Virtual Prototyping of Vehicle Control Systems

Dr. Michael Hoffmann
Mechanical Dynamics GmbH, Marburg

To be presented at the
AVEC ´96 - International Symposium on Advanced Vehicle Control,
June 24-28 1996
Aachen, Germany

1. Introduction

Due to the increased complexity of modern vehicle control systems accompanied by the demand for shortening the development time, simulation techniques have become a crucial success factor. As it is well known the most important decisions are already made in a pre-prototype stage. Therefore, it is essential that these decisions can rely on performance tests made with a virtual prototype on the computer.

This paper illustrates what ADAMS - a mechanical system simulation tool - interfaced with other CAE-tools can contribute to an efficient virtual prototyping approach. The theoretical section focuses on available modelling elements, interfaces to arbitrary simulation environments, and customization of the simulation environment to specific working processes.

A special toolbox developed for the use in the automotive environment will be explained in more detail. It contains a library of automotive components and analysis methods to be used by experienced analysts as well as designers. One objective of the toolbox is that everyone involved in the development process can investigate how component changes affect the overall system behaviour.

In the last part application examples are illustrated. First, the steps undertaken for the development of a semi-active suspension control system are discussed. Second, a virtual prototyping environment for slip control systems is outlined.

2. Mechanical System Simulation Using ADAMS

Within the automotive industry the mechanical system simulation software ADAMS has become a standard for simulating the kinematics and dynamics of an automobile.

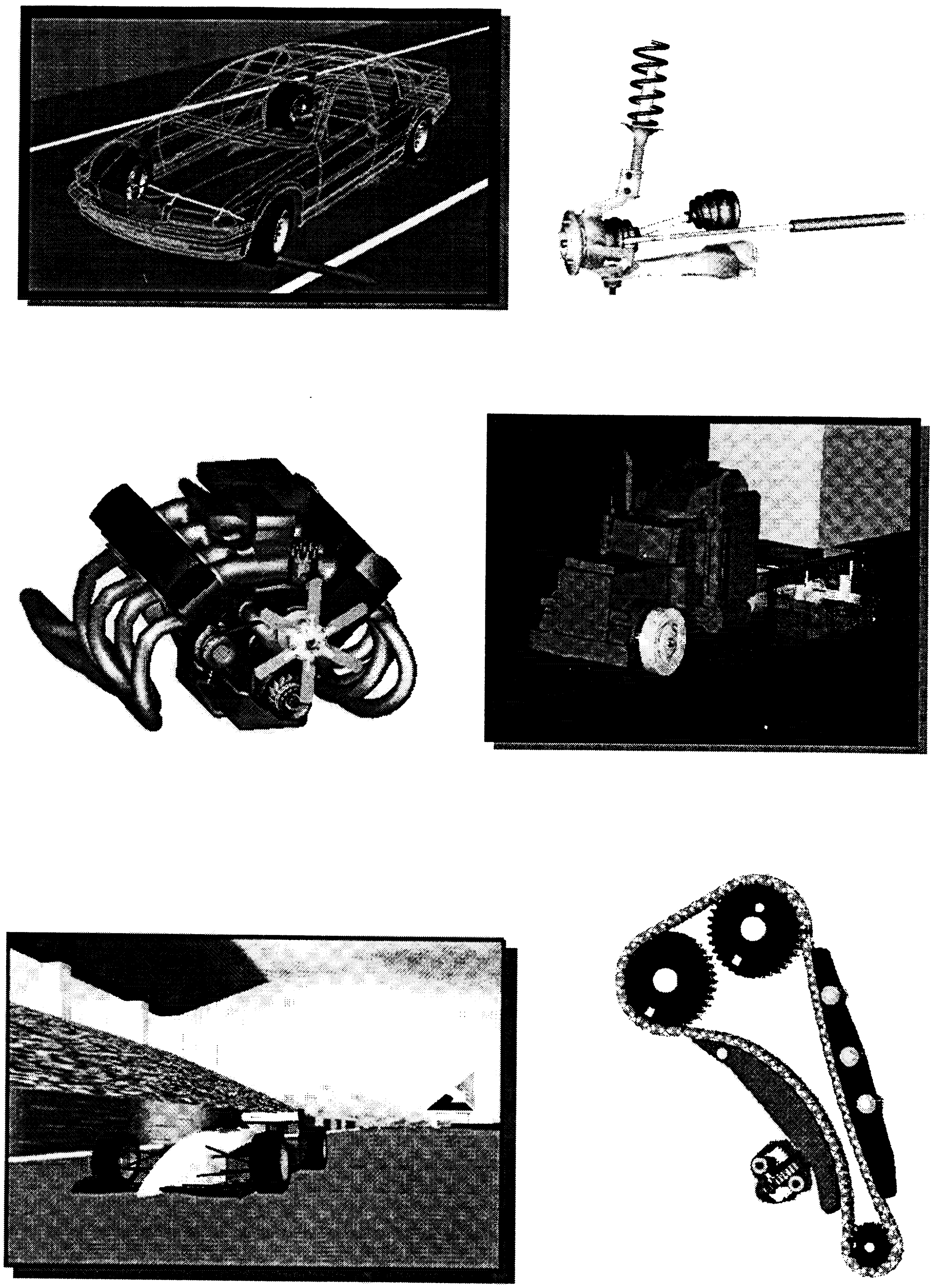

Fig. 1: Examples of automotive systems modelled with ADAMS

Fig. 1 illustrates a small subset of automotive systems modeled with ADAMS. The systems shown include full vehicle models with suspension linkages, anti-roll bars, struts, steering mechanism, brakes, drivetrains, engines, tires, cam and valve mechanism. These systems are used to predict and evaluate non-linear, large displacement vehicle response to inputs from the following: drivers, wind gusts, aerodynamics lift and drag, and road unevenness.
One of the most attractive features of ADAMS is that the users do not have to generate the complex equations of motions; they only have to be able to physically describe the geometry, mass, inertia, compliance, damping, and external forces of a mechanical system in terms of idealized elements. They graphically build a virtual prototype in the same way one builds a physical system, by creating and assembling parts, connecting them with joints, and driving them with motion generators.

