Dedicated Simulations Of Heavy Road Vehicles

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ABSTRACT

The TNO Road-Vehicles Research Institute in the Netherlands is currently involved in a number of projects with both national and international manufacturers of heavy road vehicles, and vehicle research institutes. In these projects, TNO supports the industrial partners in using dynamic simulation models of large road vehicles. Simulations are typically used for validation of product performance and dynamic analysis of vehicle behaviour. In this respect, dynamic simulations are used as an evaluation and optimisation tool during product development.

This paper discusses a number of activities in which TNO is involved and are related to modelling and analysis of dynamic vehicle behaviour.

Main topics in this paper will be:

- A market investigation performed amongst Dutch manufacturers of heavy vehicles and vehicle components. The purpose of the investigation is to analyze the need for advanced tools in the development of new products and the role that dynamic simulation models can perform in this aspect. The paper will discuss the different phases in the market study and the results acquired.

- The second part of the paper will discuss a typical research performed with the simulation program BAMMS. The research was performed in the frame work of the project mentioned above. The purpose of the project was to verify improved pitch behaviour of an air spring suspension used in a passenger bus. Modelling approach as well as some simulation results are discussed.

- In the sample project described, extra effort was put in developing modelling and analysis tools that are generically applicable in a larger number of simulation projects. Using these tools, the modelling process is simplified as much as possible without losing flexibility in the models.

MARKET STUDY FOR SIMULATION MODELS

PROJECT PHASES DEFINED

For a number of reasons, Dutch truck manufacturers make little use of dynamic simulations to support product development. One of the reasons is the unfavourable ratio between required investments (both personnel and financial) and improved efficiency of product developments. This statement holds for the case that general purpose multi-body codes are employed. For a company to be using models of general purpose simulation programs, often at least one employee has to be fully aware of all aspects of dynamic modelling and simulations and must be a full time user of the code.

Therefore, TNO is advocating the use of so-called *dedicated simulation tools*. A dedicated simulation model is specified in close dialogue between TNO and the industrial user. Consequently, the model is made at TNO and installed and used at the site of the user. The host computer can be a PC running under Windows or a UNIX work station.

At TNO, a research project [1] was initiated, funded by the Dutch Ministry of Economic affairs, to collect specifications of a cost effective simulation approach for the industrial partners. In a following phase, TNO will investigate whether these specifications can be realised with available software.

In the project, a number of phases are defined:

1. Meeting with representatives of a number of manufacturers of commercial vehicles (and vehicle com-

Table 1: Companies involved in the market study project

Company	Key Product
1	Trailers
2	Caravans
3	Hydraulic Dampers
4	Trailers
5	Airport Crash Tenders
6	Regulation/Homologation
7	Passenger Busses
8	Air spring Suspensions

ponents). Main topic of the discussion is the use of simulation models in the development of new products.

2. Based on the results of phase 1, a questionnaire is written and send to Dutch manufacturers of heavy vehicles and vehicle components. In this questionnaire, subjects discussed are the use of calculation software and typical needs in the design process of new products. The results of the questionnaire will be used to specify a proper method to perform dynamic simulations

3. The results of both the meetings and the questionnaires are combined and presented in a half day workshop. During the workshop, attendants are invited to assist in defining a number of pilot cases to evaluate simulation models. Intentionally, two different pilot cases will be made, one for a single unit vehicle and one for a typical truck-trailer combination.

RESULTS OF COMPANY MEETINGS

Meetings where held with representatives of eight different companies. The key products of the companies are listed in Table 1.

Preparation of the meetings was done by TNO. To get the discussion started, the partners were asked if they could recognize the situation depicted in Figure 1. This picture illustrates the importance of an effective communication in product design and production. The possibility of use of dynamic simulation models in this picture was discussed.

From the meetings, the following conclusions were drawn:

- For manufacturers of vehicle components such as springs and dampers, use of dynamic simulations is closer to the current design approach than for manufacturers of complete vehicles.

