CHAPTER 6:

CONCLUSION

6. Conclusion

6.1 Concluding review

The need for a suspension optimisation system arose from difficulties experienced during the design of the Okapi 6x6 armoured personnel carrier. It was realised that an optimisation system is required for vehicle concept design, at which stage little information regarding the geometry of the vehicle and suspension is available. It was proposed that a two-dimensional vehicle dynamic simulation program would be sufficient for use during the initial design phase, at which stage it could also be coupled to a mathematical optimisation algorithm which could point to possible optimum designs.

From an overview of work done in the field of suspension optimisation it is apparent that first order optimisation has been done in the past in this area via parametric studies. The latest development is, however, the application of mathematical optimisation algorithms in conjunction with computer aided simulation of the vehicle system, to determine optimum values for the design variables through the minimisation of a suitably chosen objective function. This development is in keeping with the application of a multidisciplinary design optimisation approach in almost every other engineering field. The work that has been done to date in the area of vehicle optimisation all achieved specific design optimisation goals but the methods used are not general enough to be applied directly to the current problem. Furthermore the existing methods can be computationally intensive when applied to the design of multi-body systems and may require specialised hardware and software.

A number of classes of optimisation algorithms is available for design optimisation. Most of these algorithms have successfully been applied to engineering optimisation problems. One of the optimisation algorithms that stand out is the LFOPC algorithm. This algorithm is a proven robust method and is particularly suited for use in problems where numerical noise and discontinuities may occur as typically experienced in the computer-aided analysis of mechanical systems.

The overall objective of this study was therefore ***the application of a formal mathematical approach to the optimisation of vehicle suspension characteristics*** with the following specific goals being set:

i. The process should be general enough to be applied to different vehicles consisting of a single vehicle body and up to four axles.

ii. The optimisation process must be able to optimise non-linear suspension characteristics for the different suspension components, namely springs, dampers, bump-stops and tyres. The specific design variables to be used must be user configurable.

iii. The specific objective function used must be user configurable.

iv. The optimisation process should be suitable for use during the concept design stage of the vehicle. During this stage only limited information regarding the geometry of the specific vehicle and suspension is available.

v. The system should be usable by the project manager, who may have a limited knowledge and experience of vehicle dynamic analysis.

In order to achieve the above goals accurately, yet within acceptable economy, a two dimensional mathematical model for the simulation of the vehicle dynamics was developed. Six piece-wise continuous linear approximations were used to describe the non-linear suspension characteristics of each spring, damper, bump stop and tyre used in the simulation model. Basically the vehicle model consists of five solid bodies, one representing the vehicle body and one body for each of up to four axles on the vehicle. Six degrees of freedom are used to describe the motion of the system of bodies. The suspension is modelled by using an equivalent trailing arm approach. The governing equations of motion are derived via the application of Newton's second law. Accelerations are determined for each time instant once the forces acting on the bodies due to the prescribed road inputs are calculated. Using a fourth order Runga Kutta numerical integration scheme the velocities and displacements of the bodies are computed at uniformly spaced time intervals.

The application of the robust and reliable LFOPC optimisation algorithm in conjunction with the vehicle dynamics model is also described. Using the LFOPC algorithm a set of design variables, linked to vehicle parameters, can be determined that minimises a specific user defined objective function.

Although the literature overview warns against the difficulties of linking a multi-body code directly to a mathematical optimisation algorithm, this approach was nevertheless taken in this study. Recent advances in computer processing power and the use of a multi-body code that is simple yet realistic, made this route more attractive. Further motivations were the robustness and reliability of the LFOPC algorithm that was to be used for the optimisation.

The simulation program Vehsim2d implements the two-dimensional vehicle model and input to the program is kept as limited as possible. The simulation program Vehsim2d was qualified by comparing its results with that of the simulation program DADS and with experimental measurements of the actual behaviour of the Okapi vehicle. For the qualification the vehicle was simulated and driven over a 200 mm half round bump at a speed of 20 km/h. Comparison between simulated and measured data shows very good correlation. From this qualification it is concluded that the simulation program Vehsim2d gives realistic results and can be successfully used as a simulation program during vehicle concept design.

