 30 km/h	0.82	2.50	1.39	0.78	0.20	0.21
New Belgian 40 km/h	0.90	1.96	1.08	0.87	0.20	0.55
Average	*2.04*	*1.50*	*2.15*	*1.69*	*0.72*	*0.69*

In general greater damper stiffness is required for the bump direction and lower stiffness in the rebound direction. The above average values and other subjective considerations suggest the four sets of damper characteristics listed in table 5.3 for further investigation.

Table 5.3: Suggested damper characteristics

Damper configuration	x_3	x_4	c_2	c_3	c_4	c_5
Baseline	-0.20	0.55	3310.00	16175.00	11818.00	37368.00
Baseline x Average	-0.41	0.83	7130.29	27312.51	8508.96	25926.06
Suggestion 1	-0.40	0.83	7130.00	27310.00	8500.00	25900.00
Suggestion 2	-0.20	0.55	3310.00	16175.00	8500.00	25900.00
Suggestion 3	-0.40	0.55	7130.00	27310.00	11818.00	37368.00
Suggestion 4	-0.50	0.80	6000.00	40000.00	6250.00	20600.00

The damper characteristics suggested and that of the baseline are shown in figure 5.51.

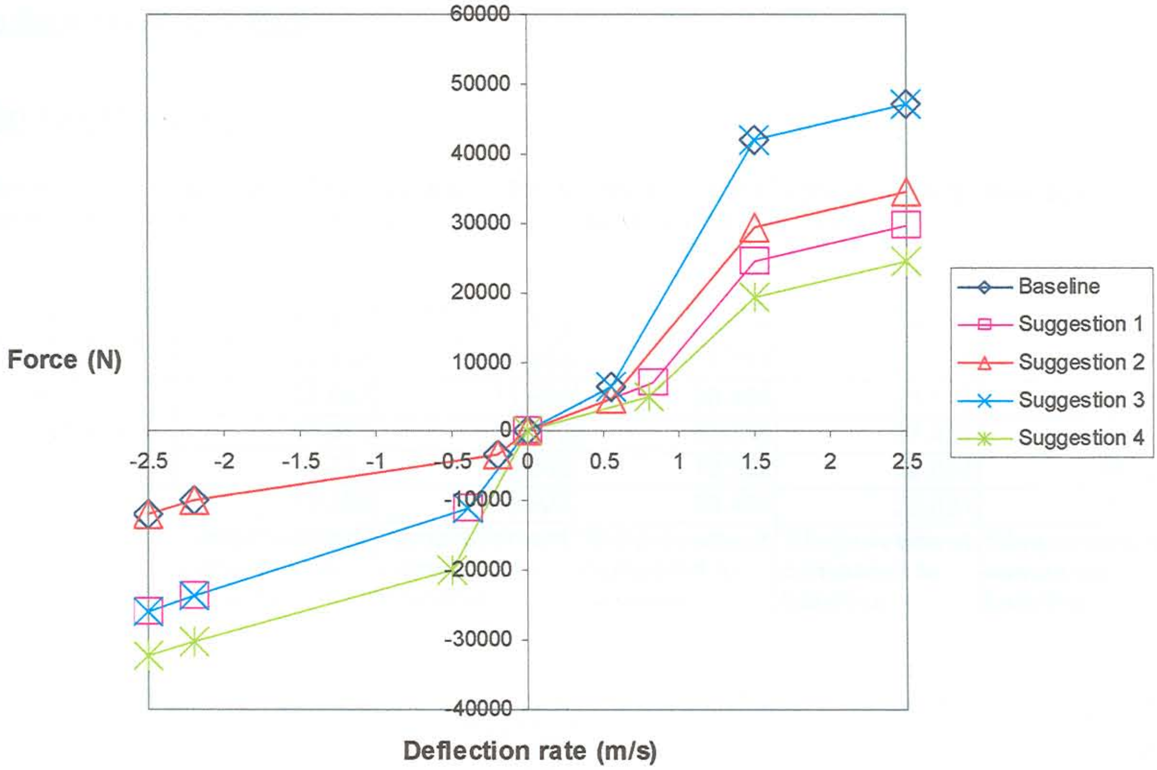


Figure 5.51: Comparison of suggested dampers with baseline damper characteristic

Suggestion 1 effectively uses the rounded-off average values as shown in table 5.2 and 5.3. Damper suggestions 2, 3 are used to investigate the influence of respectively lowering the rebound stiffness and increasing the bump stiffness separately. The damper characteristic of suggestion 4 is obtained through subjective inspection and evaluation of the optimum damper graphs (given in section 5.5).

Simulations with the above suggested damper configurations were performed for the new Belgian @ 40 km/h, dirt road @ 60 km/h, and for the ditch bump @ 30 km/h route profile–speed combinations. Tables 5.4 to 5.6 below show the influence of these choices of characteristics on the VDV 4h values.