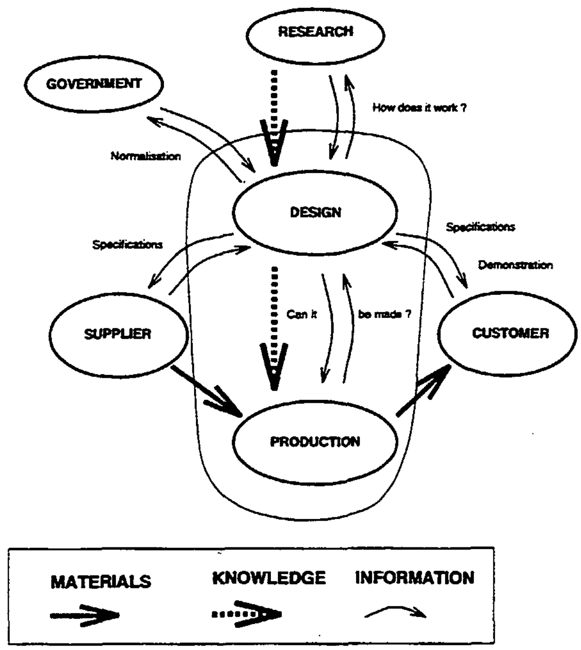

Figure 1: Communications relevant during product design

- Based on practical application, users of simulation models can be divided into two groups:
    1. **Users that use simulation models in the design phase** In this group, the need for calculation programs ranges from spread sheet calculations to complete analyses of non-linear time domain simulations over prescribed road irregularities and steering manoeuvres. For users of relatively simple models, an advanced and graphical user interface is no necessity because an averaged session takes no longer than some 20 seconds. For these users, a simulation model, can be *presented* in a spreadsheet environment that they are familiar to work with. Once the model has proven its use to these users, it will lower the entry level to use more complex simulation models.
    2. **Users that use simulations to demonstrate products** A number of companies realise the positive effect of using simulation models for demonstration of products. In this aspect, both internal and external marketing of a new product was mentioned. One of the companies already uses a simulation model to demonstrate the proper choice of caravan given a specific towing vehicle.
- At the majority of the companies, external research

companies are not selected lightly for reason of confidentiality of information. For this reason, companies have different classes of knowledge and component suppliers. Often, component suppliers are also knowledge suppliers.

- In viewing simulation results, inevitably the question arises whether models are valid. This often results in the need to perform detailed validation measurements. Another aspect is that companies expect models to be specifically made for their products. Therefore, accurate knowledge of geometrical, inertial and other data of vehicle components is essential. Collection of model parameters often requires detailed knowledge of the modelling approach. This emphasises the importance of a good relationship between the designer of the model and the supplier of the vehicle components.

- For simulations in general there was a lot of interest. Many people realise however that for an *ad hoc* problem, the initial investment for making a simulation model is relatively high in relation to the gain in design efficiency. However, a majority of the companies tend towards a modular approach in the complete product range and have relatively small design modifications between new product versions. For these companies, simulation models that are built using a similar modularity will become cost effective when used in multiple researches after the initial investment.

- Key aspect in the previous point however is that models must not be a generalised representation of the dynamic behaviour of a road vehicle. For models to be useful, detailed modelling of the suspension is a must. This however places a heavy constraint on the ability to create models for a reasonable price. A possible solution would be to compose models from a validated modelling database with strict separation between model component parameters and model component topology. In this approach, a typical air spring axle suspension can be modelled using variable geometry data and subcomponents such as springs and dampers.

RESULTS OF THE QUESTIONNAIRE

Based on the results of the company visits, a list of questions was composed and sent to some 50 Dutch manufacturers in transportation industry. Some 20 questionnaires were returned. The results of the questionnaire are summarised.

- Considering size of product series of the companies, an even distribution was encountered from manufacturers of single products to product series exceeding 200 products.

- In the averaged company responding, a total of 10 % of personnel is employed in work preparation, planning and product development. Of remaining personnel, 70 % is employed in production.

- Only a small part of the companies use external research companies in the design of new products. Most companies prefer to perform design tasks in-house.

- In many cases, customers play a big role in defining the specifications of the product. Therefore, the need exists to communicate the specifications and properties of products and component of products.

- Designing and constructing in exchangeable components has a high priority in product design.

- One of the biggest needs during product development is the ability to optimise products. Given the current complexity of products, this optimisation asks for an advanced calculation support. Simulations are gaining more acceptance in offering a feasible solution for this problem.