In order to represent non-mechanical subsystems like hydraulics, pneumatics, controls, and others, the following system modelling elements are available /1/:

algebraic equations $y = f(\mathbf{q}, \dot{\mathbf{q}}, t)$

differential equations $\dot{y} = f(y, \mathbf{q}, \dot{\mathbf{q}}, t)$ or $F(y, \dot{y}, \mathbf{q}, \dot{\mathbf{q}}, t) = 0$

transfer functions $G(s) = \dfrac{y(s)}{u(s)} = \dfrac{a_0 + a_1 s^1 + \ldots + a_k s^k}{b_0 + b_1 s^1 + \ldots b_k s^k}$

linear state equations

$$\dot{\mathbf{x}} = \mathbf{A}\,\mathbf{x} + \mathbf{B}\,\mathbf{u}$$
$$\mathbf{y} = \mathbf{C}\,\mathbf{x} + \mathbf{D}\,\mathbf{u}$$

general state equations

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}, \mathbf{u}, t)$$
$$\mathbf{y} = \mathbf{g}(\mathbf{x}, \mathbf{u}, t)$$

with the denominations:

q	arbitrary states of the ADAMS model
y	output the subsystem
u	input to the subsystem
x	states of the subsystem
t	time
s	complex frequency
A,B,C,D	system matrices

bold indicates vector quantities.

With these basic building blocks one can systems such as model sensor dynamics, simple PID-controllers up to state space controller including observer models. Non-linear controllers are implemented through user-written subroutines which are hand-written or automatically created by code-generators from control design packages like MatrixX or Matlab.

Although a modern mechanical system simulation tool should have all modelling elements for describing mechatronic systems, openness of the software system is equally important. "Open system" means the ability to interface with other CAE-environments, like CAD, FEA, Controls, and others, Fig.2.

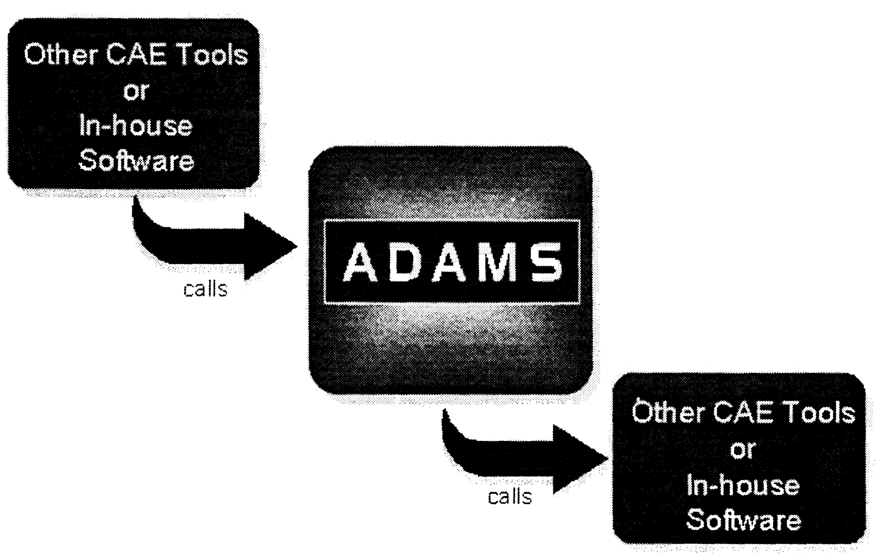

Fig. 2: Open architecture of ADAMS

Various approaches have been used to interface with other simulation environments. Richards, for example, translates the block diagram description of a hydraulic subsystem in terms of ADAMS general state equations and lets ADAMS integrate the complete system /2/. The companies FESTO KG and Mannesmann Rexroth prefer the so-called „Simulator Backplane" method where two simulation environments are running separately and exchange information at predetermined intervals. FESTO uses this method to couple ADAMS with pneumatic systems (including controls) /3/, Rexroth for coupling hydraulic and controls with ADAMS /4/, Fig.3. Both companies are taking advantage of the ability to link ADAMS as a subroutine to an arbitrary simulation environment.

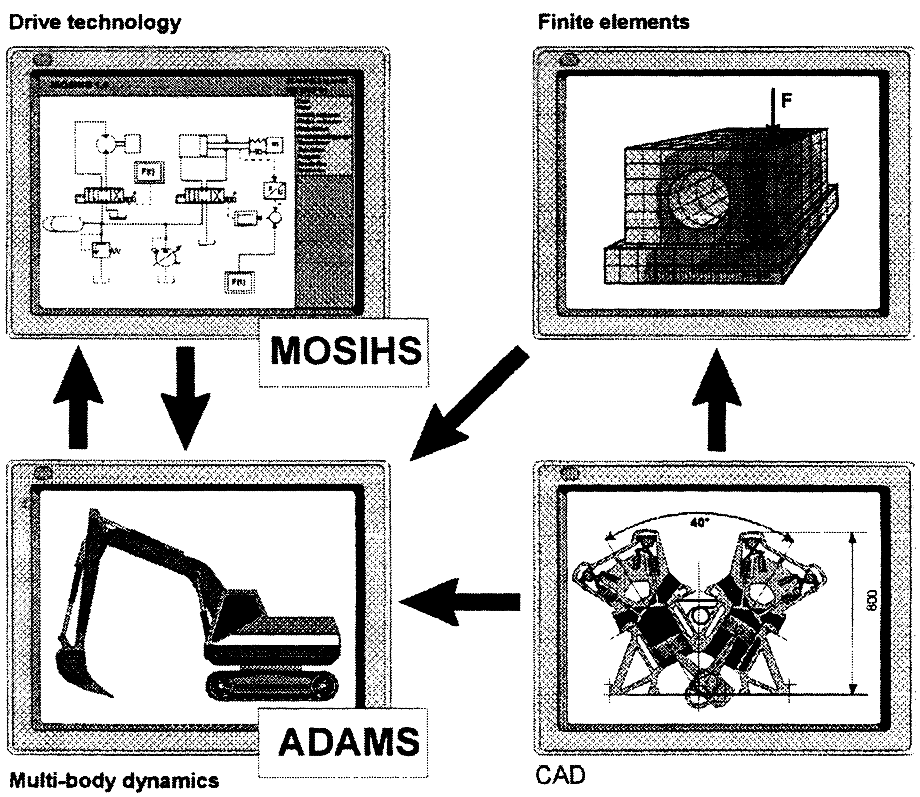

Fig. 3: Coupling of ADAMS and MOSIHS

Basically, the two alternatives exist also for interfacing ADAMS with control design packages like MatrixX and Matlab. Either incorporate the control algorithms into ADAMS through user-written subroutines where the code has been generated by the autocode generators /5/ or embed the non-linear mechanical system into the block diagram description by making ADAMS a

