SIMULATION APPLIED TO RIDE COMFORT SUSPENSION OPTIMIZATION

Daniel Vilela
Vehicle Synthesis, Analysis and Simulation
Product Engineering – General Motors do Brasil Ltda.
Av. Goias, 2769 – CT#1
CEP 09501-970, Sao Caetano do Sul, SP
Brazil
daniel.vilela@gm.com

Edilson Hiroshi Tamai
Department of Mechanical Engineering
Polytechnic School - University of Sao Paulo
Av. Prof. Mello Moraes, 2231
CEP 05508-900, Sao Paulo, SP
Brazil
edhtamai@usp.br

Abstract. *Traditional suspension tuning for ride comfort takes use of a series of physical prototype evaluations by skilled drivers, who analyze the vehicle performance in subjective terms. In this approach, the suspension components (springs, shock absorbers, bumpers, etc) are usually optimized one at a time, regardless of the consequences of the interactions among them in the global suspension behavior – this not uncommonly leads to sub optimized suspension configurations. Another problem with this approach is the fact that it is completely dependent upon physical component prototypes, whose costs and construction lead times can not be afforded in the current tight development cycles. Finally, this approach is subjected to uncertainties due to its subjective nature – even with extremely skilled drivers, it is not possible to assure that their evaluation is completely absent of influences other than the suspension configuration being put at test. This paper presents an objective approach, based on simulation tools, whose target is to define optimized components for the suspension without the need of physical prototypes. It takes use of a vehicle dynamics simulation tool, used to analyze the vehicle behavior in different road conditions for the parameters of interest and an optimization tool based on the robust engineering method.*

Keywords: *vehicle dynamics, suspension, optimization, ride comfort, simulation.*

1. Introduction

The use of simulation tools to evaluate automotive vehicles' behavior is becoming more and more common in the automotive industry in all development areas (Buchholz, 2002). The market push for better products and faster product renovation (what means faster development time) is forcing the industry to use analytical tools, which are capable of helping the engineers during the development cycle, reducing the lead-time for a new model launch and also helping to reduce the development costs. Specifically talking about ride comfort, much has been made in the last years to make better and more reliable vehicle dynamics simulation tools. However, this progress in the simulation tools capacity and precision has not always been followed by an increase in the simulation tool intensive use during the suspension tuning. One motive is the lack of a good correlation between the dynamic variables (accelerations, forces, velocities, etc) that can be obtained by the simulation packages and the ride comfort evaluation parameters. In order to make an engineering approach, the subjectivity nature of these comfort parameters must be correlated with the objective measurements of dynamic variables. In this paper, it will be shown how the problem of translating the ride comfort evaluation parameters into objective variables has been treated at General Motors do Brasil - GMB (Vilela et all, 2002).

The same problem arises in the evaluation of handling quality (Data, 2002), where the proposed objective indices for handling feelings allow the use of simulation in the design optimization phase. In a similar procedure, the subjective evaluation is analyzed, a criterion is developed using objective measurements of dynamic characteristics of the vehicle and standard maneuvers (inputs) are selected for simulation and experimental tests.

Another point that deserves special attention is the optimization technique to be adopted. Here, the concept of robust engineering (Ross, 1988; Phadke, 1989) is being applied to this task. The main point that has lead to the use of this tool is the fact that the suspension components do not usually work in-dependently, i.e. the influence of one component upon the performance of the others is commonly very strong. Thus, an approach like "optimize one at time" can not be used here. The robust engineering technique deals very well with this aspect of the problem, helping in the identification of the components that are more sensitive in the global suspension performance and the best combination of them.

2. Vehicle Dynamics Simulation Tool

The vehicle model consists in a multibody model, where the full vehicle is described. Global dimensions, masses, moments of inertia, suspension geometric points and attachments must be described, besides the suspension components (springs, shock absorbers, bumpers and antiroll bars) description in terms of their characteristic curves (force x displacement or force x velocity).

