Variable damping rates – how to calibrate them in the trade-off between comfort and safety

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Abstract

Presuming to have the availability of slowly variable damping rates – e.g. as function of the vehicle velocity – it is investigated and presented a method how to optimise good calibration of such functions as a starting point for final calibration on a vehicle.

Taking fundamental approaches to vehicle dynamics we show by a realistic case study, the best trade-off behaviour between “tire load variation” (Safety) and “vertical Driver acceleration on the seat” (Comfort).

As the tool chain a high quality 3D-Vehicle simulation software (IPG-CarMaker) is collaborating with an professional Calibration Optimization software (AVL-CAMEO). This method not only gives the vehicle dynamicist what he wishes, but also help to sharpen his perception of how best to achieve it.

The paper is targeted to show how advanced but user friendly DoE-Application supports engineering judgment, by identifying the potential mechanisms most critical in a vehicle’s dynamics design and how it displays this information in a way that helps the engineer make informed judgment about the inevitable compromises.

Using a simple but realistic example this paper explains possible steps to optimise the damping of a vehicle at different road speeds, such as might be useful for a basic and low cost relatively slow acting variable damper.

1 Background

Today many vehicles are being fitted with suspension dampers which can have their characteristics changed under control of a Control Unit. This can not only allow improved overall satisfaction for the vehicle's end customers and hence marketability, but also allows the same damper hardware to be fitted to different models or variants with cost saving for the OEM.

This paper explores the power of an analytic method to optimise the calibration of suspension dampers to suit different driving conditions and finding a good balance between the ride and handling properties.

The method can be extended to include many of the other multiple parameters involved in developing a vehicle's ride and handling, some of which will be explored here.

This is not a real case study but a realistic journey through the sort of development process that a vehicle might go through. It is illustrated by applying the method to a proposed E.V. version of a vehicle platform with its new variable damping system.

2 Introduction

Suspension springs allow the wheels to follow the profile of the road surface while the vehicle body follows the primary features of the road, isolating it and its occupants from smaller and higher frequency uncomfortable secondary disturbances ("Primary Ride" and "Secondary Ride "respectively.)

The pitch inertia property of the vehicle has a significant effect on the achievable quality of the primary ride and should be considered in the vehicle's concept design.

Before attempting to define the damper characteristics it is first essential to establish that the road springs are matched to the vehicle mass and inertia in such a way to give a subjectively "flat" primary ride (minimum pitch disturbance and quickly regaining a level ride) e.g. after crossing a long wave bump

Different road speeds ideally require different spring and damping regimes, so normal passive vehicles will just use a single compromise spring setting.

Insufficient damping of this spring-mass-inertia system would allow excessive post bump oscillations which would be uncomfortable for the occupants, and too much damping has effect of increasing the transmission of shocks from road to the vehicle.

Both cases can lead to excessive fluctuations in contact load between tyres and road, causing poor handling and braking.

Some dampers can be switched between 2 or 3 different settings switched by a Electronic Control Unit and greatly reduce the compromise. Further systems offer pseudo "continuous" control of damper force but even these are often defaulted to a small number of "passive settings" – at least at the start of development. Another advantage is that as well as offering a better ride and handling compromise for the target vehicle, the same damper hardware, with different software calibration, can be fitted to variants or even to other models.

The situation is further complicated by the effect of introducing compliant buffer to limit wheel travel within the package space and also the additions of side to side spring systems to limit vehicle roll "Anti Roll Bars" (ARB)

Using a simple but realistic example this paper explains possible steps to optimise the damping of a vehicle at different road speeds, such as might be useful for a basic and low cost relatively slow acting variable damper.

As real damper hardware comes in different forms a simple two gradient damper will be used in this example. For a real application the model suiting the supplier's own damper could be substituted.

As dampers are very difficult to model these "optimised" results would provide a sound starting point for specifying the dampers, but inevitably there further refinement by way of rig and road testing.