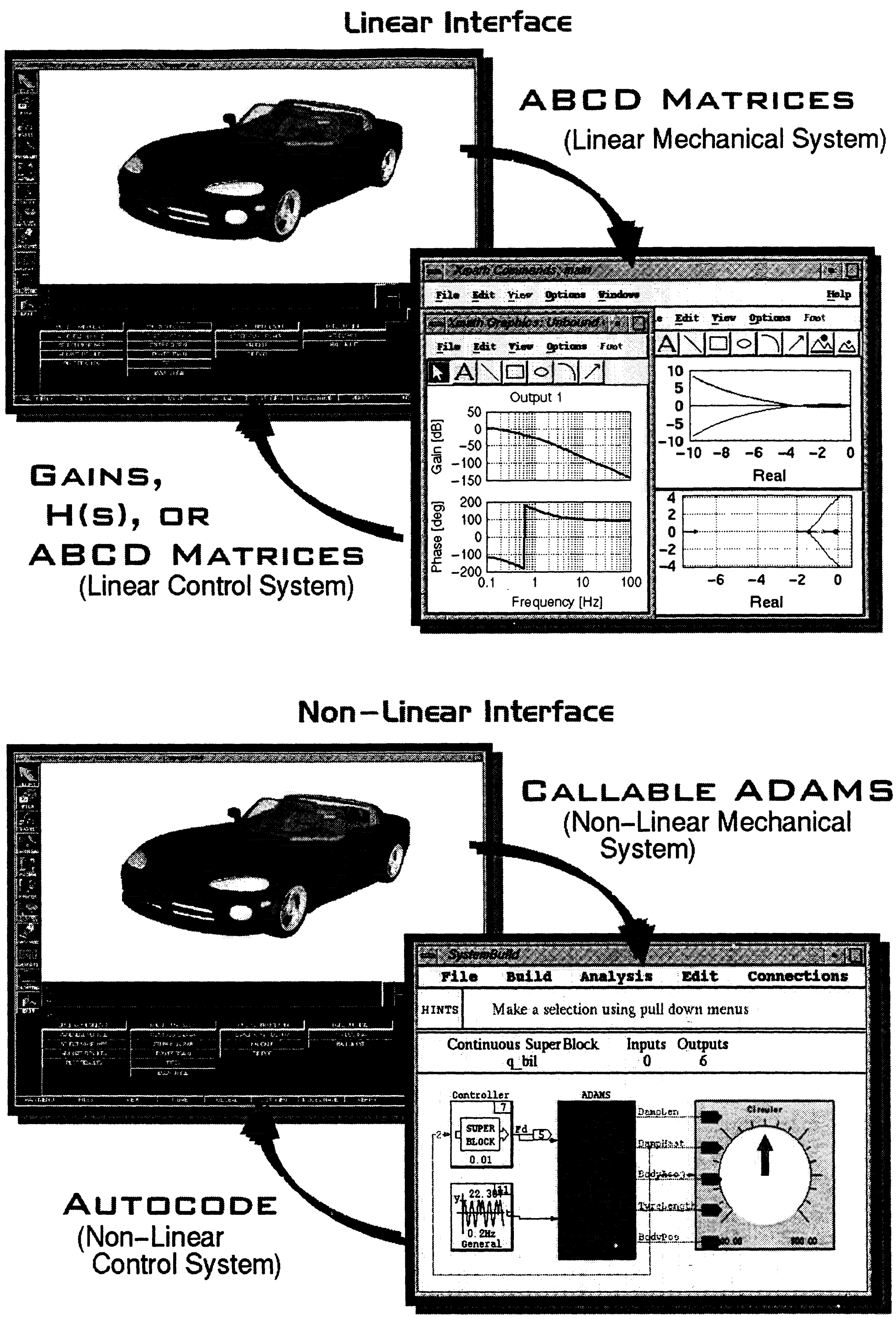

Fig. 4: Interfacing ADAMS with control design software, above exchange of linear systems, below exchange of non-linear system description

MatrixX (or Matlab) UserCodeBlock /6/. If linear models are considered to be sufficient, a simple file transfer of the ABCD-matrices is all the users have to do. Figure 4 summarizes the interfacing possibilities to control design packages: In an early design stage, it might be sufficient to linearize the mechanical system and transfer the state space description in terms of ABCD-matrices to the control system design environment. There, the appropriate control strategy can be chosen, designed, and brought back to the ADAMS environment in terms of feedback gains, transfer functions or state space description. In a later design stage, non-linearities have to be taken into account. Then, the detailed mechanical system can be exported to the control design package via Callable ADAMS or the non-linear control laws can be imported to ADAMS - depending on the users preferences.

An efficient usage of simulation tools within the development process requires more than just providing the analytic capabilities described above. The modelling and simulation process and the ability to adopt this process to the specific environment of particular companies and departments have become a crucial success factor. This is especially true since the profile of a standard user has shifted from an analysis expert to a standard designer who simply wants to investigate how the component he/she is responsible for is affecting the overall system performance. Thus the focus is on ease-of-use, library of parametric models, and seamless integration of mechanical system simulation into the development process /7/.

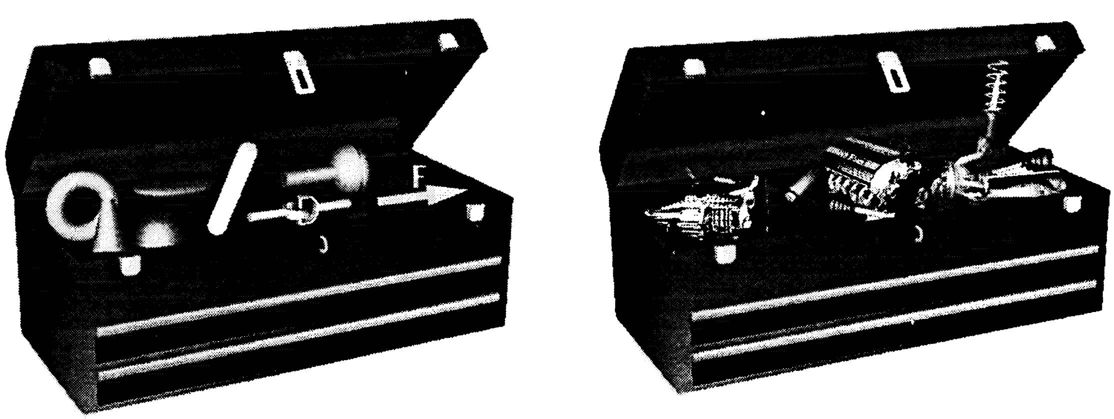

Fig. 5: Standard mechanical system toolbox and special automotive toolbox

Traditionally, an ADAMS user works with a toolbox containing elements such as parts, joints, forces, and motion generators, Fig.5. When building a mechatronic system there is no need to think in terms of equations of motions and matrix operations. However, a level of abstraction is still required of the user, instead of thinking directly in familiar product components, e.g. wheel spindle, steering system, etc. New to mechanical system simulation is the ability to customize the application toolbox, or have it customized, to contain the industry specific components. This has been jointly undertaken by Mechanical Dynamics and a consortium of automotive companies in order to develop an automotive toolbox, called ADAMS/Car /8/. Fig. 6 depicts a typical workflow when using ADAMS/Car. A full vehicle model may consist of an arbitrary numbers of subsystems which are all of parametric nature and can be investigated separately. E.g. the user may change the geometry of the front suspension, then define the properties of the car body, automatically assemble the system, perform a virtual test program, and investigate graphically the results. Strengths of ADAMS/Car are the graphical modelling environment and an underlying database of subsystem models, property descriptions, and test programs.