As described by Vilela and Gueler (2003), the software used here is based in an internally developed code by GMB called VPG (Virtual Proving Ground). This software works with approximately 20 degrees of freedom and has been developed with the main purpose of obtaining dynamic loads for component fatigue prediction. The nature of fatigue prediction demands loads with accuracy of less than 3% difference to the real loads, what this software does very reasonably as shown by figure 1 and 2.

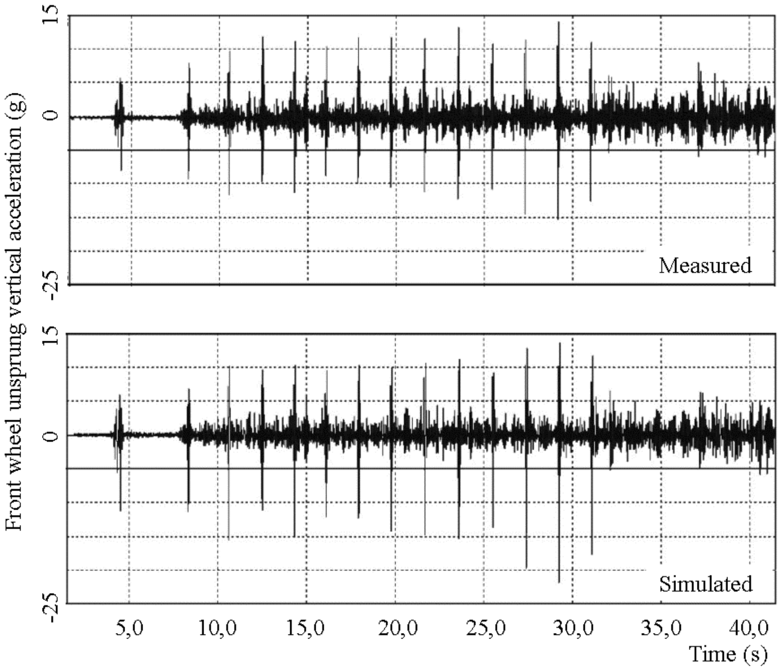

Figure 1. Front wheel unsprung vertical acceleration time history correlation.

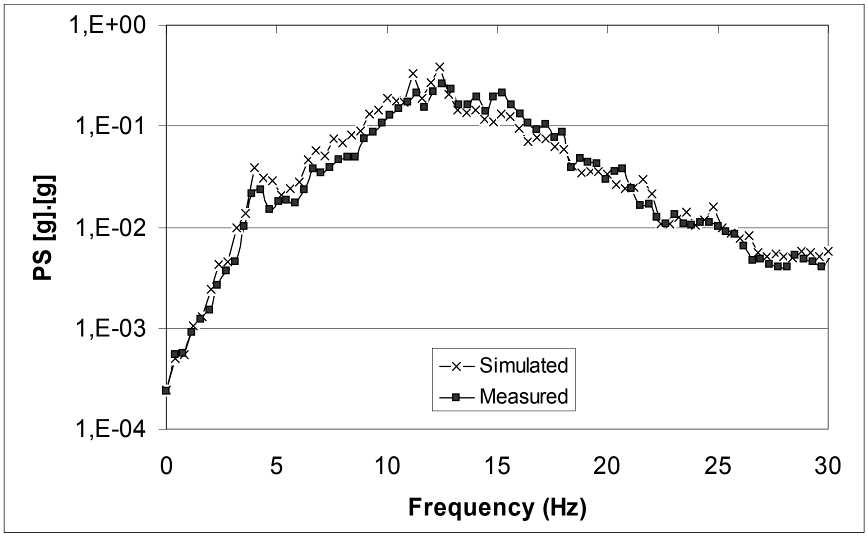

Figure 2. Power Spectrum - Front Unsprung Mass Vertical Acceleration.

Figure 1 presents the measured and simulated front wheel unsprung vertical acceleration. Figure 2 presents the power spectrum of the front unsprung mass vertical acceleration.