Table 5.4: Comparison of VDV(4h) values for the different suggested damper configurations on the dirt road at 60 km/h

Dirt road 60 km/h

Damper configuration	VDV(4h) - CG Acceleration	VDV(4h) - Pitch acceleration	VDV(4h) - MP1 Acceleration	VDV(4h) - MP2 Acceleration	Average
Baseline	17.312	14.454	29.104	28.912	22.446
Optimum	12.498	10.985	18.817	21.919	16.055
Suggestion 1	12.647	11.991	20.484	21.145	16.567
Suggestion 2	17.373	15.472	30.228	27.451	22.631
Suggestion 3	12.774	11.363	19.952	22.014	16.526
Suggestion 4	13.362	10.923	20.426	22.821	16.883
	%Improvement compared to baseline	%Improvement compared to baseline	%Improvement compared to baseline	%Improvement compared to baseline	%Improvement compared to baseline
Optimum	27.81%	24.00%	35.35%	24.19%	28.47%
Suggestion 1	26.95%	17.04%	29.62%	26.86%	26.19%
Suggestion 2	-0.35%	-7.04%	-3.86%	5.05%	-0.83%
Suggestion 3	26.21%	21.39%	31.45%	23.86%	26.37%
Suggestion 4	22.82%	24.43%	29.82%	21.07%	24.78%

Table 5.5: Comparison of VDV(4h) values for the different suggested damper configurations on the ditch bump at 30 km/h

Ditch Bump 30 km/h

Damper configuration	VDV(4h) - CG Acceleration	VDV(4h) - Pitch acceleration	VDV(4h) - MP1 Acceleration	VDV(4h) - MP2 Acceleration	Average
Baseline	68.517	7.217	89.463	95.088	65.071
Optimum	36.758	8.247	48.79	60.819	38.654
Suggestion 1	48.242	7.419	64.521	66.232	46.604
Suggestion 2	68.173	8.192	88.577	98.695	65.909
Suggestion 3	50.265	6.866	66.345	64.747	47.056
Suggestion 4	40.957	7.861	54.867	58.99	40.669
	%Improvement compared to baseline	%Improvement compared to baseline	%Improvement compared to baseline	%Improvement compared to baseline	%Improvement compared to baseline
Optimum	46.35%	-14.27%	45.46%	36.04%	40.60%
Suggestion 1	29.59%	-2.80%	27.88%	30.35%	28.38%
Suggestion 2	0.50%	-13.51%	0.99%	-3.79%	-1.29%
Suggestion 3	26.64%	4.86%	25.84%	31.91%	27.69%
Suggestion 4	40.22%	-8.92%	38.67%	37.96%	37.50%

Table 5.6: Comparison of VDV(4h) values for the different suggested damper configurations on the new Belgian paving at 40 km/h

New Belgian 40 km/h

Damper configuration	VDV(4h) - CG Acceleration	VDV(4h) - Pitch acceleration	VDV(4h) - MP1 Acceleration	VDV(4h) - MP2 Acceleration	Average
Baseline	24.678	3.516	31.035	29.901	22.283
Optimum	18.634	4.019	26.013	22.787	17.863
Suggestion 1	26.842	3.392	31.873	33.924	24.008
Suggestion 2	22.41	3.492	28.967	26.906	20.444
Suggestion 3	28.171	3.178	33.106	35.659	25.029
Suggestion 4	30.602	3.869	35.247	39.102	27.205
	%Improvement compared to baseline	**%Improvement compared to baseline**	**%Improvement compared to baseline**	**%Improvement compared to baseline**	**%Improvement compared to baseline**
Optimum	24.49%	-14.31%	16.18%	23.79%	19.83%
Suggestion 1	-8.77%	3.53%	-2.70%	-13.45%	-7.74%
Suggestion 2	9.19%	0.68%	6.66%	10.02%	8.25%
Suggestion 3	-14.15%	9.61%	-6.67%	-19.26%	-12.32%
Suggestion 4	-24.01%	-10.04%	-13.57%	-30.77%	-22.09%

The results from tables 5.4 to 5.6 are graphically summarised in figure 5.52.