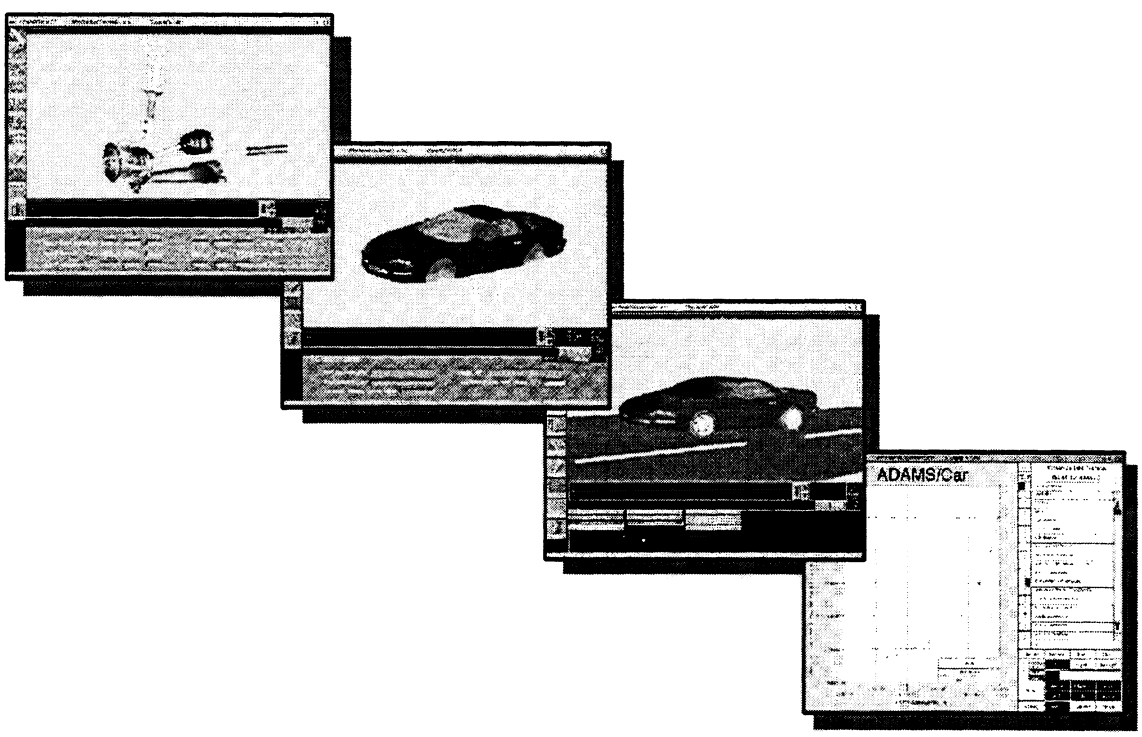

Fig. 6: Workflow of ADAMS/Car: Subsystem modelling, system assembly, system testing and evaluating.

3. Applications

The first example deals with the development of a suspension control system. Goal of an active or semi-active suspension control system is to reach optimal comfort (i.e. minimum body movements) whenever it is possible and optimal safety (i.e. maximum driving stability) whenever it is necessary. One possible approach to the control design could be to do all the work with a detailed full vehicle model. Disadvantages of such approach are:

- The model is non-linear, thus the known algorithms from control design like pole placement or quadratic linear regulator do not work, because they are limited to linear systems.
- The number of degrees of freedom normally exceeds 50 resulting in large computation requirements and in complex systems where model validation without a guideline from reduced models is hard to achieve.

Therefore, a stepwise approach with successive refinements of model and controller was undertaken.

In order to get a first orientation and a feeling for the problem, it is advisable to start with a linear model having a small number of degrees of freedom. Dealing with a quarter car model already allows classification of different control strategies into promising ones and less successful ones. During this stage one can, for example, determine:

- An upper performance limit of the controller by assuming that all states of the system can be measured./9/
- An initial assessment regarding influence of sensor noise and actuator dynamics.
- Design sensitivities regarding simplifications of the control strategies.

Fig. 7 shows an example of linear analysis where the frequency response of a quarter car model is depicted for conventional suspension systems and an active system using only feedback of the vertical body velocity („Skyhook Principle“).

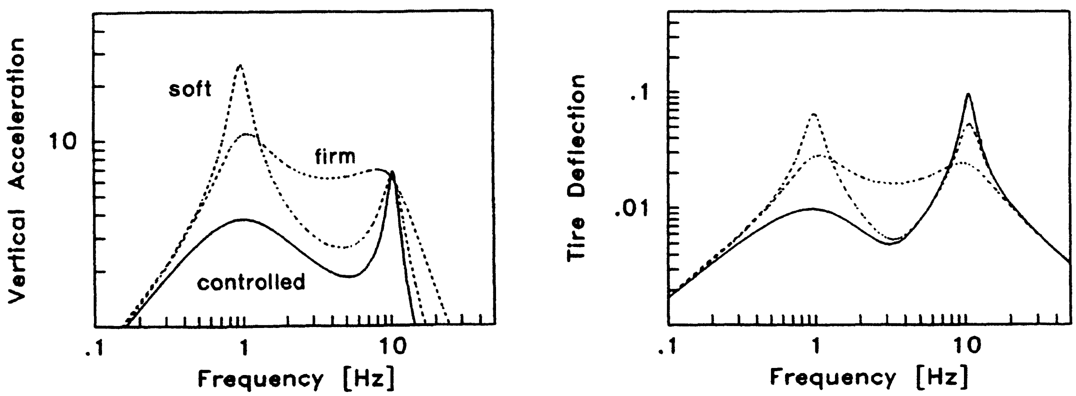

Fig. 7: Frequency response of a quarter model (solid lines: active „skyhook“ principle, dashed lines: conventional suspensions)

Keeping in mind that a vehicle is a non-linear system especially due to the suspension kinematics, damper, spring, and tire characteristics, dealing with linear models can only be a starting point for subsequent non-linear simulations. For further development and validation of the control algorithms it is necessary to include the above mentioned non-linearities. However, it is still sufficient to study a model with reduced degrees of freedom as in the first step. This reduced non-linear model can now clarify several questions like:

- How much performance do I lose when applying semi-active control instead of active control (i.e. using a passive element like a controllable damper instead of an active actuator)?
- What are the requirements for sensor resolution and accuracy?
- What is the effect of computational delay of the target controller?