Based on this accuracy, it was decided to use the same base code in a new software specific for ride comfort analysis, named Virtual Ride. One advantage is the use of the same dynamic model of the vehicle in the fatigue and comfort analysis, allowing easier and better integration of different design phases.

3. Ride Comfort Objective Parameters Correlation

The correlation between the ride comfort parameters with the dynamic variables of the vehicle is one of the most important steps to reach a simulation procedure that can represent the physical prototype evaluation. The points here shown are described by Vilela et all (2002). The first point is to define the ride comfort parameters to be analyzed. In the occasion of this work, they were:

- Harshness: capacity of the vehicle suspension in filtering high frequency, low amplitude road in-puts.
- Absorption Capability: capacity of the vehicle suspension in absorbing the impact with medium size obstacles on the road surface, like cats' eyes or little parts of stone.
- Jounce Bumper: evaluates the vehicle behavior when passing through pot holes, concerning the bump impact felt by the driver.
- Ride Balance: evaluates the vehicle behavior when passing through cross ditches or similar obstacles on the road, concerning the pitch stability of the vehicle.

Defined the parameters to be evaluated, a good way to represent these parameters within the simulation is to define the kind of road input where each one of them is more evident and, if possible, isolated from the others – in this step, the participation of the expert drivers from the proving grounds is very important, since they can contribute with their practical expertise in defining these more suitable road inputs. For the parameters taken into consideration, the following inputs were defined as being the most suitable:

- Harshness: Belgium blocks track.
- Absorption Capability: one side of the vehicle upon cats' eyes (50 mm high) and the other on a smooth paved road.
- Jounce Bumper: series of pot holes in both sides of the track.
- Ride Balance: cross ditch followed by a flat road.

Finally, it must be defined which dynamic variables are correlated to each ride comfort parameter – for this work, the following parameters were taken into consideration:

- Vertical acceleration at the driver position.
- Front and rear forces for the spring, shock absorbers and bumpers.
- Body pitch and roll accelerations.

It was possible then to combine the variables above through weight matrices, resulting in values that can be correlated with the subjective grades given by the expert drivers at the proving ground. It must be remembered that these grades attributed by the drivers are subjected to differences due to its subjectiveness. When testing one specific configuration at the proving ground, it is usual to have the opinion from more than one driver for a final conclusion. Here it is shown the comparison among eight different suspension configurations of a Sport Utility Vehicle (SUV). These configurations were evaluated by two different drivers at the Cruz Alta Proving Ground (CAPG – City of Indaiatuba, Sao Paulo, Brazil) and were also simulated using the concept explained above. The results are summarized in the figures 3 to 7. These are the same configurations used to the optimization with the robust engineering concept, as it will be shown in the next section.