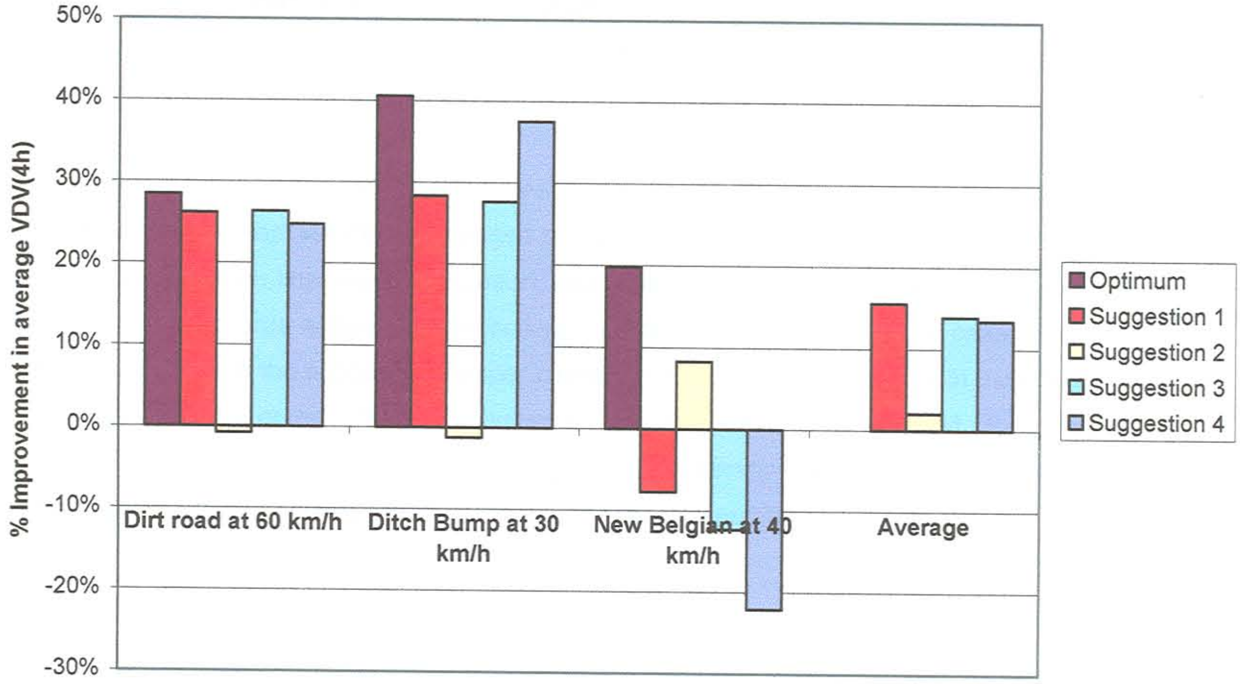


Figure 5.52: Average % improvement in VDV(4h) values for different suggested damper configurations at different road-speed combinations

From the results listed in tables 5.4 to 5.6 and depicted in figure 5.52 the following conclusions are evident:

i. Decreasing only the rebound stiffness (suggestion 2) improves the ride comfort over the new Belgian paving but increases the VDV values over the dirt road and the ditch bump.
ii. Increasing only the bump stiffness (suggestion 3) improves the ride comfort over the dirt road and the ditch bump but gives worse ride comfort over the new Belgian paving.
iii. Increasing the bump stiffness and decreasing the rebound stiffness (suggestions 1 and 4) improves the ride comfort over the dirt road and the ditch bump, but gives worse ride comfort over the new Belgian paving.
iv. The damper configuration of suggestion 1 gives overall the highest % improvement in the average of the VDV values over the three road inputs.

From these results it can be deduced that, in general, an increase in the damper bump stiffness decreases the severity with which the bump stops are "hit" during large suspension deflection in the bump direction, as is usually experienced on the dirt road and when encountering ditch bump profiles. Decreasing the rebound stiffness also aids in "resetting" the suspension travel after bump movement of the suspension. On the new Belgian paving smaller amplitudes of suspension deflection are experienced and therefore lower damping will improve the ride comfort in this instance.

Preliminary discussion with Gabriel [73] revealed that it is possible to increase the bump stiffness of the damper to the value specified in suggestion 1, but not as much as that specified by suggestion 4. Decreasing the rebound stiffness to the levels of suggestion 2 or 4 are also possible.

For overall better ride comfort, and lower forces in the suspension, it is suggested that the damper characteristic for the Okapi vehicle be changed to that given in suggestion 1 - see figure 5.51. With this damper configuration improved ride comfort, and lower suspension forces will be experienced on road profiles inducing large suspension deflections. A concession is made in the case of roads with smooth surfaces, where the suggested damper characteristic will give a decrease in the ride comfort. Due to the fact that the primary mobility requirement for the Okapi vehicle is good off-road mobility, this concession can be afforded. For the vehicle under consideration here it is much more important to improve the ride comfort during off-road conditions than on smoother road surfaces.

5.7 Qualification

Using DADS, and the vehicle model for the Okapi vehicle as described in section 3.19, simulations were performed for the vehicle fitted with three different dampers. Here assistance was received from LMT [62]. The dampers used are a Gabriel damper, a Samil damper, and the damper suggested here by the Vehsim2d optimisation study, i.e., that of suggestion 1. The respective damper characteristics are shown in figure 5.53.