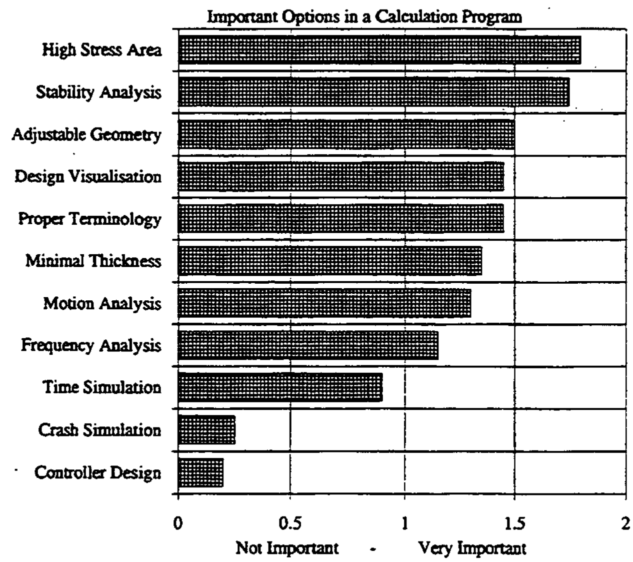

Figure 2: Important options for calculation programs

- All participants have MSDOS hardware, 25 % of the participants also use UNIX work stations.

- From Figure 2, the conclusion can be drawn that evaluation of the high stress area and stability analysis are found most important.

- 80 % of the participants use CAD software. As a result, a great demand exists for linking simulation models with CAD programs.

- Flexibility in adjusting calculation programs to the in-house company situation is considered as an important feature.

After the presentation of the results of the questionnaire to the different partners, the possibilities of continuation of the project were discussed. As a conclusion of this discussion, six of the manufacturers present would assist in defining and evaluating a number of pilot models. In the current status of the project, the models are in a varying range of development. During a pilot phase, the models will be evaluated for their usability in modelling and describing the dynamic behaviour of heavy vehicle combinations. Emphasis will be placed on development of modelling and analysis tools and on evaluation of the user interface in the models. In the next section, the modelling approach and simulation results of one of the pilot cases is discussed.

MODELLING OF AN AIR SPRING SUSPENSION

THE MODELLING APPROACH

The simulation models are made with the modelling and simulation program BAMMS. This program is an in-house development which started at the Delft University of Technology in 1985 [2, 3]. Currently, TNO and the Delft University of Technology jointly develop and use the program. A short summary of the BAMMS modelling approach reads:

- Dynamics of three dimensional multi-body systems are described using Newton-Euler's equations.

- The program works with a separated modelling and simulation phase. In the modelling phase, all model equations are composed to a set of equations for the complete model. Equations for all model components are stored in *modelling macros*.

- All modelling and simulation macros are defined as user accessible ASCII files that are interpreted by the main program.

- At the end of the modelling phase, model equations are sorted and minimised to create a Fortran 77 simulation file.

- Simulations are performed in stand-alone programs compiled from the results of the modelling phase. Simulation programs inherit the modelling program user interface including the macro parsing facility.

SIMULATION MODEL DESCRIPTION

The research is performed in assignment of and in cooperation with 'Weweler Nederland B.V.'. This company designs and manufactures air spring suspensions for heavy commercial vehicles and trailers. The purpose of the research was to analyze the relation between vehicle suspension and passenger comfort for a midsize passenger bus. The pitching behaviour is considered an important aspect in this relation. Redesign of the rear suspension by "Weweler Nederland B.V." is expected to improve this pitching behaviour.

The standard suspension of the vehicle consists of two rigid axles suspended by leaf springs. The values of damping and stiffness of the main suspensions were believed to result in low damped pitch modes of the vehicle between 1 and 2 Hz.

The simulation research is performed parallel to the design of the new suspensions at Weweler and is performed with two simulation models. The model of the vehicle with the air spring suspension is shown in Figure 3.

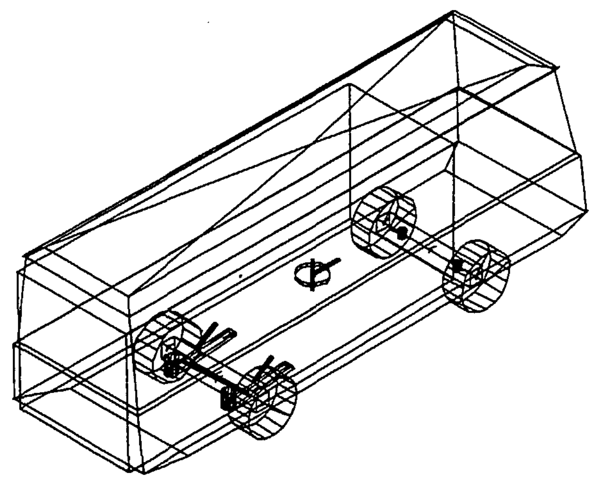

Figure 3: Overview of the air spring model

The models are designed with a large degree of modularity. In the project, axle modules are defined with identical interfaces. Schematics of both axle types can be found in Figure 4 and in Figure 5.