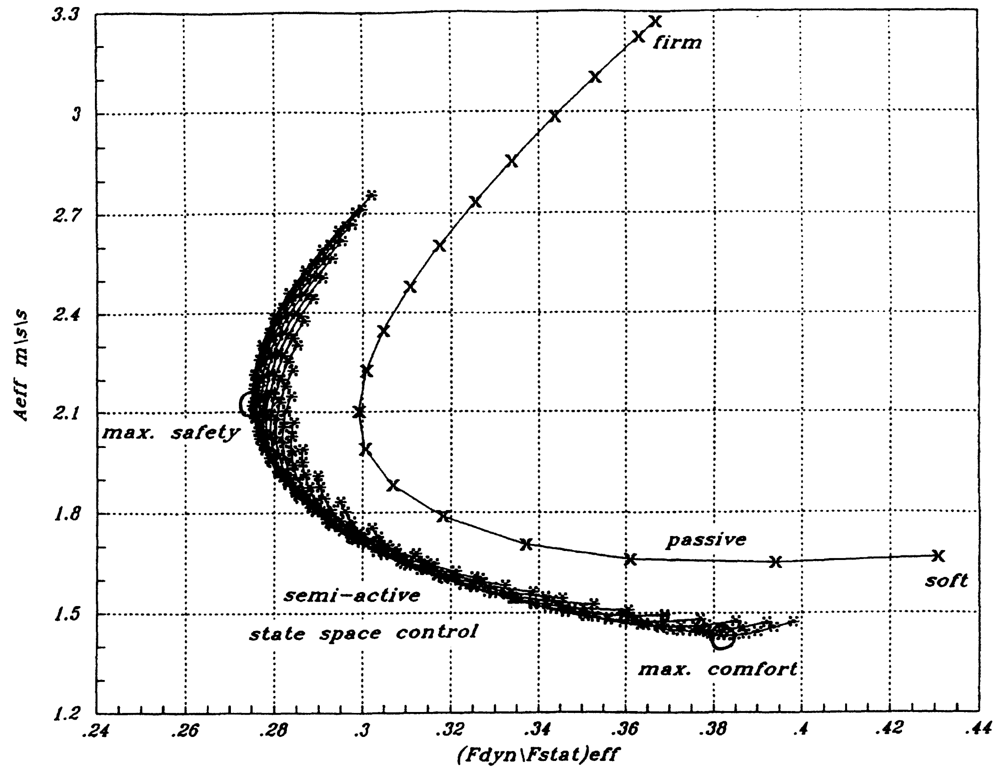

Fig. 8 Feedback gain variation of a damping control system compared to passive suspension systems.

Simulation has to be done in the time domain. For investigating the above mentioned questions some reference road profiles had been defined. Fig. 8 shows simulation results for a ride on a rough road. Effective values of body acceleration and dynamic tire force variation are shown for a non-linear quarter car model where the feedback gains of the vertical body velocity and damper velocity have been varied.

For a final validation of the chosen control algorithms on the basis of computer simulations and for comparison with actual test drives performed later in the development process, virtual test drives with a full vehicle model were carried out. Fig. 9 depicts the ADAMS model and some comparison with actual test drives. The use of simulation tools had been very beneficial to the development of this semi-active suspensions system described in more detail in /10/. However simulation can not totally substitute actual testing. Fine tuning of the controller on test tracks remains still necessary.

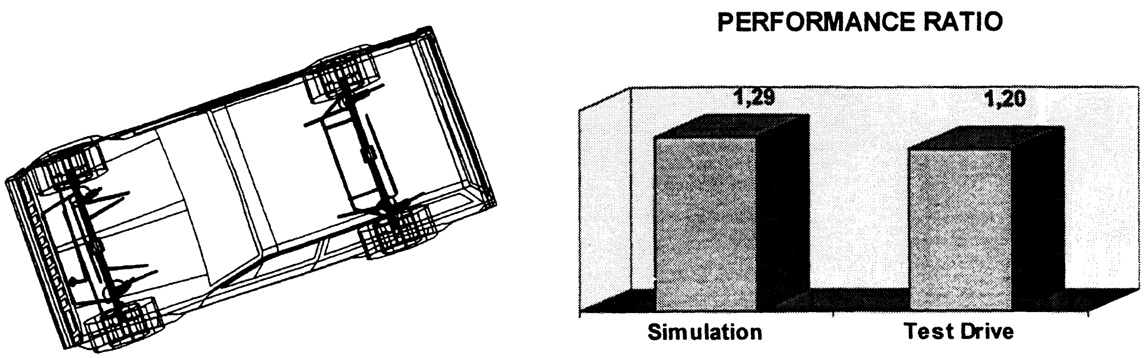

Fig. 9: ADAMS model and predicted vs. actual performance of a damping control system (performance ratio: rms-value of body acceleration of standard vs. controlled suspension)

The second example deals with the incorporation of slip control systems into ADAMS (see also /11/). The most realistic model of an slip control system can be achieved by embedding the control code which is used in the real car in the virtual prototype /12/ /13/. However, as these control algorithms represent the know-how of the control system supplier only object code is currently delivered to the automotive manufacturer. Thus, the manufacturer has to treat the control system more or less as a black box; at the most, he will be able to vary a few parameters.

An evaluation of the working process of an chassis development department showed that besides the actual control code there is a need for parameterized control systems which structure is documented and can be changed by the chassis engineer. While the actual control code can serve for final „prototype testing on the screen“ the more flexible control code can be used to investigate alternative control strategies.

This parametric control strategy /14/ is based on the sliding control theory where the whole idea is to increase/decrease the brake pressure in order to operate in an optimal slip range $slip_{opt}$. The sliding surface s is defined by:

$$s = wheel\_acc - (slip - slip_{opt})*K$$

with wheel_acc: wheel angular acceleration where the slip is calculated by:

$$slip = (v_{ref} - r_{dyn}*\omega) / v_{ref} \geq 0 \quad \text{(when braking)}$$

v_{ref}	longitudinal component of vehicle velocity
r_{dyn}	effective wheel radius
ω	wheel angular velocity

The simplest anti-lock control is now to increase the brake pressure for s>0 and decrease it for s<0. For a more realistic control we introduce different thresholds and pressure gradients for increase and decrease, Fig. 10. Further refinement of the controls include "select low" on the rear axle and a learning algorithm to adjust the pressure gradients during the control.