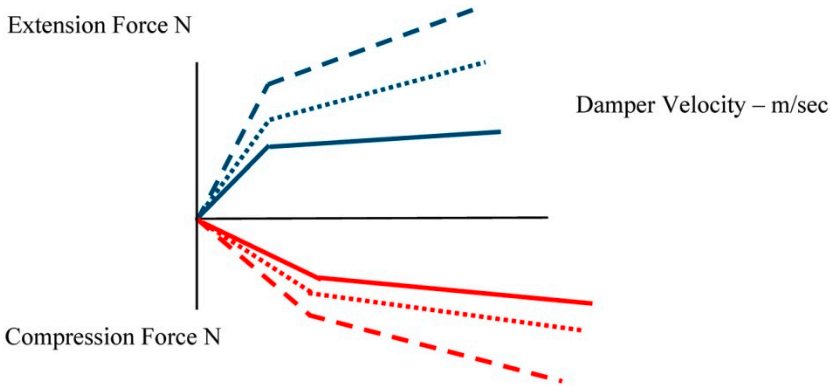

Fig1. Example of a simple 3 stage switched damper

3 Objectives for this Example.

Scenario (1) Achieving "Flat" Primary Ride for comfort by calibrating Rear Springs and Pitch Inertia with carry over damping

At first recovery from traversing a long wave bump the front and rear axle heights should ideally be in phase and of equal amplitude, giving a pitch free attitude. After the first recovery from the disturbance there should be no more than one small oscillation.

Furthermore pitch velocity over the whole manoeuvre should be minimised (for comfort and less driver distraction).

Scenario (1) Using damper setting carried over from the donor vehicle Rear Springs and Pitch Inertia are optimised to achieve flat ride.

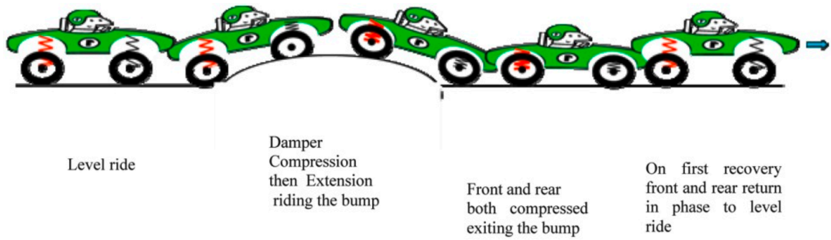

Fig 2. Illustration of "flat" ride over a primary ride input

Scenario (2) Achieving "Flat" Primary Ride now also allowing the rear dampers to be optimised

For the same target as in scenario (1), in addition to the Springs and Pitch inertia the rear damper parameters are also optimised.

Scenario (3) Maximizing tyre contact over a bumpy road varying the dampers for different Road Speeds

During Cornering, acceleration, and braking the tyre grip is a function of normal load on the tyre. If load is temporarily reduced e.g. during a disturbance on a bumpy road it takes some time and distance after the vertical load is restored to fully recover grip. Consequently the total grip available during the event is reduced.

With variable damping it is possible to offer better optimisation of damping for different road speeds. This scenario varies the dampers to find the best matches for comfort and grip over a range of road speeds.

4 Optimize Road Springs & Pitch Inertia to achieve flat ride

Before tuning the dampers it is important that basic spring rates best match the straight line primary ride requirements for different speeds and loading cases. This would traditionally be established by iterative practical trials on a prototype vehicle or iterative simulations of the motion.

In our example the OEM has a choice of where to package the heavy masses of the two batteries in the vehicle which will affect the pitch inertia, but with the objective of keeping the Front/Rear weight distribution the same.

The front spring rate has been dictated by a target ride frequency, but the rear spring together with the pitch inertia, can be optimised.

The first example demonstrates this and the power of the method.

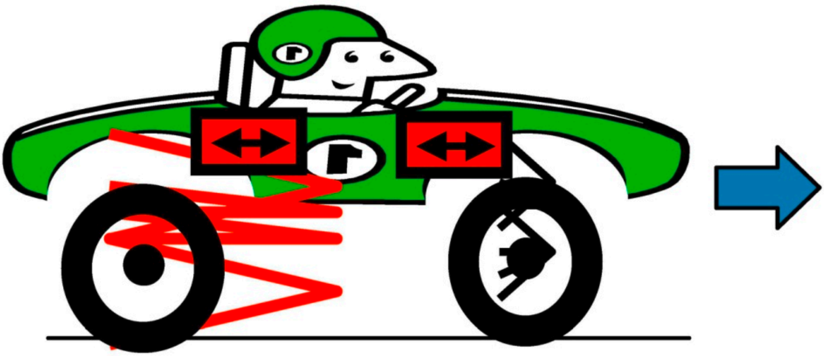

Fig 3. Illustration of variations tested in order to gain "flat ride"

5 The Tool chain used

As the tool chain a high quality 3D-Vehicle simulation software (IPG-CarMaker) is collaborating with an professional Calibration Optimization software (AVL-CAMEO). This method not only gives the vehicle dynamicist what he wishes, but also help to sharpen his perception of how best to achieve it.