Essential differences between both vehicle models are in the rear suspension:

- The *leaf spring* model contains similar typed axle models for front and rear axle. Differences between

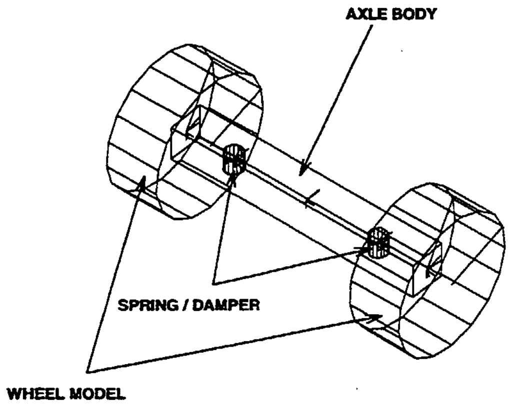

Figure 4: Overview of the front axle models

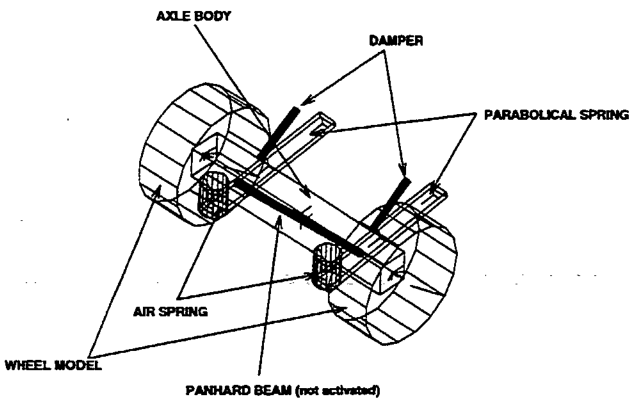

Figure 5: Overview of the rear axle of the air spring model

front and rear are parameters of inertia, damping and stiffness of the suspension. Constant vertical stiffness is applied to model leaf springs. Viscous damping is modelled as a non-linear damping characteristic.

- The *air spring* model contains the designed air spring suspension for the rear axle. In longitudinal and lateral direction, the rear axle is connected to the vehicle by means of parabolical springs. For the vertical suspension of the rear axle, a set of air springs is mounted parallel to a set of dampers. Level control is included in the model as a steady state module. Air springs are modelled using Poisson's law for a gas with a compressibility coefficient $k = 1.4$.

The remaining model components are identical:

- **Wheel models** Vertical and lateral behaviour of tires in the vehicles is modelled. Lateral tire behaviour is modelled using steady state versions of the *Magic Formula* tyre equations [4].

- **Vehicle load variation** Mass and inertia of the payload are represented as a box with variable dimensions and homogenous mass distribution. The amount of payload can be set to any value between empty and full. This feature is used in the analysis to calculate the dependency of vehicle vibration modes on vehicle load.

- **Non-linear damper models** Vertical suspension dampers in the system are modelled with force characteristics as a function of deformation velocity.

TIME DOMAIN ANALYSIS RESULTS

In the analysis, the following results were to be obtained:

- Comparing the new air spring suspension to the leaf spring suspension;

- Finding an optimised value for the damping coefficient of the rear suspension.

Both results are obtained by performing time domain simulations and frequency analysis.

Time domain simulations are performed to validate sensitivity of the vehicles to road irregularities. Main interest was focused on the pitch motion of the vehicle. From eigenfrequency analysis, pitch modes were found to be in the frequency range from 1 to 2 Hz. Simulations are performed on a single sine road surface with a wavelength of 10 meters. At driving speeds of 30, 60 and 90 km/h this generates a road frequency of 0.83, 1.67 and 2.5 Hz respectively.