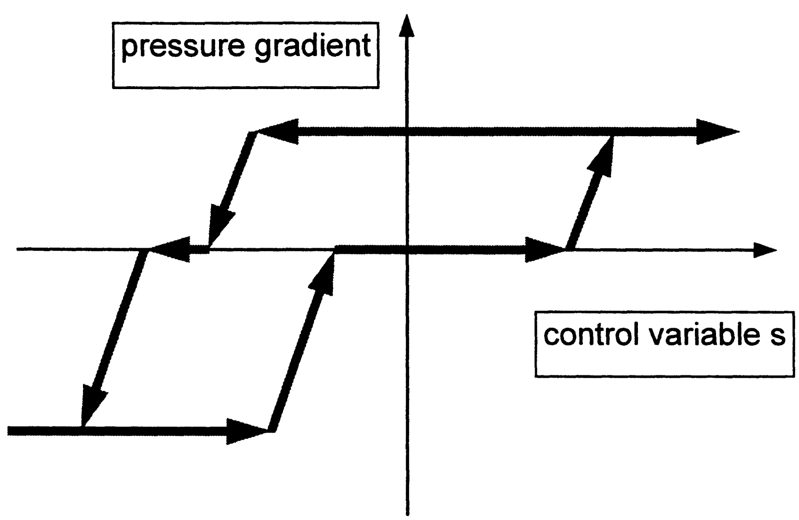

Fig. 10: Pressure gradient hysteresis

For the traction control system there are two control elements, namely: brake pressure on the drive axle and the engine torque, i.e. a link to the motor management. The desired pressure and torque are calculated similar to the ABS-mode. The control algorithms take the engine inertia into account, i.e. at the beginning of a control cycle brake intervention is dominant and will be reduced subsequently.

The input panels for setting up a vehicle with a slip control system and conducting performance studies are depicted in Fig. 11. The "driver input" panel defines the initial velocity of the vehicle, selects the wanted gear, activates and deactivates the controls and defines driver input like braking, accelerating, and steering. The control gains, brake, and engine torque gradients are set in the ABS and ASC+T panels.

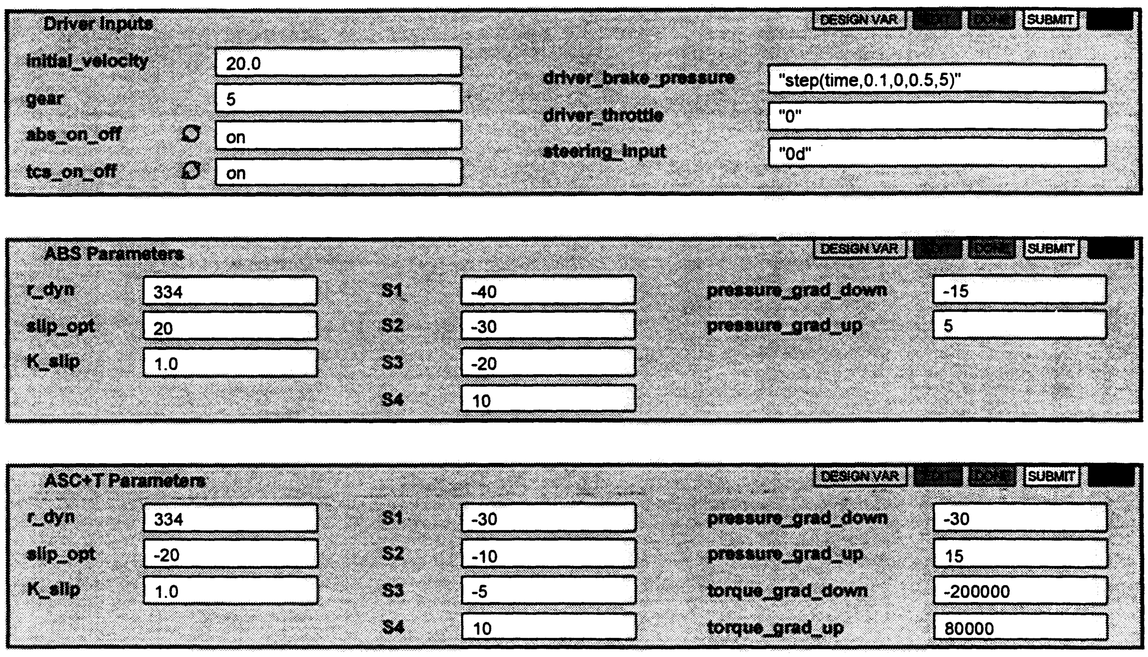

Fig. 11: Input panels for setting-up the slip control system

By these input panels and a corresponding menu structure the engineer is guided through the model setup. He can easily conduct performance studies and investigate sensitivity to parameter variations.

The simulation environment described above was used for the first time to visualize the performance of a BMW 750i with the slip control systems ABS (anti-lock brakes) and ASC+T (traction control). Starting point of the model creation process was a basic full vehicle model described in the DMP, a textual preprocessor which is still widely used among simulation experts.

As non-simulation experts wanted to perform analyses the vehicle model was transfered into the graphical modelling environment ADAMS/View. In fact the model file created by DMP is suitable for ADAMS/View as it is, but it is much easier to understand and modify the model, if names of parts, forces etc. are derived from real world (e.g. left control arm) instead of 'computer names' like PAR1, PAR2 and so on. Within ADAMS/View the model was extended to include engine, driveline and braking system. The tire model used is based on Pacejka's magic formula. Body graphics were imported from CATIA via IGES-data, all other graphics were created by ADAMS/View elements. The resulting model is shown in Fig. 1, upper left corner.

Like the real physical prototype the software prototype had to undergo a series of standard tests, like

- avoidance manoeuvre on a wet road
- emergy braking while cornering
- going up an icy hill
- accelerating while cornering.

In order to get an overall impression of the vehicle performance the vehicle movements were stored for each time frame on a disc and then recorded on a video tape in real-time and slow motion. The animation of the vehicle behaviour also included the visualization of the longitudinal and lateral tire forces. Thus, the global vehicle movements could be easily correlated to the tire-road way interactions, giving valueable insight to the performance of slip control systems.

Fig. 12 and 13 depict snapshots from the "emergency braking while cornering" with and without anti-lock braking systems. For the uncontrolled vehicle the applied brake pressure yields to wheel locking and the loss of steerability. Due to the large longitudinal slip there are no stabilizing side forces anymore and the vehicle slides towards the left lane. The anti-lock braking system reduces the brake pressure such that tire slip is within the range of optimal slip, i.e. that there are sufficient large side forces to keep the vehicle on the track.