CAMEO is software used to optimise multiple Target Objectives with multiple constraints. It is traditionally used to optimise calibration of powertrain ECUs and can even interact with engines under test to redefine the working envelope of the test if certain limits are exceeded (e.g. Knock or peak firing pressure [1])

Fig. 3 shows a typical Engine test bed application:

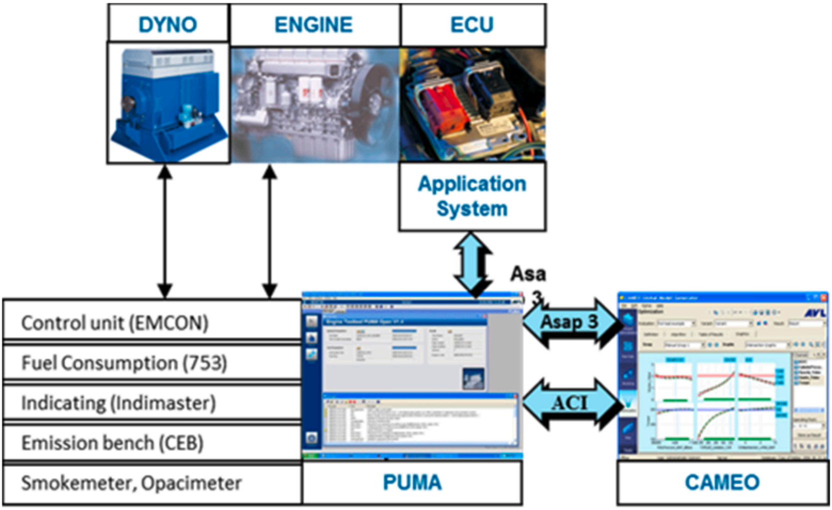

Fig 3. CAMEO on Engine Test bed

CarMaker is IPG's powerful Virtual Testing Software uses parameterised vehicle, driver, manoeuvre and roads models to explore vehicle performance.

Its flexible test-manager facility enables a range of variations of parameters to be efficiently tested and the results returned.

Models can be run many times real time to speed up analysis.

This can be controlled by CAMEO to develop the data set required for optimising the required vehicle dynamic Target Values (Fig.4).

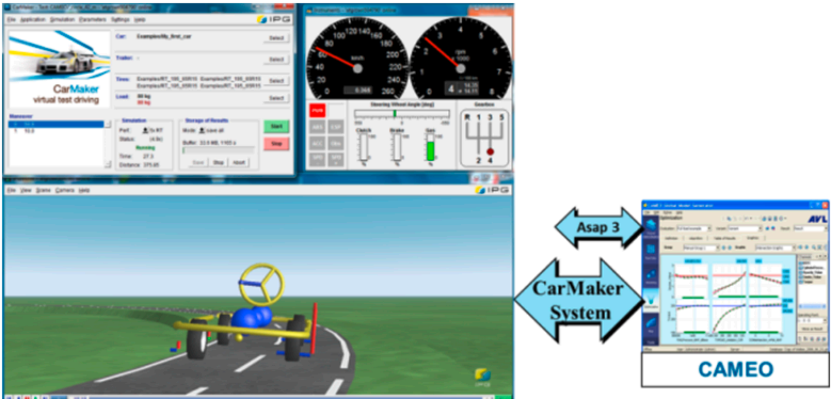

Fig 4. CarMaker connected to CAMEO

6 Scenario (1) Optimizing Pitch Inertia and Rear Spring Rate

- Definition of the manoeuvre to be optimized:
  - the vehicle is driven over a long wave bump
- Definition of the optimisation target
  - the vehicle has subjectively “flat” primary motion:
    → Minimize Δ Amplitude at Δ time=0
- Definition of the factors (variation parameters to be changed)
  - pitch inertia and rear spring rate

Fig. 5 shows, that the initial setting (based on the OEM’s donor model) did not achieve flat ride as shown below. Front rises faster and before the rear, introducing pitch to the vehicle as it recovers.