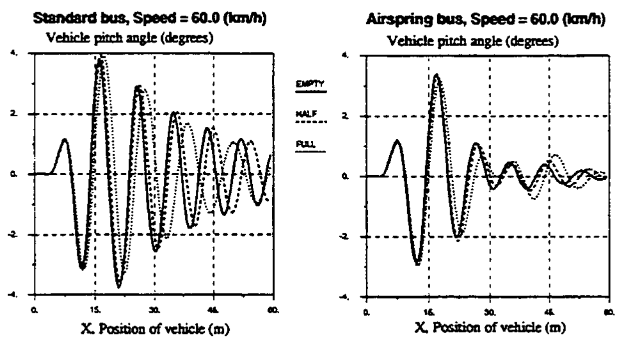

Figure 6: Pitch angle for both models at 60 km/h

The three lines in each plot of Figure 6 show simulation results for each of the vehicles as the vehicle load is varied from empty to fully loaded in three steps. From the simulations, time signals for vehicle pitch and vertical accelerations are compared. The results of the pitch angles at the speed of 60 km/h are shown in Figure 6 for both axle suspensions. The plots show large differences in damping factor and peak factor between air spring and standard suspension. For all load cases, the air spring suspension gives a better ride comfort behaviour than the leaf spring suspension. Both at the speed of 30 km/h and at 90 km/h similar conclusions can be drawn.

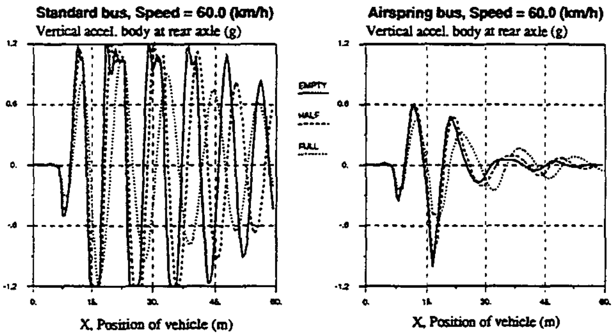

Figure 7: Vertical acceleration at rear axle for both models at 60 km/h

Figure 7 shows the vertical accelerations of the vehicle body at the location of the rear axle. At this location, the improved comfort of the vehicle due to the air spring suspension is most obvious. Especially at higher speeds, low damped oscillations occur at amplitudes higher than gravity acceleration for the standard bus. Amplitudes of accelerations for the air spring bus remain under the level of the gravity acceleration.

The simulation results indicate that road handling and passenger comfort of the bus have strongly improved due to the air spring suspension.

FREQUENCY DOMAIN RESULTS

A linear analysis is performed to calculate eigenfrequencies of both vehicles.

For a number of vehicle loads, varying between zero load and fully loaded, eigenfrequencies and eigenvectors (vibration modes) are calculated. After this calculation loop, the values of the eigenfrequencies at the different parameter settings are represented as *root loci* curves in the complex plane. Locations of the points on these curves indicate the development of frequency and damping of each vibration mode.

Leaf spring suspension In the research, root loci are transformed to curves in a frequency–damping plane to get a presentation of frequencies and damping. An interesting phenomenon can be observed in Figure 8. At a load factor slightly above half, the frequency of

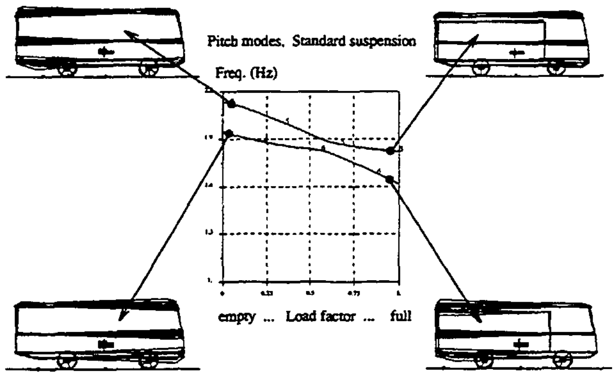

Figure 8: Pitch modes of the vehicle with leaf springs at varying load

two vibration modes (mode 5 and 6) are identical. At higher vehicle load, these modes have interchanged frequencies. In this figure, a rotation of the vehicle body around a point slightly behind the front axle (left dot on line 5) develops into a rotation around a point slightly before the rear axle (right dot on line 5) at increasing load. The frequency of this mode is slightly higher than that of mode 6 which can be explained by the fact that the pivot point of mode 5 is closer to the centre of gravity of the bus. Simultaneously, the pivot point of mode 6 moves forwards in the vehicle at increasing load. Most likely, the pivot points of both modes are close together at the point of intersection, causing the vehicle to have two practically identical vibration modes.

Response of systems with this phenomenon can vary strongly over relatively small changes in parameter values. As a result, such systems will demonstrate quite unpredictable behaviour.