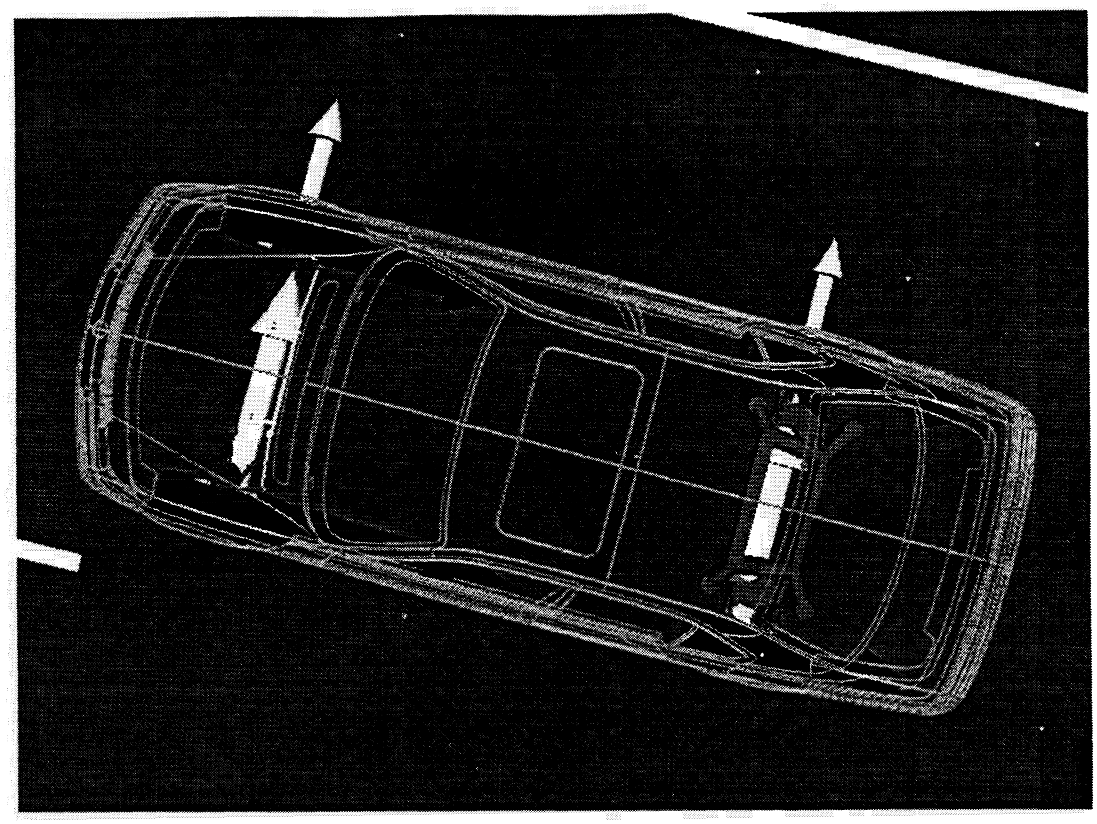

Fig. 12: Vehicle response for braking while cornering with ABS

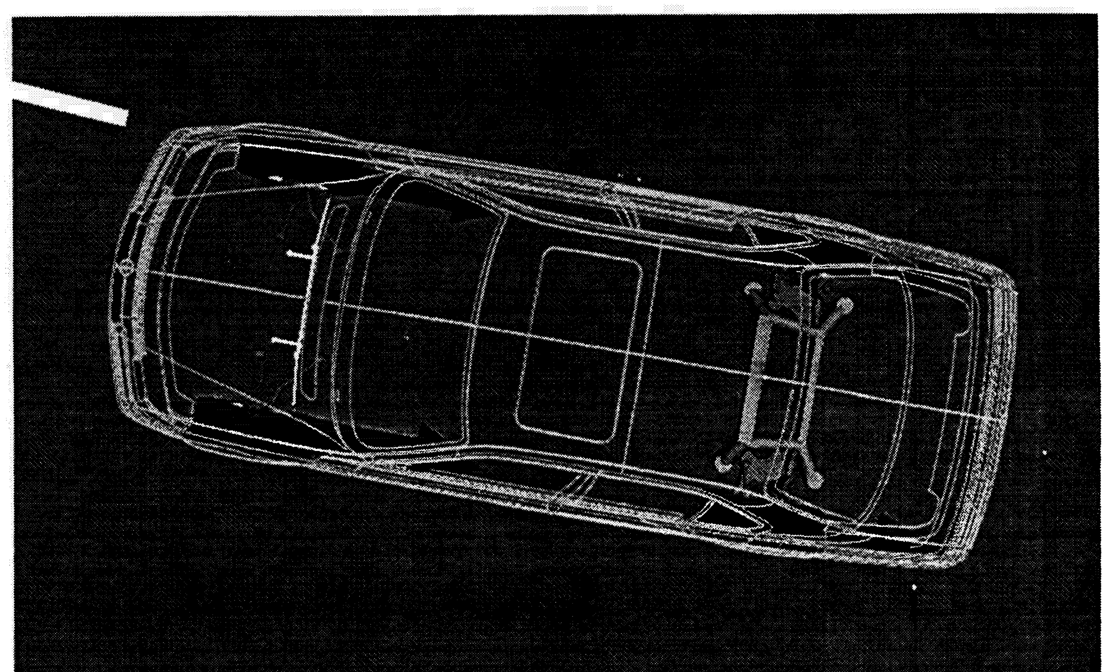

Fig. 13: Vehicle response for braking while cornering without ABS

Fig. 14 shows an example of the traction control system in action. The driver command for this manoeuvre was full throttle in the first gear while entering a main. With a deactivated ASC+T the engine torque is far too high, the rear wheels are overspinning and only traction forces are generated. Stabilizing side forces cannot been built up and control of the vehicle is being lost. A well adjusted ASC+T can handle this critical situation, however. When too much slip on the rear axle is detected brake pressure is immediately applied to the rear brakes reducing the resulting driving torque. At the same time the actual throttle position is reduced in order to adjust the engine torque. During the control cycle brake intervention is gradually reduced and throttle control dominates, finally. Fig. 14 demonstrates that due to the limitation of the longitudinal slip there are always sufficient large side forces to ensure vehicle stability.