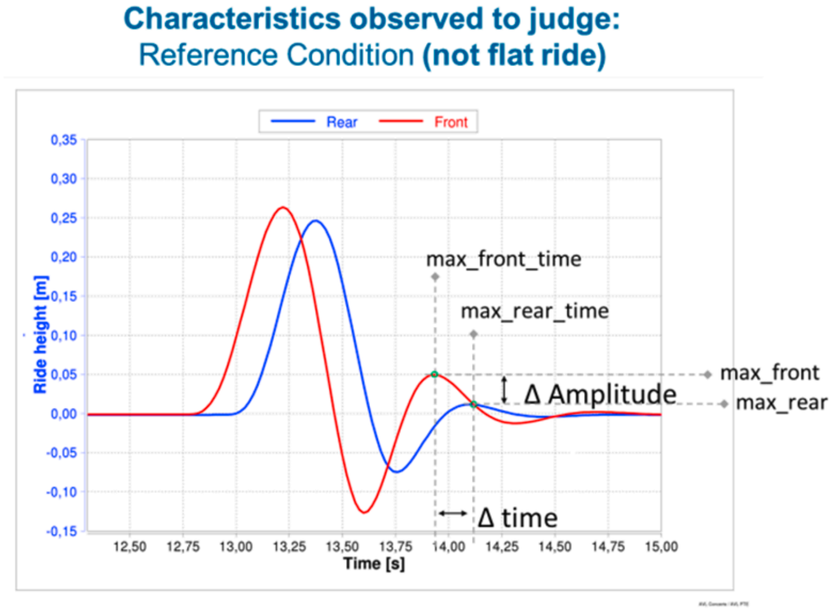

Fig 5. Initial configuration does not deliver flat ride

In order to investigate how the characteristics of interest change, when varying

- the rear spring rate and the pitch inertia

A DoE plan for variation of the influencing parameters is generated [2,3].

Fig. 6 shows the interaction between CAMEO "sending the parameters for varied virtual vehicles" to CarMaker, where a certain manoeuvre is simulated and the characteristics are evaluated and sent back to CAMEO.

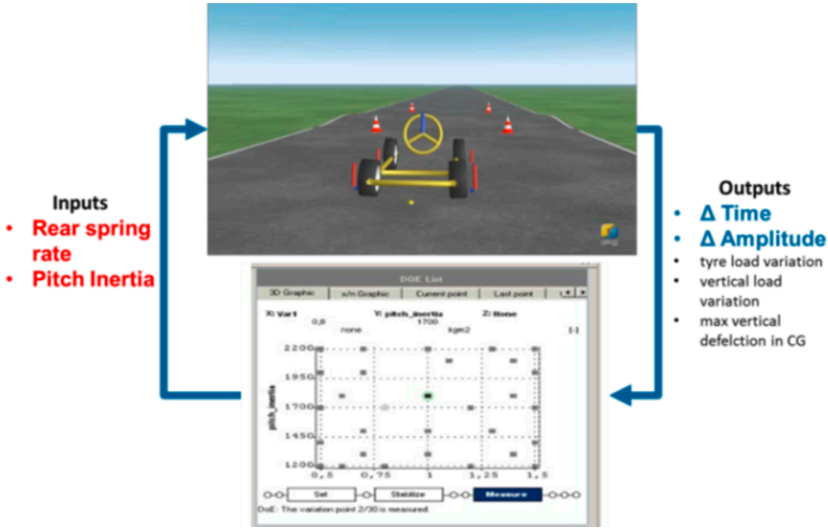

Fig 6. CAMEO – CarMaker interaction

First Results from Scenario (1)