Air spring suspension The two pitch modes of the vehicle with an air spring suspension are listed in Figure 9. The frequency of the pitch mode around the front axle (mode 8) is significantly lower than for the leaf spring suspension. This is due to principal differences between air suspensions and normal spring suspensions. The initial setting of an air spring can be adjusted more easily as the pressure level can be adjusted rather easily. As a result, a lower vertical stiffness value can be applied for air spring suspensions with a level control.

A side effect of air spring suspensions is the increase of stiffness at increasing preload due to level control. This means that the eigenfrequency of a vehicle will be more indifferent to changing the load. This can be recognised as the slopes of the lines in Figure 9 are

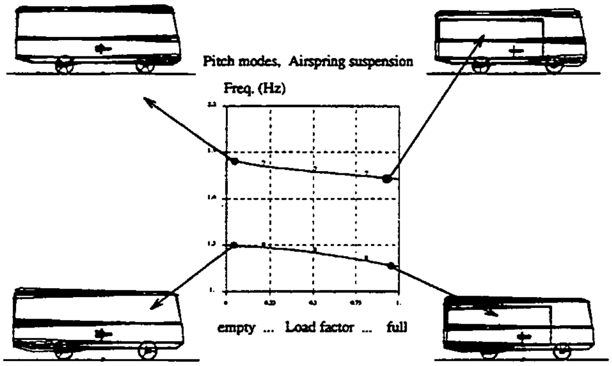

Figure 9: Pitch modes of the air spring vehicle at varying load

smaller than in Figure 8.

Calculation of the eigenfrequencies for the air spring suspension has been performed with level control activated as a static module. For each point in the curves of Figure 9, the equilibrium situation of the system is calculated. The level control algorithm is implemented in the model and is performed automatically after each parameter variation in the model.

DAMPER OPTIMISATION USING TRANSFER FUNCTIONS

One approach to obtain optimal component parameters is by linearisation of model equations and performing analysis in the frequency domain. Frequency transfer functions are calculated in a range of damping values for the rear axle. The range of damping values included the estimated bounce and rebounce damping of the air spring suspension.

The results of the frequency transfer functions are used to obtain a discomfort number based on vertical accelerations above the rear axles and ISO 2631 [5]. The complete process to generate the discomfort index number for both vehicle models is listed in Figure 10.

- The top left part of the figure shows the damping characteristic and the applied range of linearised damping characteristics for the rear axle dampers.
- The top right part shows that frequency transfer functions are calculated using a frequency signal at the rear axles for vertical road velocity input with a constant speed amplitude.
- The centre part represents the amplitude of the frequency transfer function for one value of the rear axle damping for both vehicles. The transfer function plot indicates that especially at low frequencies, the amplitude of the air spring suspension is

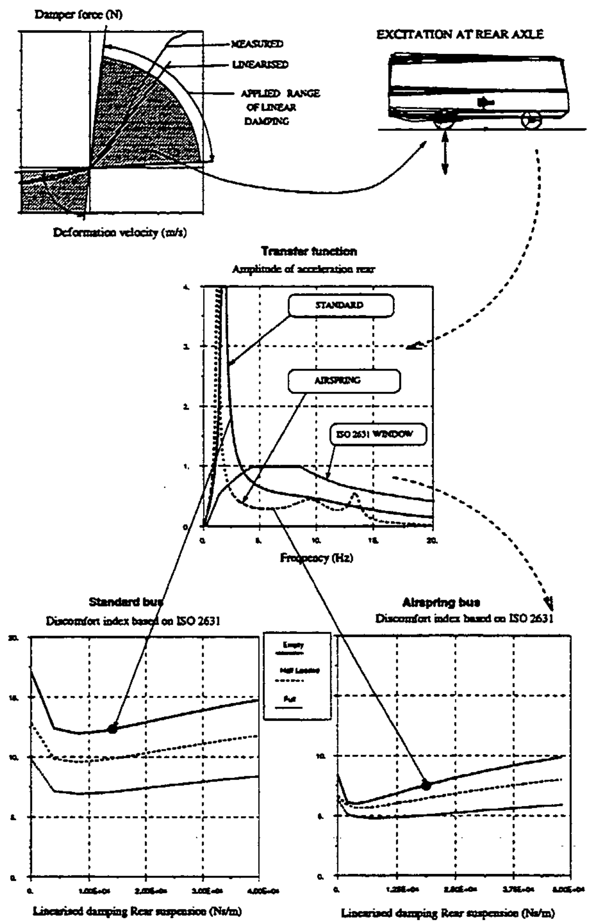

Figure 10: Generation of the discomfort index based on ISO 2631

lower than for the standard vehicle. The shift to the left of the peak value for the air spring suspension illustrates the decrease in pitch frequency already mentioned. The applied ISO 2631 discomfort window is also shown.