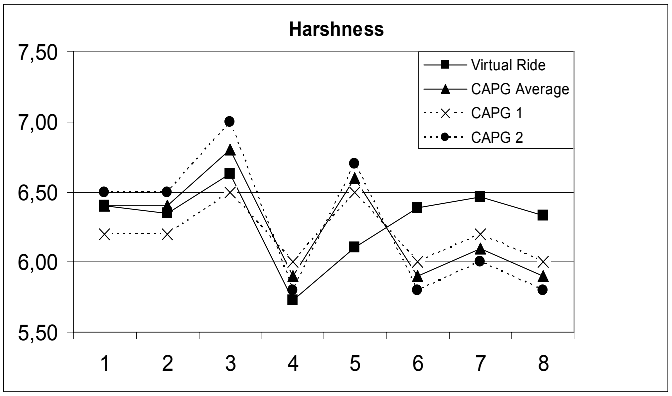

Figure 3. Harshness correlation

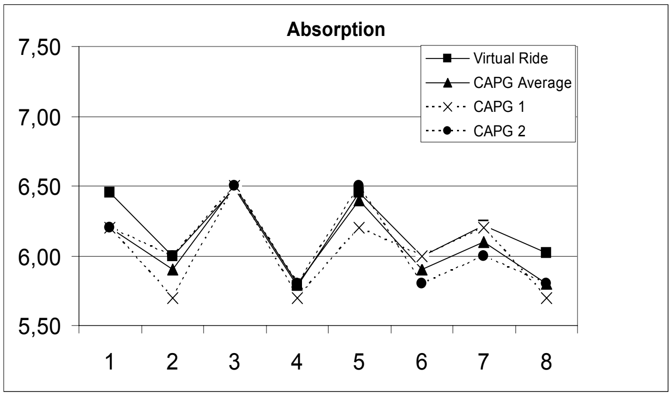

Figure 4. Absorption capability correlation

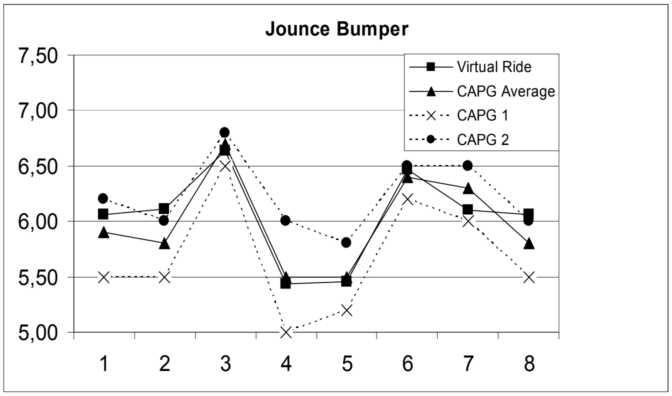

Figure 5. Jounce bumper correlation

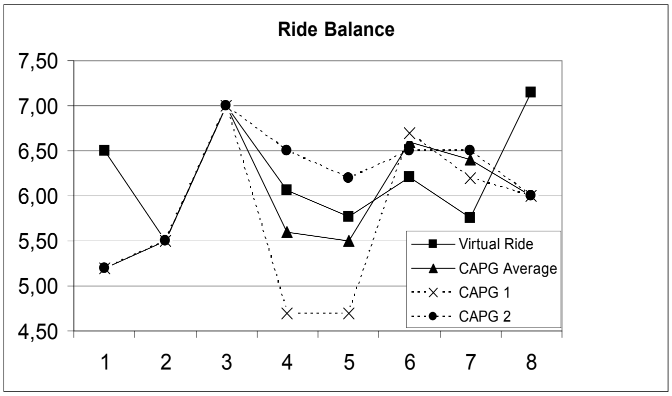

Figure 6. Ride balance correlation

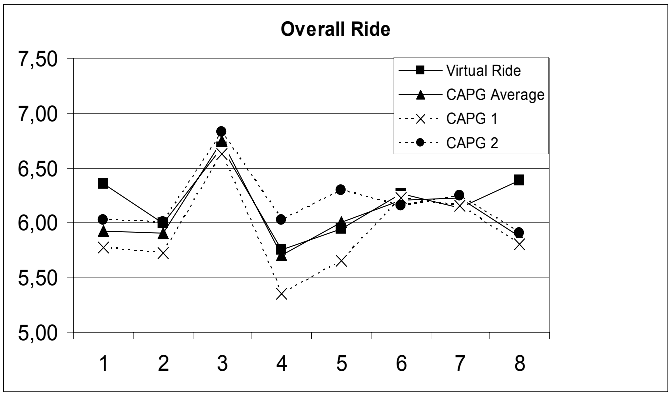

Figure 7. Overall ride correlation

Figures 3 to 7 show the simulation results (Virtual Ride), the grades given by the two different drivers (CAPG 1 and CAPG 2) to the different suspension configurations, and the average of the grades given by the drivers (CAPG Average). In the horizontal axis, numbers 1 to 8 indicate the eight different suspension configurations, and the vertical axis presents the grades of each configuration.