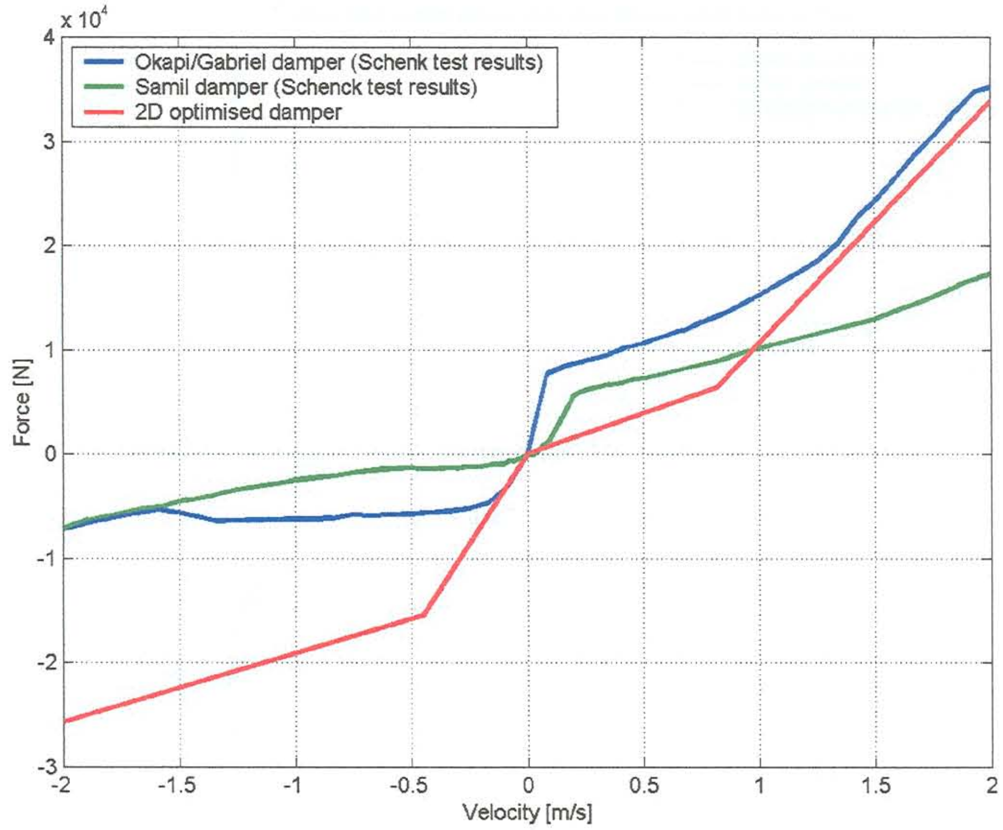


Figure 5.53: Damper characteristics used in the DADS qualification

5.7.1 Ditch bump simulations

DADS simulation results over the ditch bump at 40 km/h are depicted in figures 5.54 and 5.55. From these results it can be seen that that the 2D Optimised damper produces much lower accelerations at the driver seat (figure 5.54) and for the front axle (figure 5.55). For this damper the pitch velocity magnitudes are also lower than for the other dampers, while the variation of the left front wheel force is of the same magnitude.