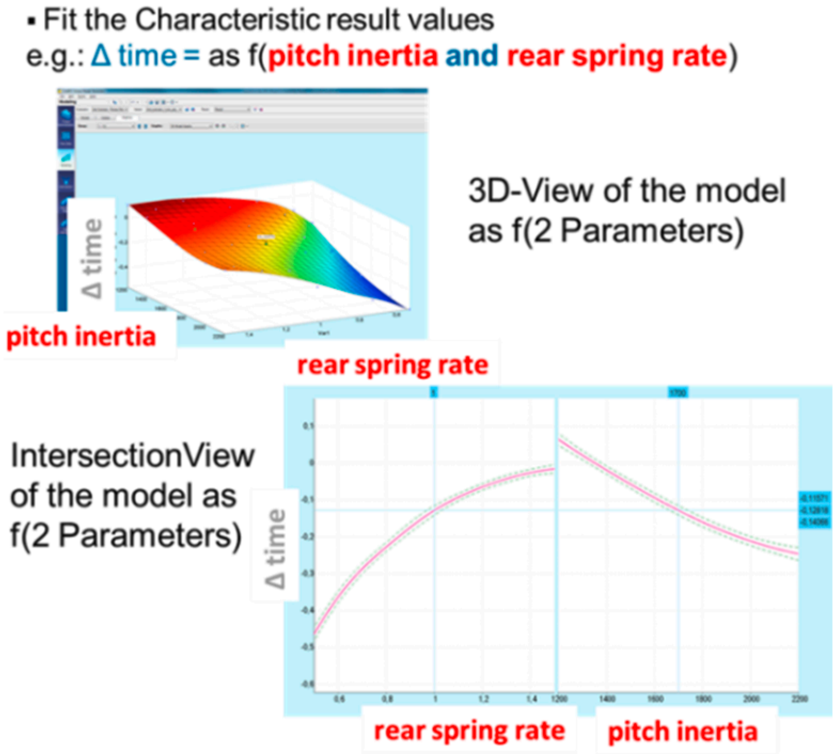

Fig 7. First results: Response models for delta time in recovery phase as function of changed rear spring rate and pitch inertia

7 Finding First optimum and showing the effect of varying the inertia and spring rate on the resulting "flatness "of the ride

In Order to reach the flat ride condition the optimisation target is set to minimize the delta_amplitude and as constraints there is set the delta_time to 0, as shown in Fig. 8:

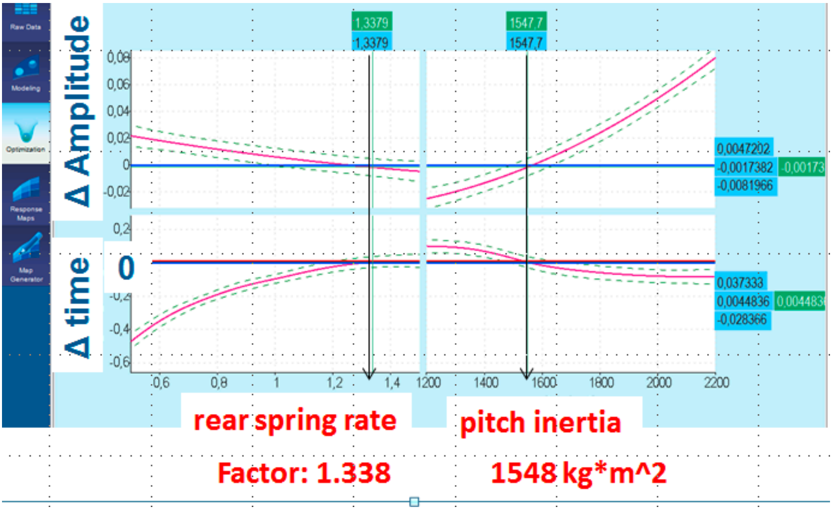

Fig 8. Optimisation for scenario 1

8 Scenario (2) Optimizing Pitch Inertia, Rear Spring Rate and Rear damper settings (Compression and Extension)

Objectives

- Minimise pitch velocity over the whole manoeuvre
- Keep also the flat ride condition!
- Minimise tyre load variation
- Minimise pitch velocity

The parameters allowed to be optimised and thus are varied by DoE are now:

- Rear damper settings (Compression and Extension)
- Rear springs
- Pitch inertia

Damper settings in this case are achieved by changing the gain of the damper force – but keeping the same shape

Fig. 9 shows a typical damper curve, which will be used as the starting point. Separate amplification factors for the compression and extension forces will change the whole shape and this factors will be optimised too.

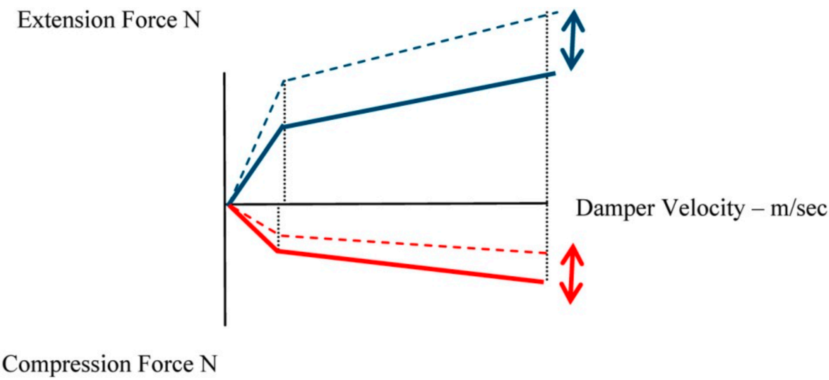

Fig 9. Changing overall gains of each damper by amplification factors for compression and extension

Results for scenario (2)

After driving with more than 200 virtual vehicles, selected by and S-optimal DoE within the design space of the 4 varied parameters, the simulated "long wave bump – manoeuvre", the highly nonlinear response models for the Objectives can be built. As Figure 10 shows these models were used to minimize the integrated Pitch angle along the recovery phase after the bump, while keeping the flat ride conditions: Delta_Amplitude = 0 and Delta_Time =0.