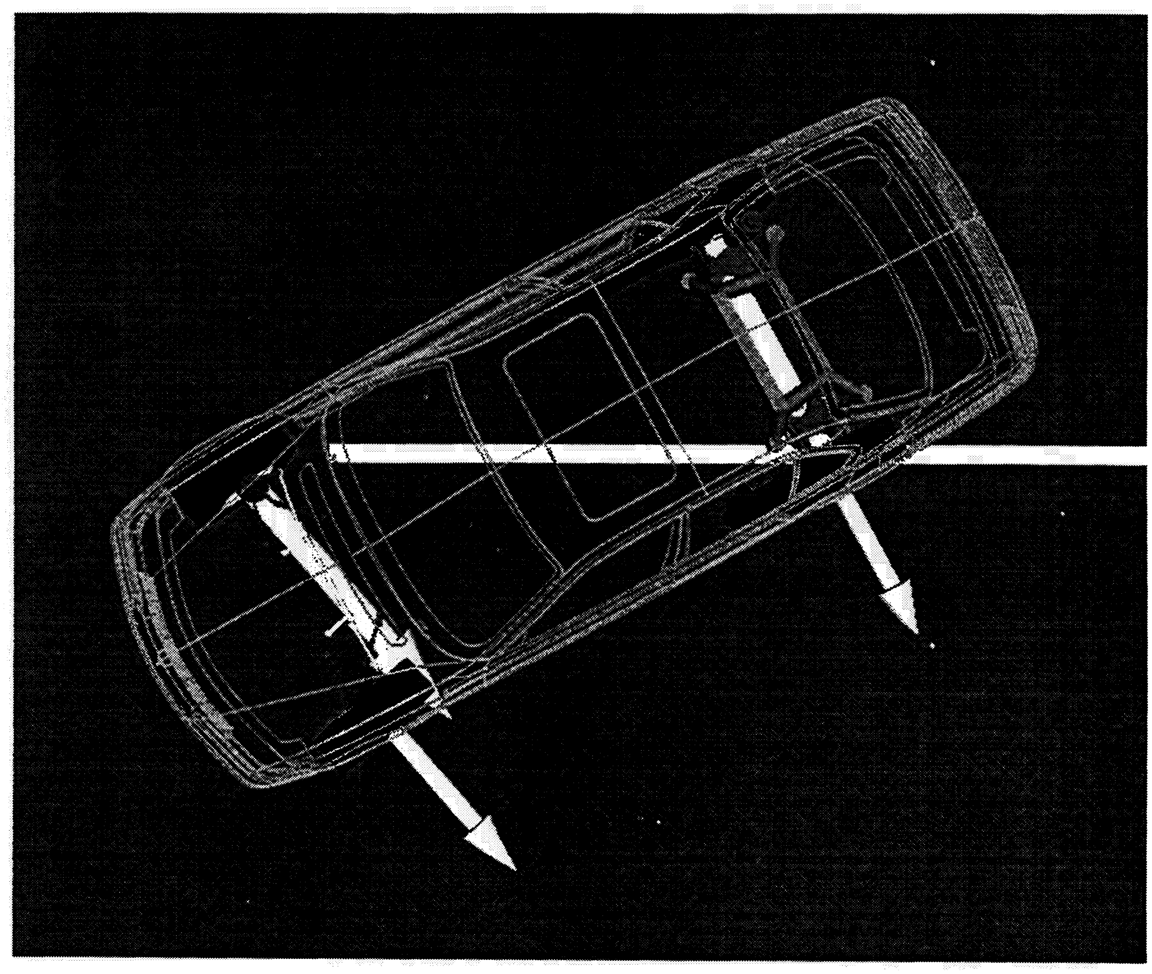

Fig. 14: Vehicle response for accelerating while cornering with ASC+T

The simulation of the driving manoeuvres described above showed among others the trade offs one has to scope with when designing a slip control system: In order to allow fast reaction to changing surface conditions high pressure gradients are required. Controlling the slip in a very limited range demands small pressure gradients, however.

Experience shows that the combined visualization of the overall vehicle movements and the tire forces leads to an extended usage of full vehicle simulations: On the one side the animation can be used to quickly illustrate complicated facts to non-experts in controls. Furthermore, the animation is also appreciated by vehicle tests engineers because they now can see quantities like tire forces which they normally only estimate.

4. Conclusions

The application examples shown represent some more steps towards a system level approach within the chassis development process. Basic investigations as well as complicated circumstances can be investigated with software prototypes before a physical prototype has been built. The creation of parametric models of vehicles and control systems and the customization of the graphical interface to the specific needs of the chassis engineers are essential for a broad usage of the simulation tools.

With the increased usage of mechanical system simulation where models are shared on a company wide basis interfacing to product data mangement systems is gaining importance. Besides the continuing effort of improving analysis capabilities and ease-of-use this will become a focus of future development.

5. References

1. ADAMS 8.0 User Manual, Mechanical Dynamics Inc., Ann Arbor, 1994
2. G. Richards, Simulation of a Power-Steering System through a Coupled MSS/Hydraulic Approach Using ADAMS and AMESIM Results, 10th European ADAMS Users´ Conference, Frankfurt, 1995

3. W. Engler: Coupling of ADAMS with Pneumatic Systems Simulation Software, 10th European ADAMS Users´ Conference, Frankfurt, 1995
4. Dr.-Ing. M. Piechnik: Simulating Hydraulic-Driven Mechanical Systems, 10th European ADAMS Users´ Conference, Frankfurt, 1995
5. M. Hoffmann: The Balancing Briefcase: Interfacing ADAMS and MATRIXx, 1992 Int. ADAMS Users' Conference, Ypsilanti, Michigan, 1992
6. D. Minen, M. Hoffmann: Techniques for Simultaneous Simulations Running Xmath/SB and ADAMS, TEDAS srl, 1994
7. W. Gonska: The Necessity of a CAE Tool's Integration into the Process Chains of the Automotive Industry shown with the Example of ADAMS, 1993 Japanese ADAMS Users' Conference, ISI-Dentsu, Tokyo, 1993
8. M. Guttilla, E. Fischer: ADAMS Customization in the Automotive Industry, 9th European ADAMS Users' Conference, Frankfurt, 1994
9. M. Chalasani: Ride Performance Potential of Active Suspension Systems, ASME Symposium on Simulation of Ground Vehicles and Transport Systems, Anaheim, 1986
10. A. Dreyer,J Gräber, M. Hoffmann, P. Rieth, S. Schmitt: Structure and Function of the TEVES Brake and Suspension Control System BSCS, FISITA ´92 Congress, London, 1992
11. W. Gonska, M. Vesimäki, M. Hoffmann: Virtual Prototyping of BMW Slip Control Systems, 1994 Japanese ADAMS Users' Conference, ISI-Dentsu, Tokyo, 1994
12. Gräber: ADAMS in Vehicle Control System Development, 6th European ADAMS Users' Conference, Wiesbaden, 1990
13. Judaschke, F. Kemmler, B. Lammen: Simulation with ADAMS in the Development of the Automotive Stability Management System, 10th European ADAMS Users' Conference, Frankfurt, 1995
14. M. Hoffmann: Structure of a Simple ABS/TCS, Mechanical Dynamics GmbH, Marburg, 1994