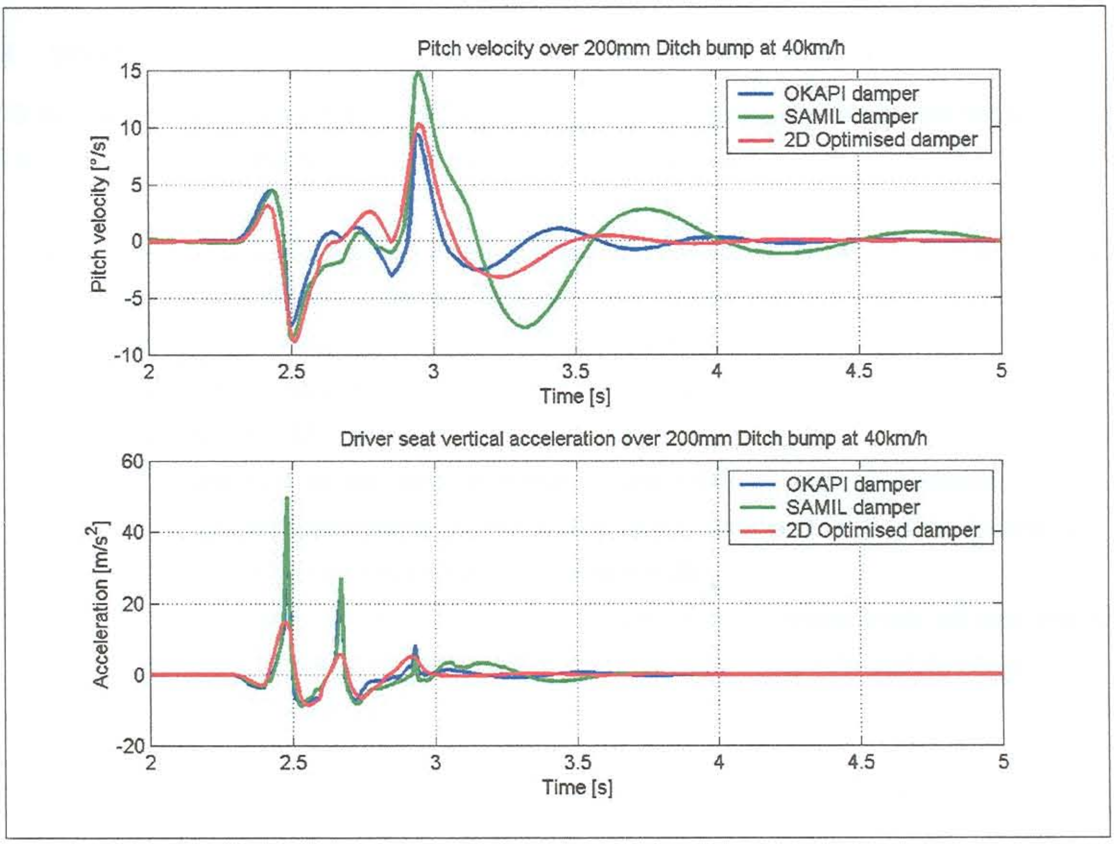


Figure 5.54: DADS simulation results for ditch bump at 40 km/h

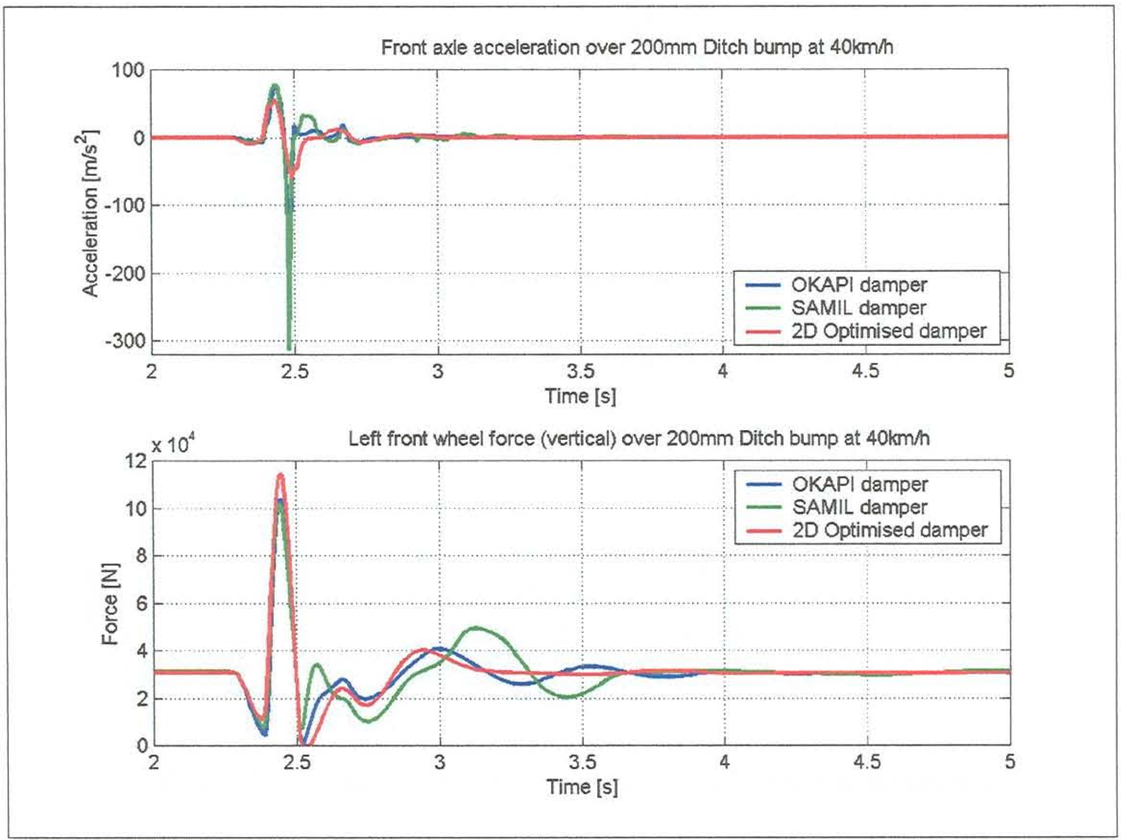


Figure 5.55: DADS simulation results for ditch bump at 40 km/h

5.7.2 Gravel track

DADS simulation results for a portion of the gravel track at 40 km/h simulations are shown in figures 5.56 to 5.59. From the simulation results the following can be seen:

i. The 2D Optimised damper produced lower PSD (power spectrum density) values for the axle accelerations in the frequency region 3 to 10 Hz - see figure 5.56.