4. Optimization

Since a simulation tool is available to determine ride comfort parameters, it is important to define the methodology with which it will be used. The concept of robust engineering (Phadke, 1989) is presented here. This concept is especially suitable when we are faced to a problem where the parameters to be designed must be optimal not only in a specific working condition, but through a wide range of conditions.

Usually the ride comfort is developed for one specific load condition (only the driver for example) and, after reaching a satisfactory result with some suspension con-figuration in this load condition, this same configuration is checked in other load conditions (up to full payload) to see if the results are satisfactory. It is not difficult to see that this procedure does not lead to an optimal configuration concerning all the load range. Considering that is not possible to forecast how the customer will load the vehicle, we can define the load condition as being a “noise” for the system evaluation.

The robust engineering deals with a parameter optimization (suspension components curves) combined with a noise defined as the load condition in which the vehicle is being evaluated. The optimization that can be performed through this methodology is a discrete one, i.e. some discrete values for each parameter must be chosen and the robust engineering will point which one of these is the best one, taken the defined noise into consideration. It takes use of balanced experiment arrangements (orthogonal arrays, please refer to Ross (1988) for more details) that can indicate the parameters that give the best results for the evaluation functions in question. In this work they are the ride comfort parameters results. With these orthogonal arrays, it is not necessary to evaluate all the possible combinations of design parameters (factorial array), decreasing the number of numerical simulations. This optimization approach does not need the calculation of the evaluation function gradients, which is an important advantage in this case, where there is not an easy way to calculate such gradients.

There are many orthogonal arrays developed and they must be chosen for each specific problem, taken into consideration the number of design parameters to be used and the how they will be discretized. The graphics shown in the last section are from an orthogonal array called L8, which defines 8 experiments to be performed in order to determine 7 different parameters. For the problem with the SUV they were:

- Front spring rate (linear);
- Rear spring curve (non-linear);
- Front shock absorber curve (non-linear);
- Rear shock absorber curve (non-linear);
- Front bumper height and curve (non-linear);
- Rear bumper height and curve (non-linear);
- Tire pressure.

The noise level chosen was the vehicle load, with the level 1 being the curb (vehicle with full fuel tank and no cargo load) plus driver load and the level 2 being the GVW (gross vehicle weight) load condition.

Taking the data from the experiments performed through the use of simulation, it is possible to obtain then the best parameters for the problem, considering the noise defined. The results obtained from Virtual Ride are correlated to the subjective grades; therefore they have a criterion of "the higher the better" (within a range of 0 up to 10). The results for each design parameter are then defined in terms of signal-to-noise ratio, as follows:

$$\frac{S}{N} = -10.\log\left[\frac{1}{2}.\left(\frac{1}{L_1^2}+\frac{1}{L_2^2}\right)\right] \tag{1}$$

In equation (1) L1 is the result with noise in level 1 (curb plus driver load) and L2 is the result with noise in level 2 (GVW condition). The higher values of the signal-to-noise ratio indicate the best parameters. The table 1 shows the experiment matrix (L8) and the results obtained through the simulation:

Table 1. L8 experiment matrix with simulation results for both conditions and S/N ratio observed

Experiment	**Optimization Parameters (levels)**										
	Front Shock Absorber	*Rear Shock Absorber*	*Front Spring*	*Rear Spring*	*Tire Pressure Fr/RR*	*Rear Jounce Bumper*	*Front Jounce Bumper*	**Load 1**	**Load 2**	**Average Grade**	**S/N**
1	current	15% harder	current	current	**33/28**	**low / high density**	current	6,00	6,20	6,10	15,70
2	current	**10% softer**	current	current	37/32	high / low density	**at the rod**	6,00	6,00	6,00	15,56
3	current	**10% softer**	**2.2l model**	**low rate**	**33/28**	**low / high density**	**at the rod**	7,20	7,00	7,10	17,02
4	current	15% harder	**2.2l model**	**low rate**	37/32	high / low density	current	5,20	6,00	5,60	14,90
5	**10% harder**	**10% softer**	**2.2l model**	current	**33/28**	high / low density	current	5,50	5,80	5,65	15,03
6	**10% harder**	15% harder	**2.2l model**	current	37/32	**low / high density**	**at the rod**	7,00	6,50	6,75	16,57
7	**10% harder**	15% harder	current	**low rate**	**33/28**	high / low density	**at the rod**	6,00	6,50	6,25	15,90
8	**10% harder**	**10% softer**	current	**low rate**	37/32	**low / high density**	current	5,70	6,00	5,85	15,33