- The area below each frequency transfer function is multiplied with the ISO window resulting in one point in the curves at the bottom of Figure 10. The resulting curves can be used to rate a certain configuration relative to other configurations. The x-axis of the curves represents the applied linear damping at the rear axles.

A number of observations can be made from the curves:

- Curves for the air spring suspension are at lower values compared to the standard suspension throughout the defined range of damping values. This means that, for all damping values applied, the air spring suspension gives better ride comfort than the standard suspension.

- For both suspension types, the level of the acceleration decreases with increasing load. This can be explained by the fact that the peak frequency of the ISO filter (see centre part of Figure 10) is at a value higher than the body eigenfrequencies of the vehicle. Further increase of the vehicle inertia will give a further decrease of the eigenfrequency.
- The bottom right plot in Figure 10 shows another interesting aspect. The minimal value of the discomfort curves shifts to higher values of damping at an increasing load of the vehicle. This leads to the conclusion that a load dependent adaptive damping of a suspension will further improve passenger comfort.

CONCLUSIONS OF THE SIMULATIONS

From the simulation research the following results are obtained:

- The comfort and handling of the vehicle with the proposed air spring suspension for the rear axle is essentially better than that of the leaf spring suspension. In the air spring suspension, the difference in eigenfrequency of the two pitch modes has increased to approximately 0.6 Hz. Also, behaviour of the vehicle throughout the load range is more constant. In the leaf spring suspension, pitch modes will interfere depending on vehicle load. This may cause rather unpredictable and varying vehicle response.
- Limited optimisation of the rear axle damping coefficient indicates that the current value is close to optimal.
- The results indicate that optimisation of damper characteristics using time domain and frequency domain simulations is possible. Further application of the methods depicted can be used to optimise the damping ratio during bounce and rebounce.

SIMULATION MODELS FROM DATABASE

Results of the preceding parts of this paper indicate that BAMMS can be applied as a modelling and simulation environment for Dedicated Simulation Models. Another conclusion, however, is that the method for modelling must be simplified in order to generate models in a cost effective way. An important step to improve efficiency of the modelling process is to generate a library of components and parameters of commonly used vehicle suspensions. The structure of this library must be such that parts of it can easily be removed or added for specific users so that each user has the minimal set of components required for creating his models. Also, the method must allow for easy extension of the number of vehicle components or modification of existing components.

In recent projects, modelling in BAMMS has developed into a specific direction supporting these demands. A number of BAMMS features are used to meet the desired specifications: The main feature used is the fact that BAMMS is an interpreter of macros stored as ASCII files. This basically means that removing a macro file will deprive BAMMS of a certain part of its functionality.

The feature is used in developing a library of macros specifically for customers that want to create a range of vehicle models using a limited set of possible vehicle suspensions. By deleting the non-used part of the BAMMS components library, users will only receive (and pay for) the axle types he needs for his models.

A number of macros are defined in a hierarchy of model components. With these macros, models of vehicles are made in a top-down approach.

1. **SYSTEM**
   In the top level macros, complete vehicle body units are modelled. A generic name is used by describing each vehicle body as a *system*. Each vehicle body typically defines a unique reference frame. In this level, users can select one of a number of different types of vehicle *systems*. Differences between existing systems are mainly in the type and number of links to other systems. The group exists of the minimal number of vehicle units required to create any type of articulated vehicle.

2. **COMPONENT**
   In the second level of macros, possible components in vehicle systems are modelled. Examples of components considered are axles, engines and links to other vehicle systems. For model visualisation purposes, components can also represent colour maps or body hull shapes to be used in the vehicle system in question. Each of the existing components can have a varying number of *component types*. For instance, the axle component, can be used to model a range of axle types.
   Dedicated simulation environments are typically defined by restraining the number of components and components types. Users will be limited to modelling a certain range of heavy vehicles when all macros for models of typical passenger car suspensions are removed from the macro library.