The robust LFOPC optimisation algorithm is linked to the Vehsim2d code. With this optimisation algorithm the user may select the required design variables and link them to certain vehicle / suspension characteristics. Constraints on the design variables can also be prescribed. By selecting suitable objective criteria and weights the user builds an appropriate objective function that is to be minimised. Using the LFOPC optimisation algorithm a systematic search is effectively done through the design space for the optimum sets of design variable that minimises the objective function.

To initially evaluate the optimisation system examples of optimisation runs were performed to optimise certain damper and spring characteristics. These examples are also used to explain and demonstrate the Vehsim2d/LFOPC optimisation system to the reader. For the specific example vehicle, a reduction of 24.4 % in the objective function, linked to ride comfort over a specified road profile and at a representative speed, was obtained by optimisation of the bump and rebound characteristics of the damper.

In a further and more comprehensive case study the Vehsim2d / LFOPC optimisation system was used to compute optimum suspension characteristics for the Okapi vehicle over, respectively, a dirt road, new Belgian paving and a 200 mm ditch bump route profile. 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 as a preferred damper characteristic for the Okapi vehicle.

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. However, in the case of smaller amplitude 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 a qualification was done of the damper characteristics for the damper suggested by the optimisation study. Simulation over the ditch bump profile with the optimised damper shows large decreases in the driver seat and front axle accelerations compared to that given by 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 and axle accelerations. The qualification proves that the Vehsim2d / LFOPC optimisation system may successfully be used for the optimisation of suspension characteristics during vehicle development.

In retrospect all the specific goals set at the start of this study have been achieved. The final product produced by this study, the Vehsim2d/LFOPC system, has indeed already proved its worth outside of academia, through its practical implementation by Land Mobility Technologies (Pty) Ltd, who have concluded that "The Vehsim2d software has proved to be a valuable tool for any vehicle designer" [62].

6.2 Future work and challenges

The biggest problem that remains is the fact that, for passive suspensions, each choice of road profile and speed yields a different set of optimum spring, bump stop and damper characteristics. In order to prescribe overall optimum characteristics, the optimisation should be done by simultaneously considering a wide range of profiles and speeds. The computational cost is, however, prohibitive. During this study this problem was addressed by selecting a few different road profiles, typical of those that will be encountered by the vehicle. For each profile a more or less arbitrary but appropriate speed value was assigned and the optimisation performed. The "overall optimum" was then obtained by averaging the different optimum characteristics. The challenge remains to refine the methodology such that the vehicle's specific mobility requirements can be used to determine the correct, appropriate and representative sets of road profiles and speed values to be used for the optimisation. This method should also prescribe the way in which the different "optimums" obtained should be combined to give a final preferred design.

Concurrent with the development of the Vehsim2d / LFOPC program a more efficient optimisation technique, called Dynamic-Q [67] was developed. The Dynamic-Q method consists of applying the existing dynamic trajectory optimisation algorithm (LFOPC) to successive spherical quadratic approximations of the actual optimisation problem. The Dynamic-Q algorithm has the advantage of having minimal storage requirements, thus making it suitable for problems with a very large number of variables and, even more importantly with regard to the current study, appears to require an order less number of iterations for convergence. The indications are therefore that this new method is robust and efficient, and particularly well suited for practical engineering optimisations problems where the functions are computed via time-consuming simulations. In a future version of Vehsim2d the Dynamic-Q method must be added as an alternative to the LFOPC method used in the current version. In summary, the advantage of the Dynamic-Q method should be the use of a dramatically less number of simulations and therefore quicker convergence to the optimum solution with a great resultant saving in computer time.

The ultimate challenge will be to use the Dynamic–Q method in conjunction with a full three dimensional vehicle dynamic simulation program such as, for instance, GENRIT, to enable optimisation of vehicle / suspension characteristics over a full three dimensional route profile.

6.3 Response to some questions raised at the defense of this disseratation

Why model suspension and tyre characteristics by piecewise linear functions? Why not use a cubic polynomial or spline function? This would make the function space much smoother with little, if any, increase in complexity.

Even using cubic polynomial functions will require dividing the characteristic range into at least two stages, for instance in the case of a damper into a bounce and rebound stage. For each stage at least three variables (three coefficients) need to be used. To account for both stages will require at least six variables. See the example in figure 6.1 for the bounce stage of a specific damper.