Further the engineer can slide the cursors along understanding the influences, sensitivities and interactions of the 4 influencing parameters investigated

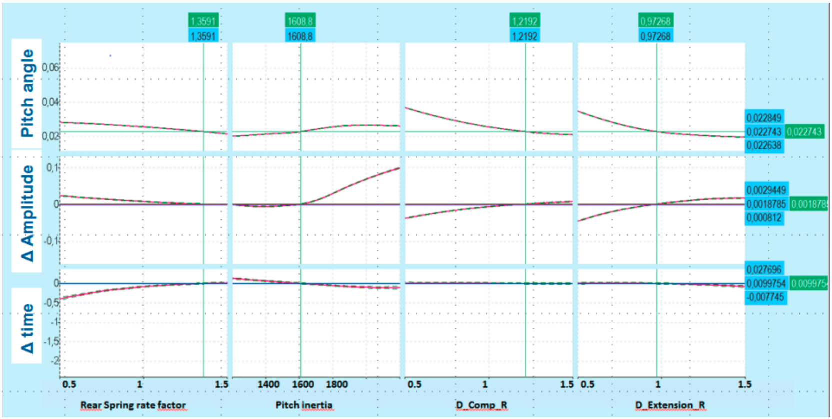

Fig 10. Intersection view at the position of with lowest possible pitch angle keeping the flat ride conditions

For verification the optimum, the gained combination for spring rate and pitch inertia is simulated. The traces of the body movements above the front and the rear axis before and after the Optimisation are compared in Fig. 11. One can see that now the recovery is in phase and further both oscillations are well damped.

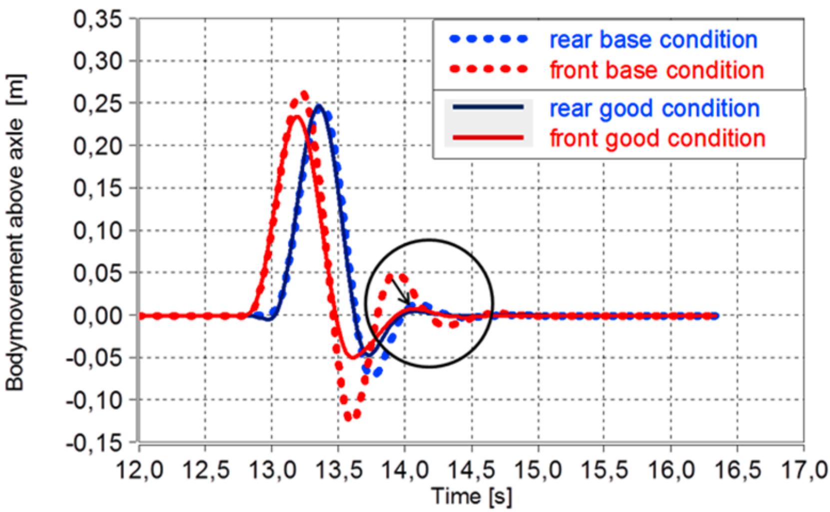

Fig 11. Comparison of the flat ride manoeuvre before and after the optimization

9 Scenario (3) Maximizing tyre contact & minimizing pitch velocity over a bumpy road varying the dampers for different Road Speeds

In the scenarios 1 and 2 base settings of pitch inertia and rear suspension at a constant road speed of 50 km/h were optimized in order to get the flat ride condition.

Taking this base, Scenario 3) explores how a simple passive damper setting might be optimised to deliver both

- a high driving comfort – expressed by low Vertical body Accelerations
- and minimised Tyre/road load variation

when driving with different speeds across a bumpy CRG-road. (CRG is a standardized efficient 3D road data representation complemented by hilliness)

To investigate and finally optimize the corresponding vehicle behaviour five parameters were varied:

- the road speed between 30 and 120 km/h

and

- the 4 Damper curve Amplification factors for Compression, Extension at Front and Rear in a range of 0.5 to 1.5

It is assumed, that the amplification factors for the damper shapes can be changed slowly as function of road speed. The required change of those factors as function of the road speed shall be optimized. It is expected that there may be one setting for “best safety” and another setting for “best- comfort.”