From the results shown in table 1, it is possible to calculate the S/N ratio for each level of the optimization parameters, as shown in the table 2.

Table 2. S/N ratios for each optimization parameter level

	Front Shock Absorber	*Rear Shock Absorber*	*Front Spring*	*Rear Spring*	*Tire Pressure Fr/RR*	*Rear Jounce Bumper*	*Front Jounce Bumper*
level 1	15,80	15,77	15,62	15,72	15,91	16,16	15,24
level 2	15,71	15,74	15,88	15,79	15,59	15,35	16,26

The results from table 2 are useful to determine which parameters most influence the results: the higher the difference between the S/N ratios for two distinct levels of the same parameter, higher the influence of this parameter. This influence is shown graphically in the figure 8.

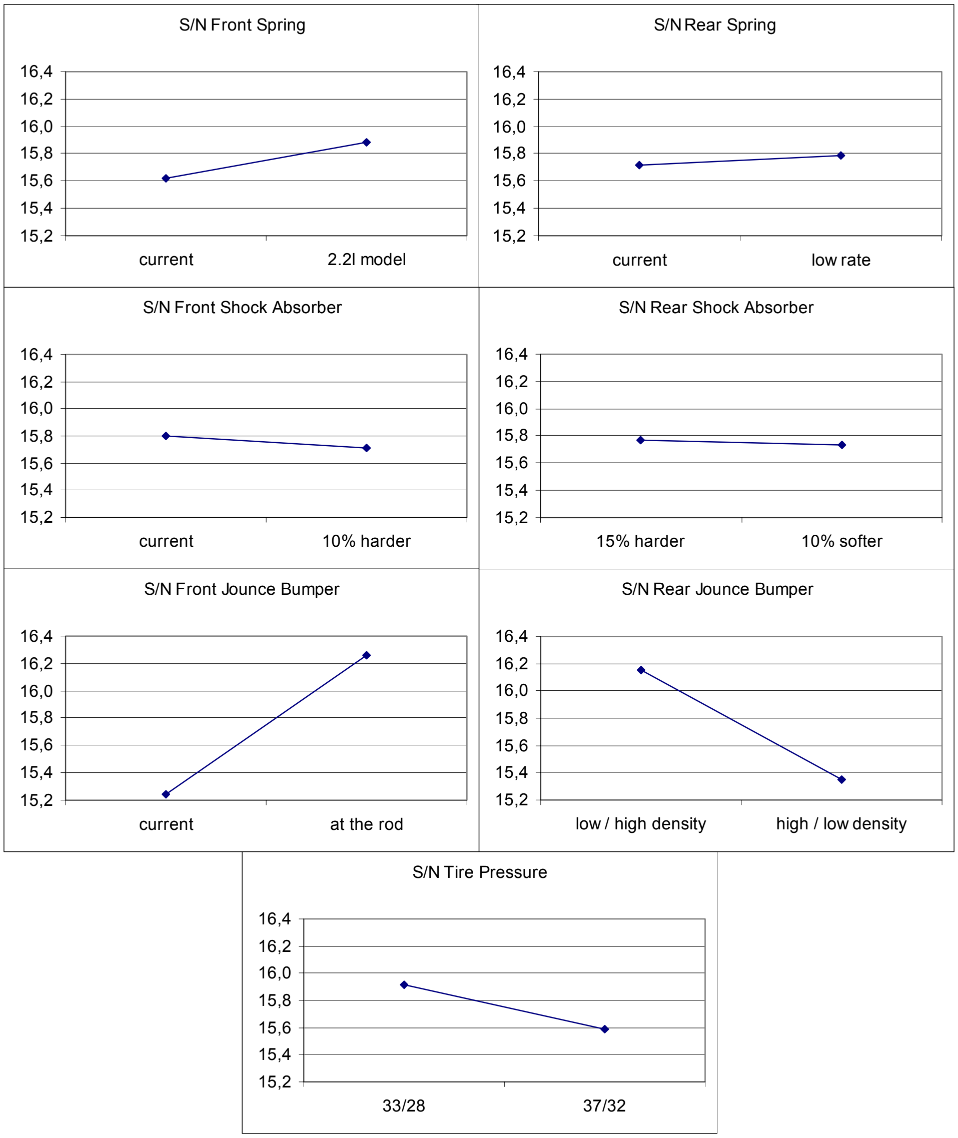

Figure 8. Graphical representation of the optimization parameters S/N ratios

Given the results from the robust engineering analysis, it is then possible to create a new model with the best parameters for each design variable and verify if it is really better than all the configurations studied. For this case, the results are presented in figures 9 to 13. In these figures, the point named "best" is the grade of the optimal configuration achieved by robust engineering.