For the same stage, using the linear approximations, five variables are used. As can be seen from the example shown in figure 6.1 the linear approximations provide as good, if not a better model than the polynomial (albeit that the latter may be smoother).

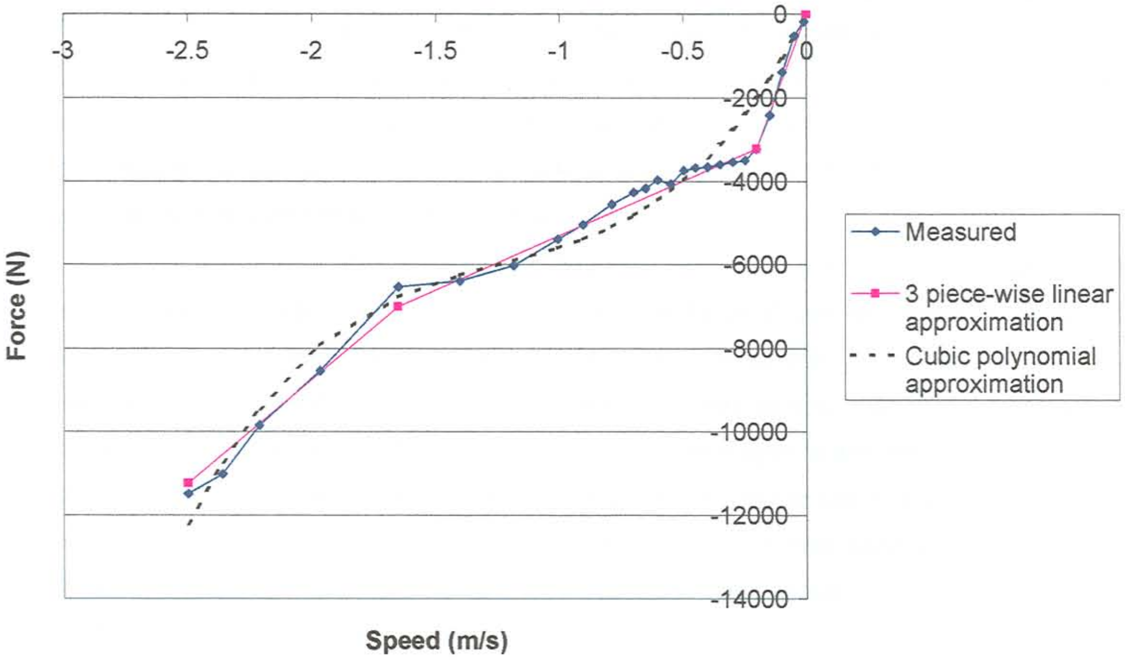


Figure 6.1: Comparison of different approximations for a specific damper characteristic

The second reason for using the piecewise linear approximation is that in reality most of the suspension force characteristics are normally piecewise linear, for example a two stage coil spring or a leaf spring with a helper spring that starts working at a certain deflection. Even damper characteristics can be divided into stages where certain valves open or close to give approximate linear damping in specific operating stages. Tyre characteristics show the same tendency, the first two stages are influenced by the carcass stiffness and tyre pressure and the last by the run-flat insert.

Thus, although the polynomial approximation provides a smoother characteristic, it was decided that using the linear approximations is more realistic and in addition the variables used can directly be linked to the damping stiffness, spring stiffness etc.

The argument for writing a new 2-d simulation program is not very compelling, though it's certainly a good learning exercise. For example, how much time does DADS require for a similar analysis? Is it necessary to write an optimisation friendly analysis? Why not just couple DADS with the optimiser?