For that task – not knowing the nonlinearities of the responding Results for

- Vertical Acceleration and
- Tire Load Variation

when driving with different speeds on the CRG.road – 600 different parameter combinations were simulated and the corresponding responses were evaluated automatically by so called “online expressions” in CarMaker.

Figure 12 shows the DoE for the 5 parameters including already 30 verification points (green), which will not be used to identify the response models but to check their quality. – Also if it might appear in the picture, that “all possible combinations would have been simulated this would be misleading: With the density of 11 candidates in 4 and 10 in one direction the full factorial combination possibilities would have been 146410 instead of 600! . So the number of Simulations to be run is comparable small and due to the capability to run the manoeuvres fully automatically and in around 5 times real-time, such a simulation run is only a matter of a bit more than 1 hour.

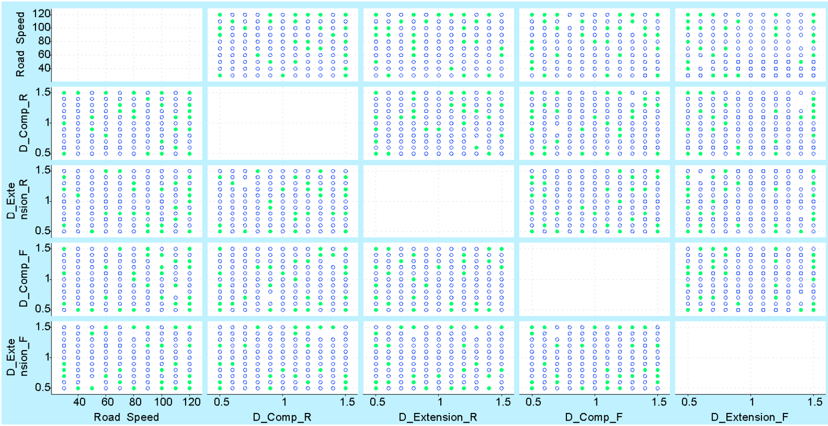

Fig 12 Design of Simulation cases

As it can be seen in the right side of Fig:: 13 the nonlinearity of the response model e.g. for the Vertical Acceleration is that high, that the CAMEO Neural Network models were needed in order to get a good fit to the simulation results.

While the influences of the 4 damper amplification factors generate more or less the shapes of typical 2nd order polynomial models, the trace of the response model for the Vertical Acceleration in direction as function of the road speed show the typical behaviour of a multi mass oscillator transfer function with a strong resonance peak at 70 km/h (Wheel on the tire oscillation, ~ 10 Hz).

In the left side of Fig. 13 the result of a multi objective optimization is shown: The yellow points mark the space of possible resulting Tire Load Variations versus Vertical Acceleration. As the optimal damper setting should show lowest possible values for both, there is not one solution available, but a Pareto front is showing the trade-off between safety and comfort. The blue position is the setting of the best comfort – interactively shown also on the right side in the two models.

As comparison also the optimum setting for best safety is marked in green. It would increase the Vertical Acceleration by 26% but reduce the Tire Load Variation to 83% compared to the settings of best comfort.

Thus it can be seen, that – at least for this critical speed – at the rear the lowest possible setting is suggested, while the conflict between comfort and safety is related mainly to different requirements from the front damper.

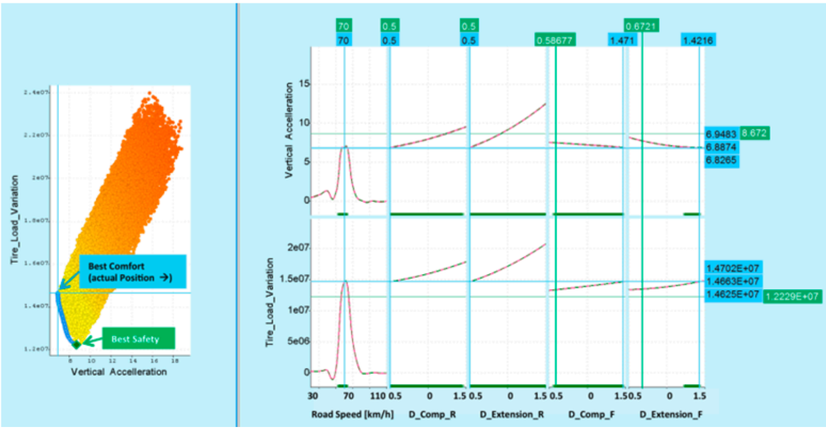

Fig 13 Pareto Trade off between Damping for “Best Comfort-“ and “Best Safety-” at the Wheel Resonance: road speed 70 km/h

Observing such trade off analysis for several road speeds the suggestion for road speed dependent curves for a Damper Control Unit are gained. Fig. 14 show this curves with “best safety”, “best comfort” or “optimized” settings respectively.