ii. The total square root of the wheel force PSD and the RMS of the dynamic wheel force for the 2D Optimised damper compares well with, and is often lower than those for the Okapi and Samil dampers - see figure 5.57.

iii. While the square root of the axle acceleration and RMS of axle accelerations of the 2D-Optimised damper are comparable to that of the Okapi damper, it also gives comparable ride comfort to that of the Samil damper (figures 5.58 and 5.59).

iv. The overall performance of the 2D Optimized damper over the gravel track, as was also found previously for the ditch bump, is significantly better than that of the other two dampers.

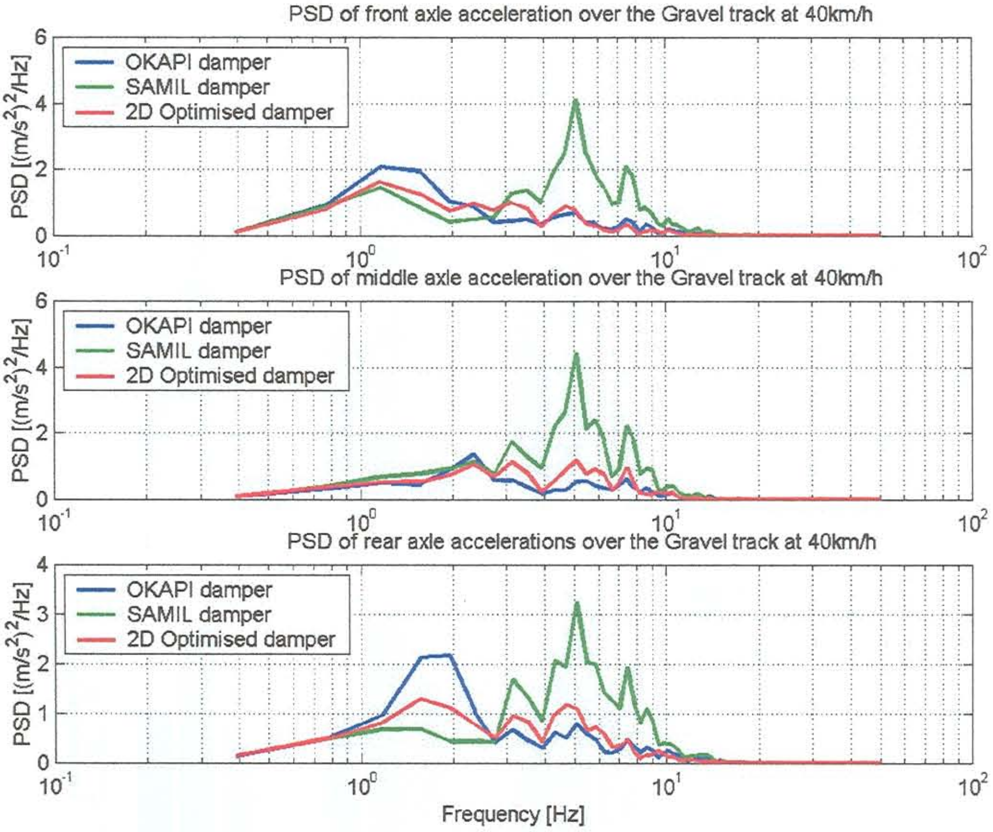


Figure 5.56: DADS simulation results for gravel track at 40 km/h

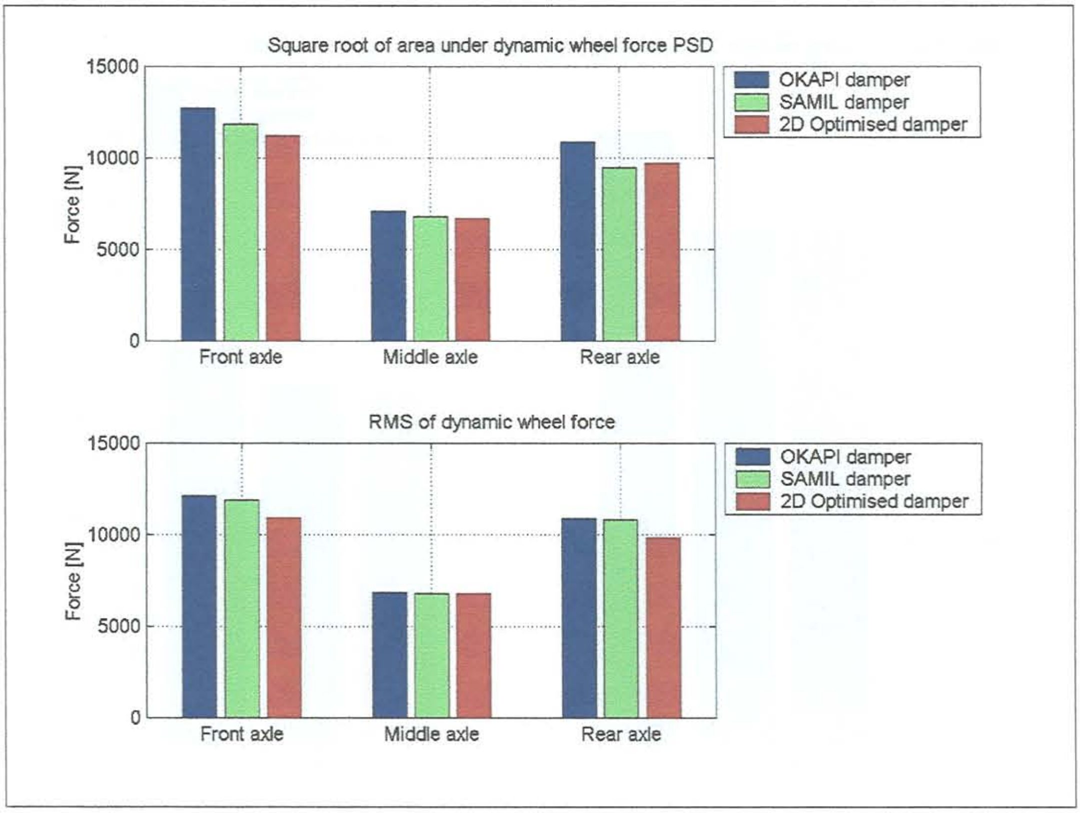


Figure 5.57: DADS simulation results for gravel track at 40 km/h

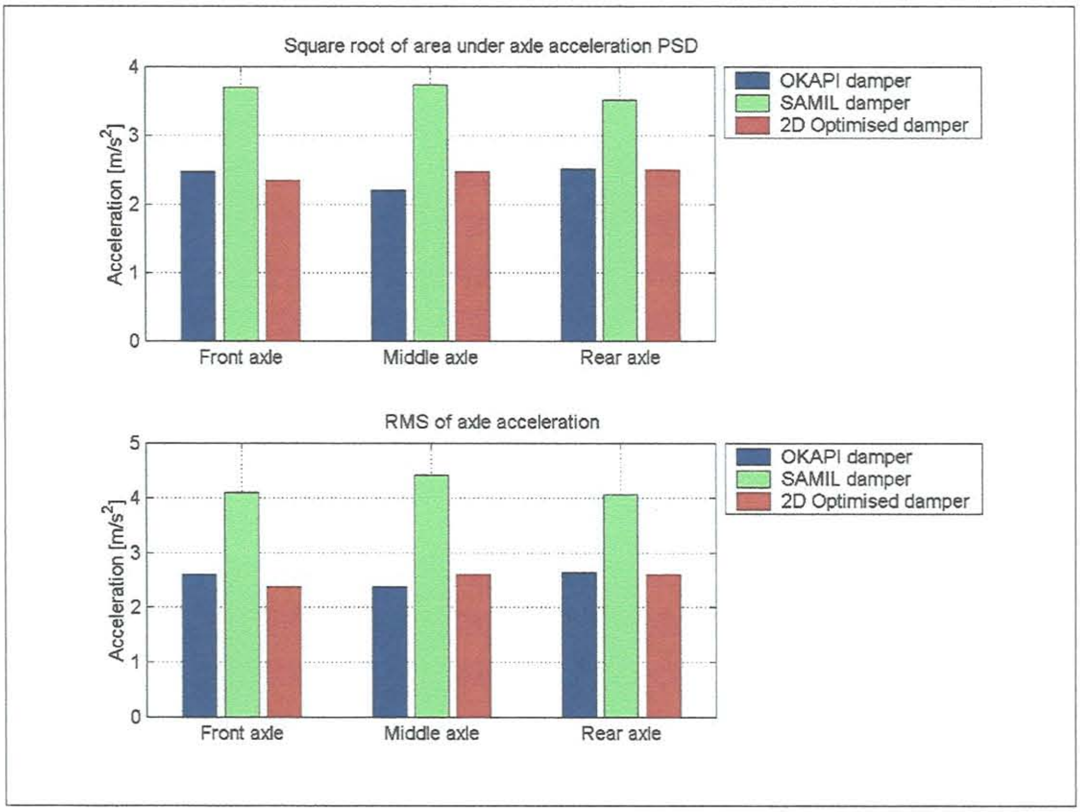


Figure 5.58: DADS simulation results for gravel track at 40 km/h