The reasons for choosing a 2-d simulation program are as follows:

- Etman [5] states that using a full 3-d analysis complicates the identification of the design parameters that are critical. He suggests that using a 2-d analysis coupled to optimisation is preferable in order to understand the problem better.
- The 3-d program available to us is the locally developed GENRIT (comparable with DADS). The runtime for GENRIT for a similar simulation is only approximately 20% longer than that for the 2-d Vehsim2d analysis. Unfortunately DADS' runtime and the Vehsim2d runtime could not be compared due to the fact that both programs are not available on the same computer. Previous experience, however, shows that the GENRIT runtime is normally faster than that for DADS. This is due to the fact that GENRIT was developed as a dedicated vehicle dynamics package in comparison with the more general DADS package. Faster runtime was however, not the main reason for selecting a 2-d simulation.
- The main objective of this work was to enable optimisation during the early design stages (even during concept design) of a vehicle. At this stage all the required input for a vehicle model for a complete 3-d analysis are generally not yet available.
- As stated in the thesis, the 2-d simulations are only used for first order simulations and more advanced simulations should be performed during later stages in the vehicle design process.
- An additional objective was to provide a program that is easy to use by the project manager of the vehicle design project. Previous experience has shown that these project managers are often not qualified and/or do not have the necessary experience to use the more advanced and complicated packages.

The maximum optimisation time was under 20 minutes. This is trivial. We have clients who's analysis alone takes hours on a supercomputer. The issue is whether the time spent to optimise generates significant pay-off.

The important issue is certainly "significant pay-off". I believe that this study has shown that such goals can indeed be achieved by the modest modelling and optimisation system developed here. This is demonstrated by obtaining a 40% improvement in ride comfort after optimising the suspension under non-trivial conditions.

Further, the faster runtime of a simple 2-d vehicle analysis during vehicle concept is certainly of value. From my own experience, the more advanced simulations do give more accurate results but, by using first order simulations coupled to the optimisation, good "ball-park" starting designs may be obtained for further and more advanced simulations.

The optimisation problem is presented with general inequality and equality constraints (g and h), but it seems only bounds on the variables are actually considered. These are normally called side constraints and should never be allowed to be violated. For example, if we let a spring thickness be a design variable with a lower bound of 0.1, what's to prevent the optimiser from trying –0.1? This would rain havoc on the analysis.

Although the optimisation code allows for both types of constraints, indeed only the inequality constraints (side constraints) were used. The problem of entering a prohibited region of the design space is described in the thesis (see page 4-6). It was specifically noted that the lower bound should be such that, for example, a negative spring stiffness is not used during the simulations. The maximum violation allowed at the lower bound is two times the delta for the specific design variable. The code was accordingly modified in such a manner that a design variable, as it is changed along the optimisation trajectory, was not allowed to go below this value. The LFOPC code is robust enough so as not to fail as a result of such drastic "intervention".

100 plus optimisation iterations seem excessive for a modern optimiser, especially with so few variables.

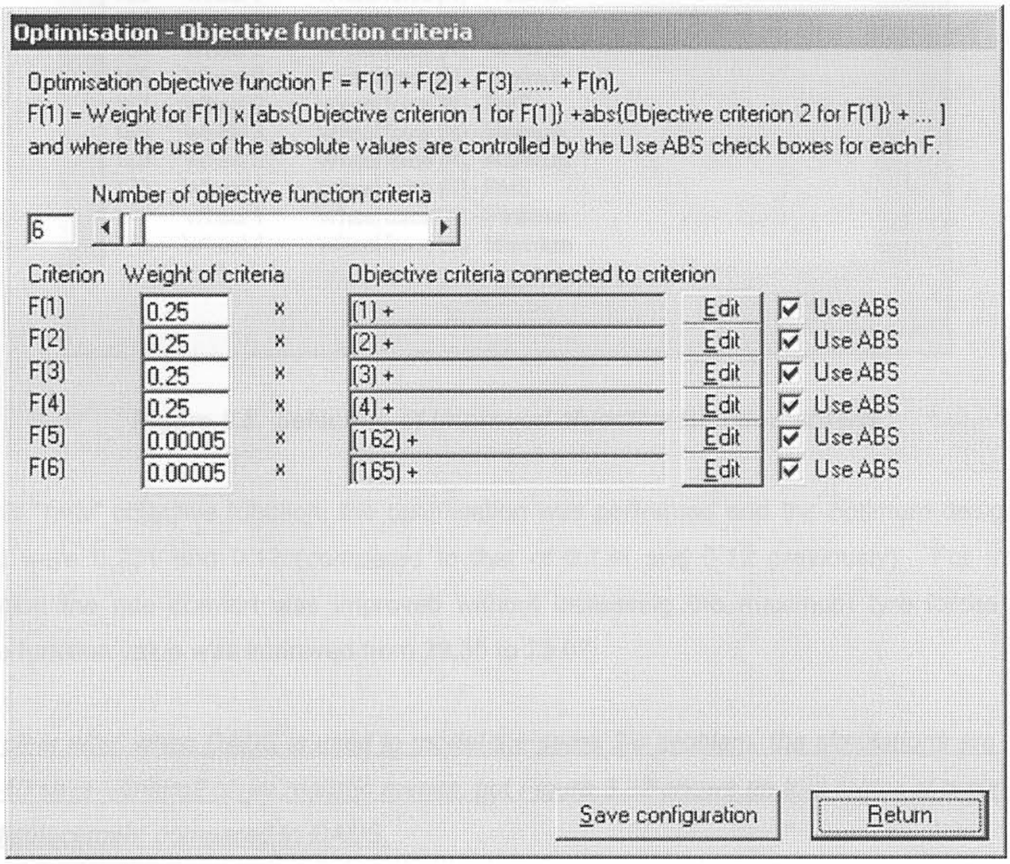
In the majority of the examples given the objective function effectively converged to its optimum value, and to engineering accuracy, within the first ten iterations. The relatively sluggish convergence of the design variables, compared to that of the objective function is not due to a deficiency on the part of the optimiser, but due to the fact that in these types of optimisation problems the optimum is not unique but corresponds to a wide range of design variable values. The tight convergence tolerances set for the examples also led to a higher number of iterations than would normally be required for engineering accuracy – see the discussion on page 4-23.