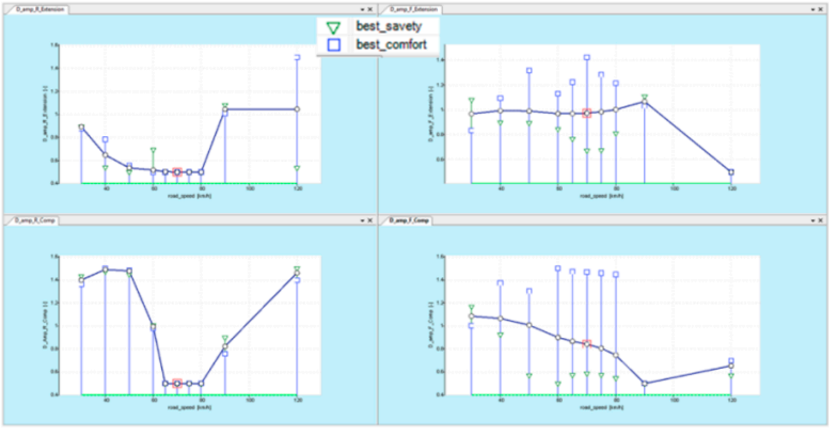

Fig 14 The 4 road speed dependent Amplification factors for the damping shapes as optimized between best savety and best comfort

10 Applying the Technique to real vehicle Programmes

Incorporating Real Damper models

Each manufacturer's damper architecture and tuneable characteristics are different so in a real application the damper model, and the variable parameters included in the optimisation would be matched to their own requirements.

Fitting vehicle variants with the same damper

The OEM may wish to fit the same damper to another model or variant –for example a sports model.

By running the optimisation for each vehicle the calibration to achieve all the variants can easily be explored. This is also useful in sizing the hardware to cover sufficient range for the variants (and real programs often find out too late in vehicle development that the hardware has been underspecified.)

Including the effect of the anti-roll bars

In roll or counter phase wheel travel the roll bars (sometimes called sway bars) add effective wheel rate. This affects the damper characteristics required.

Similar to the ride case where oscillation must be quickly damped out the roll oscillation needs to be controlled. By executing, for example a step steer the damper compromise which best achieves both ride damping and roll damping can be found.

Adaptable limits

The real hardware will have specific limits – motion, stroke, force, etc. and these can be included in the optimisation. When a limit is found the optimisation automatically resets itself to exclude these regions.

Use on the test rig or Hil rig.

Dampers are notoriously difficult to model so another powerful use of the technique is to use or 4 dampers in the lab under control of a HiL system with a vehicle and manoeuvre model in software.

Similarly this could be used with a real vehicle on the four post rig.

11 Summary

By combining IPG-CarMaker and AVL-CAMEO we have shown:

In scenario (1) a "Flat ride condition" was optimized with just adapting pitch inertia and rear spring rate when driving over a long wavelength bump

The "flat ride" condition was further improved in scenario (2) by also adapting the rear damper settings (Compression and Extension) in order to minimize the overall pitch velocity.

Finally in scenario (3) keeping the pitch inertia and the rear spring rate fixed, the damper settings were further refined to optimize "tire load variation" and "vertical body acceleration", when driving with different speeds across a bumpy road

By visualizing the trade- off behaviour, the engineer could make a well informed decision regarding front and rear damper settings as function of the road speed.

12 Conclusions

This paper has demonstrated how the use of the powerful parameterised vehicle simulation software IPG CarMaker in conjunction with AVL's CAMEO software for optimising calibration parameters can identify the range options which best meet the objectives, and in the form of Pareto Front displays this information in a way that helps the engineer make informed judgment about the inevitable compromises.

They give you perhaps, what you wish, but they don't tell you, what you should want

Norbert Wiener (1984-1964), Professor at MIT

13 Literature

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