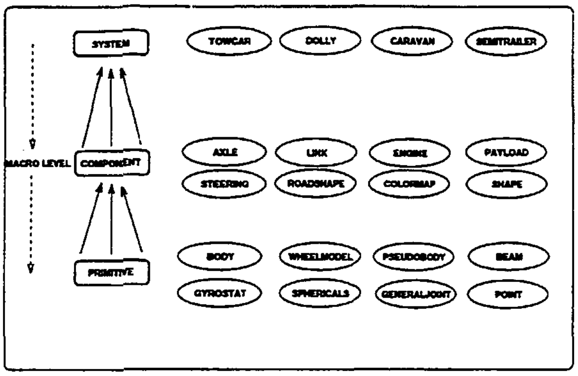

Figure 11: Overview of macro hierarchy for a modelling database

3. **PRIMITIVE**
   Each of the model components is defined using one or more modelling primitives. Modelling primitives are BAMMS macros that have already been used and tested for a number of years. Typical examples of modelling primitives are the BODY macro to generate Newton-Euler equations for a three dimensional body, the WHEELMODEL macro to create equations for a wheel at an axle hub and PSEUDOBODY to create body relative frames with the possibility of steady state variation of relative position or orientation.

Parallel to the hierarchy of macros, a hierarchy of parameter data files is defined for each of the macro levels explained. Typically, each parameter file defines a single data structure which is stored in a parameter array in a BAMMS model. Parameter array can be used to store numerical as well as textual information.

Numerical information is used to store vehicle data such as inertia, geometrical and dynamical model parameters. Textual information, typically describes the name and type of the macro and a variable number of components and/or primitives defined in the macro.

Using this method, complete model topology information is stored as textual information inside the Fortran 77 code of the model. A number of tools exist in BAMMS for retrieval of textual information, thus supplying an easy and interactive method of model documentation and model topology verification.

1. In the first level, a data file describes a complete vehicle system. The file contains all numerical parameter values for this specific vehicle system and the relative locations and types of all components defined to it.
2. In the second level, data files contain parameters for a specific predefined vehicle component. Thus, a number of data files can be present, each defining parameters and topology of an air spring axle of a certain manufacturer. Each of these axle macros can be fixed at any location and number to each of the existing vehicle systems.
3. In the third level, data files describe parameter values and/or characteristics of (parts of) modelling primitives. A typical example is a data file with an interpolation table for damping force as a function of damper relative velocity. This table may represent the characteristics of one damper from the range of products of a certain damper manufacturer. Other examples of data files in this level are tables for spring characteristics or camber and toe-in as a function of suspension travel.

All parameter data files are written in the format of the $\LaTeX$ [6] type setting system also used for typesetting this paper. The advantage of using this syntax is that all data files are ASCII files but can still be included directly in the model documentation. For people not using the $\LaTeX$ type setting system, text conversion macros can be generated to convert data files to any of the popular text editing systems available.
Maintenance and flexibility in use of parameter data files is supported by the fact that each data file can be used as a template for modification or definition of a new data file. Thus, the possibility of interactive modification of each parameter in a data file is introduced.

The above described method is currently being developed and tested. Some parts of macros used in the method exist only in a rudimentary form. The supporting text editing and macro definition components are already implemented. The overall prospect of the method looks promising.

OTHER PROGRAM FEATURES

Finalising, some already existing options in BAMMS to facilitate efficient modelling and analysis are mentioned.

Child macros structures The possibility to define data structures as a *child* of other data structures. Vehicle components, once defined as a *child* of another component macro will, remain (completely) identical to its *parent*. All inherited parameter values of a *child* component will be modified identically when parameters of the *parent* component are modified. Optionally, each parameter of the *child* component can be defined as a unique parameter so that it can also be modified independent of the *parent* component. Using this feature, vehicles can be build with a number of identical axles, each having its fixation point to the vehicle as the only independent parameter value.

Macro redefinition The possibility of unlimited modification of macro equations once a macro is used in a certain model. This possibility resembles an *object oriented* approach of model components. It is being used currently for a range of macros to increase the application range of the macro. As an example, the WHEELMODEL macro, that originally generated a set of steady state tyre equations, can be extended to model a range of both steady state and dynamic tyre models by redefinition of a limited number of macro equations.

Analysis support tools The above method discusses the modelling process only. In the analysis phase, similar methods can be applied to define and use analysis and post processing macros. In a number of projects, macros have already been defined and used creating analysis output specifically for a certain type of research or model. Again, the method applies a number of macros in different levels and supported by a number of data files. Here, data files typically define settings for parameter variation runs to be performed in an overnight batch run. Most analysis macros are based on the knowledge that 90 % of the simulation effort is invested in improvement, validation and verification of the simulation model. Once the model is correct, analysis runs can be performed in a single batch run. By complete definition of the analysis runs in a number of macros and data files, the possibility is introduced to repeat the complete analysis with minimal extra effort.

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