Further, as stated in the conclusion, concurrent with this study a more efficient optimisation technique, called Dynamic-Q, was developed. In further work it is suggested that this technique should be added to the optimisation system as an alternative to the LFOPC method.

What about realistic constraints? For example, it's easy to imagine a case where the integrated ride quality is good, but includes unacceptable accelerations, displacements or forces. If we have overall good ride quality but break an axle due to one big bump, what have we gained?

Yes, this is certainly true. Therefore careful consideration should be given to the selection and weighting of the objective function criteria. For instance in the case study the "overall optimum" gives worse ride comfort over some of the road profiles selected. Further analysis of the simulation results for the "optimum configuration" should also be done to evaluate and to pick up other problems that may arise for the specific configuration. In the case study this was done by performing, for example, more advanced DADS simulations with the "optimum damper configuration".

To illustrate the need and value of additional analysis, the optimisation example in chapter 4, was redone with inclusion of the absolute value of the maximum tyre forces (that may break the axles) in the objective function, (see figure 6.2 and 6.3):



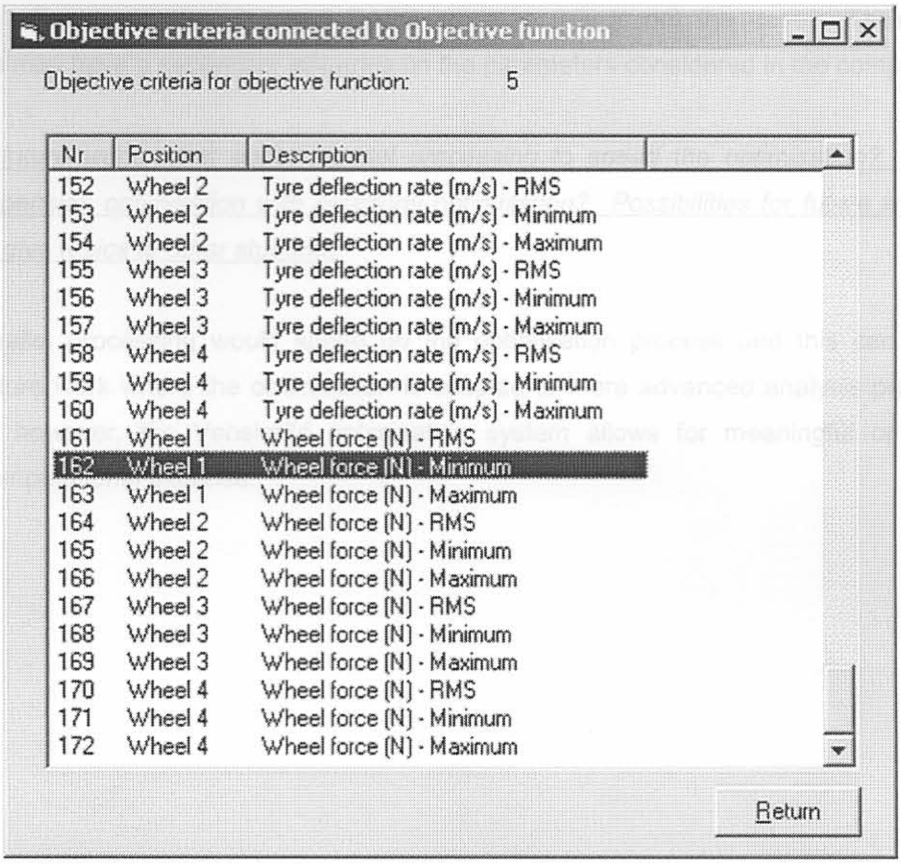
Optimisation - Objective function criteria