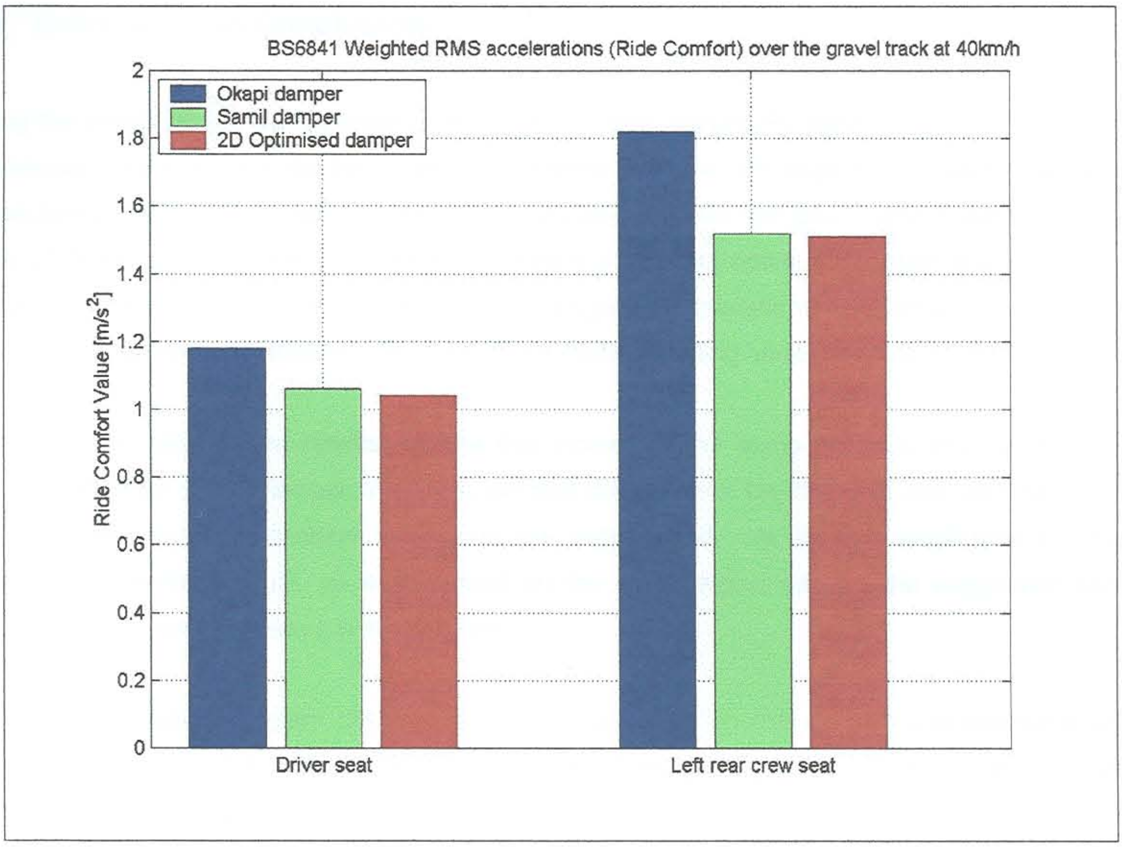


Figure 5.59: DADS simulation results for gravel track at 40 km/h

5.8 Summary and Conclusion

Using the simulation program Vehsim2d in conjunction with the LFOPC optimisation module, optimum suspension characteristics for the Okapi vehicle were obtained with regard to its performance over, respectively, the dirt road, the new Belgian paving and the 200 mm ditch bump route profiles. For each of these route profiles and prescribed speeds a different optimum damper characteristic was obtained. From these optimum characteristics a single characteristic was constructed and proposed as a suitable damper characteristic for the Okapi vehicle operating under general off-road conditions.

In general the optimisation results indicate that increasing the bump stiffness and decreasing the rebound stiffness of the damper, improves the ride comfort over the dirt road and ditch bump route profiles where large suspension deflections are experienced. At smaller amplitudes but higher frequency suspension input, as experienced on the new Belgian paving, the suggested damper characteristic gives a decrease in the ride comfort.

Using the simulation program DADS qualification was done on the damper characteristics of the damper suggested by the optimisation study. With this damper, simulation over the ditch bump profile showed a huge decrease in the driver seat and front axle accelerations compared to that of both the existing Okapi/Gabriel damper and the alternative Samil damper. On the gravel track the optimised damper also performed well by giving good ride comfort, low wheel forces as well as low axle accelerations. From this qualification it is clear that the Vehsim2d / LFOPC optimisation system provides realistic results that can successfully be used for the optimisation of suspension characteristics during vehicle development.