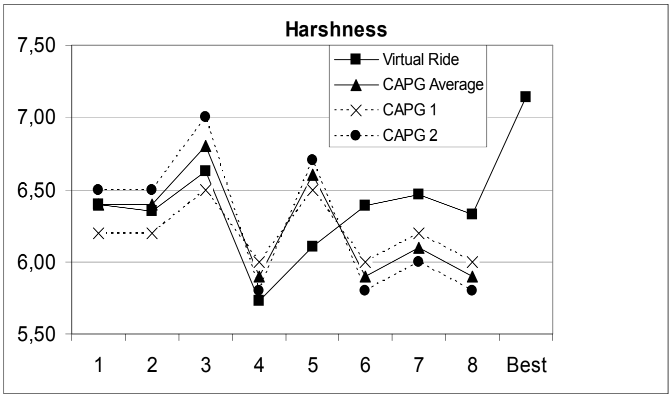

Figure 9. Harshness optimization results

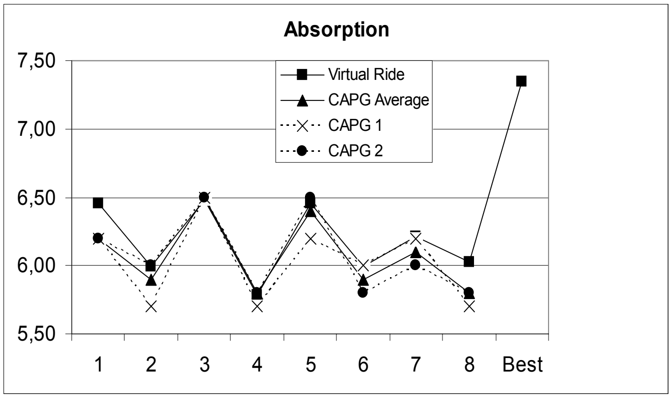

Figure 10. Absorption capability optimization results

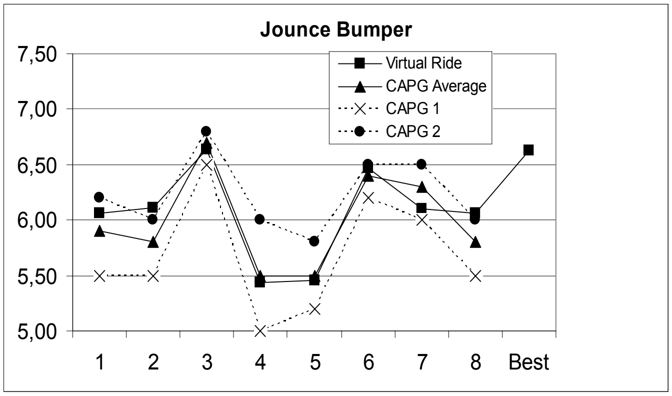

Figure 11. Jounce bumper optimization results

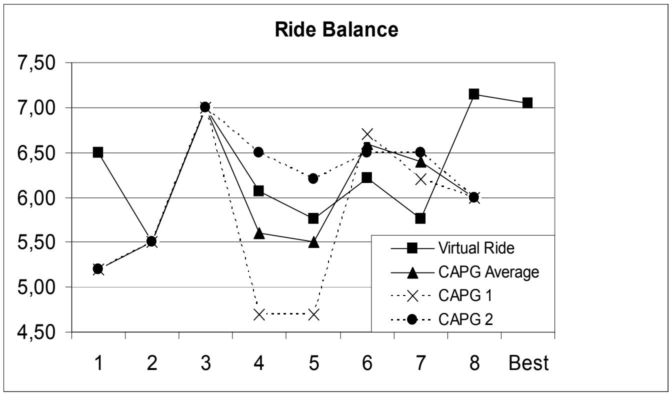

Figure 12. Ride balance optimization results

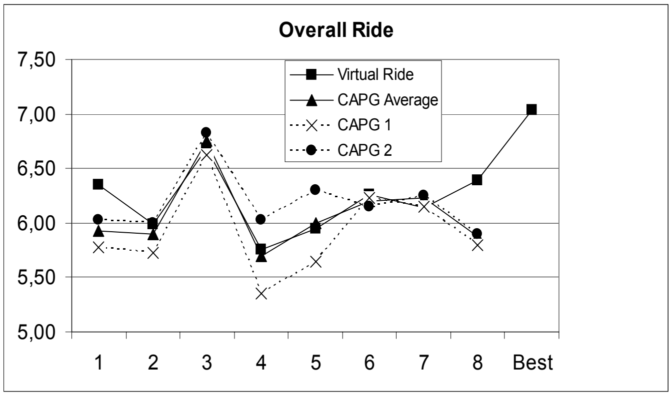

Figure 13. Overall ride optimization results

The optimal configuration is achieved considering a balanced combination of the criteria, but it does not mean that it is the best in a particular criterion. In figure 12 (ride balance), for instance, the configuration number 8 is better than the optimal configuration.

5. Conclusions

The vehicle dynamics multibody simulation tool developed for load calculations at GMB, the Virtual Proving Ground, proved to be a good basis for a new simulation tool to evaluate ride comfort, having enough accuracy for the task.

The methodology and software (Virtual Ride) developed to correlate the dynamic variables from the simulation and the subjective grades from the expert drivers has also proved its capabilities, as shown in the comparative between the simulated values and the grades given by the drivers. It must be remarked that this correlation is not universal, as the grades given by the drivers from different vehicle categories are not either. In this sense, some “grade templates” must be defined for each vehicle category, and this is an on-going work at GMB, as this tool is being applied to the different new projects. However, the optimization is not dependent upon these grade templates, since the dynamic variables behind the final results are not affected by them.

Finally, the robust engineering has shown very good results in terms of design parameter optimization. The fact that it is a discrete parameter tool does not jeopardize its performance at all, since the real vehicle suspension components will not have continuous possible settings also. The discretization of the range helps in defining the values that are already available at the market for some component, reducing the component development cost and lead time for validation tests. The optimization procedure herein shown have been applied with success in the latest projects at GMB, leading to less (or none at all) early development prototypes and very good suspension settings for the first physical prototypes, leaving room for the proving ground engineers to work more intensively at the fine adjustments not yet possible within the simulation tools and at quality issues of the components. This procedure is also providing over 50% of decreasing in the number of physical prototypes, effectively decreasing the development costs and time at GMB.

6. References

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