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: 6

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
F(5)	0.00005	x	[162] +	Edit	☑ Use ABS
F(6)	0.00005	x	[165] +	Edit	☑ Use ABS

Figure 6.2: Selection of improved objective function criteria



Objective criteria connected to Objective function

Objective criteria for objective function: 5

Nr	Position	Description
152	Wheel 2	Tyre deflection rate (m/s) - RMS
153	Wheel 2	Tyre deflection rate (m/s) - Minimum
154	Wheel 2	Tyre deflection rate (m/s) - Maximum
155	Wheel 3	Tyre deflection rate (m/s) - RMS
156	Wheel 3	Tyre deflection rate (m/s) - Minimum
157	Wheel 3	Tyre deflection rate (m/s) - Maximum
158	Wheel 4	Tyre deflection rate (m/s) - RMS
159	Wheel 4	Tyre deflection rate (m/s) - Minimum
160	Wheel 4	Tyre deflection rate (m/s) - Maximum
161	Wheel 1	Wheel force (N) - RMS
162	Wheel 1	Wheel force (N) - Minimum
163	Wheel 1	Wheel force (N) - Maximum
164	Wheel 2	Wheel force (N) - RMS
165	Wheel 2	Wheel force (N) - Minimum
166	Wheel 2	Wheel force (N) - Maximum
167	Wheel 3	Wheel force (N) - RMS
168	Wheel 3	Wheel force (N) - Minimum
169	Wheel 3	Wheel force (N) - Maximum
170	Wheel 4	Wheel force (N) - RMS
171	Wheel 4	Wheel force (N) - Minimum
172	Wheel 4	Wheel force (N) - Maximum

Figure 6.3: Selection of improved objective function criteria

Using this "new" objective function, the optimisation was performed and the optimum design values obtained were 0.731 and 0.12 (compared to that of 0.726 and 0.12 previously). For this "new" optimisation the ride comfort was improved without increasing the maximum tyre forces and the objective function value was improved from 29.55 to 25.07.

It is not clear why, when DADS is used to model the same 2-d problem, the simulations are different. Page 3-40 says Vehsim2 gives realistic results, but Figure 3.32 shows up to a factor of two difference with in displacement compared to DADS.

The main factor influencing the simulation results over such an extreme obstacle as the 200 mm bump used in this instance, is the specific tyre model used. The tyre model used in the Vehsim2d program is a tyre model developed for the GENRIT program and is different from the tyre model used by DADS. During the development of this tyre model measured and simulated tyre forces was used to qualify the tyre model. Even when comparing values obtained from the DADS model with the measured results, agreement between the simulation and measured values is not obtained.

Furthermore, in encountering such an extreme obstacle, the tyres also experience horizontal forces. The horizontal acceleration in the Vehsim2d program is neglected and the vehicle speed is simulated as constant. For the more advanced DADS package this is not the case. These horizontal accelerations may have a secondary influence on the parameters considered in the comparison.

In terms of future work, what about parallel processing to speed the optimisation? What about coupling suspension optimisation with structural optimisation? Possibilities for future work could be expanded to give topics to other students.

Certainly parallel processing would speed up the optimisation process and this can certainly be applied in future work where the optimisation is coupled to more advanced analysis programs. For the present, however, the Vehsim2d optimisation system allows for meaningful optimisation at affordable computational expense.