

Handling Analysis of a Three-Axle Intercity Bus

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ABSTRACT

This paper describes the methodology adopted at debis humaitá IT Services Latin America, for performing handling analysis commercial vehicles. Its application to an intercity bus with 3 axles is presented. The objective is to improve primary suspension characteristics alone, with respect to both comfort and handling and to study the behavior of the full vehicle with respect to handling and to improve it through the changes of primary suspensions characteristics. The methodology adopted was the development of a complete multibody model of the bus (Figure 4) in ADAMS, considering all the major non-linearities of the actual vehicle, such as air spring and shock absorber curves, suspension bump stops and tire model (Delft). Once having the model, several analyses were carried out including, modal, single lane change, double lane change, steering impulse and sine steering sweep. The results of these analyses were evaluated and modifications to the design were suggested in order to achieve the objectives of this work (to improve the primary suspension characteristics and also the handling behavior of the full vehicle). These modifications were implemented at a physical prototype and measurements have not been carried out yet. However, qualitative impression (not yet quantitative results), indicates an improvement in overall vehicle handling behavior.

INTRODUCTION

An important aspect of highway bus operation, besides transporting passengers is its load carrying capacity. A significant amount of a bus revenue comes from this source. In order to increase this capacity while complying with government axle load regulations it was adopted, in this vehicle, the inclusion of a third axle. This axle affects handling

behavior since it implies a complete repositioning of the rear axles and an increase in the number of rear wheels. Many times, in vehicle handling analysis, it suffices a linear approach based on simple models, in order to achieve adequate behavior. However, in this case, simple linear theory does not apply, requiring the use of virtual prototyping from the early stages of design.

During the development process of the IBC-2036 vehicle, which is an intercity bus, by DaimlerChrysler do Brasil, it was requested to the vehicle dynamics group of debis humaitá IT Services Latin America to evaluate handling behavior of this vehicle, in order to improve it. This request was motivated by some undesirable effects observed in a prototype during the experimental measurements.

VEHICLE DESCRIPTION

The IBC-2036 vehicle is a three-axle intercity bus with a loaded weight of 20000 kg. All 3 suspensions are of the rigid axle type. The first axle (2 tires) suspension has 3 link bars, 1 Panhard rod, 2 air springs, 4 shock absorbers and a stabilizer bar. The second axle (the driving one with 4 tires) suspension has 4 link bars, 4 air springs, 4 shock absorbers and a stabilizer bar. The third axle (2 tires) suspension has 4 link bars, 2 air springs, 2 shock absorbers and a stabilizer bar.

OBJECTIVES

- To study the characteristics of the 3 primary suspensions and improve them.
- To study the behavior of the full vehicle with respect to handling.
- To improve vehicle handling behavior through changes of the characteristics of the primary suspensions.

METHODOLOGY

For the study of the characteristics of the 3 primary suspensions, it was developed a multibody body model for each one of them: Figure 1 - first axle; Figure 2 - second axle and Figure 3 - third axle. The models include all the major non-linearities of the actual vehicle, like air springs and shock absorber curves, suspension bump stops and tire model (Delft).

For the handling analyses, a complete multibody model of the bus (Figure 4) was developed through the merging of the 3 suspensions model, besides the inclusion of the frame (sprung mass). In order to correctly represent the vehicle, the local flexibility of the frame, in the connecting points with the suspensions, were introduced by means of a Finite Element Model of the frame.

SOFTWARE

The model was done and the analyses (simulations) were performed with ADAMS (*Automatic Dynamic Analysis of Mechanical Systems*) version 10.1.

MODELS

The model of the first axle suspension and corresponding steering system can be seen in Figure 1, the second axle suspension model in Figure 2 and the third axle in Figure 3. Figure 4 illustrates the full vehicle model.

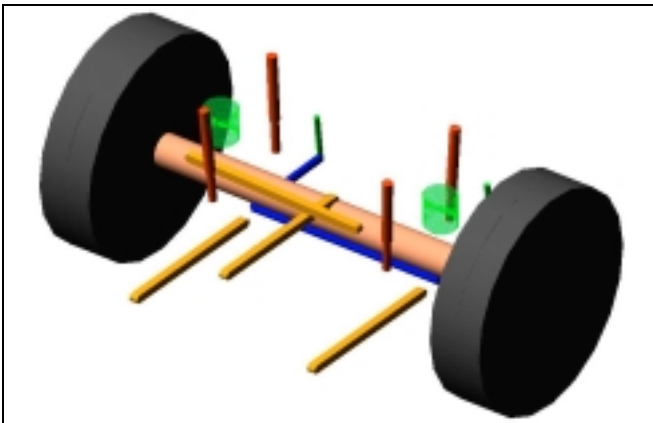


Figure 1: First axle suspension model.

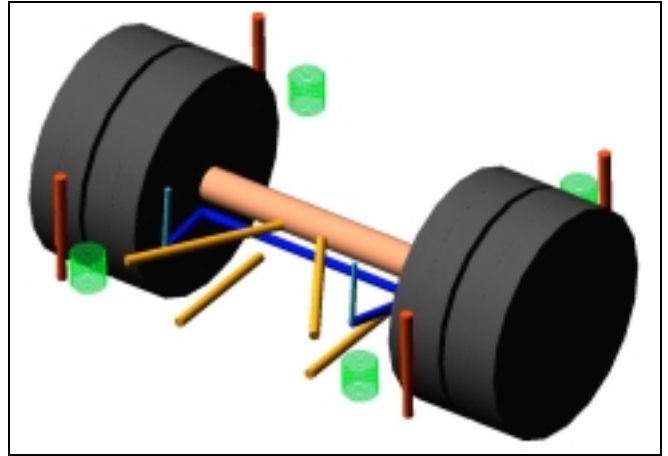


Figure 2: Second axle suspension model.

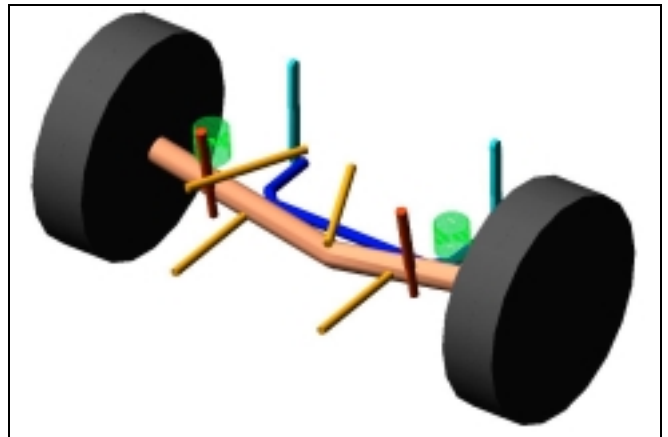


Figure 3: Third axle suspension model.

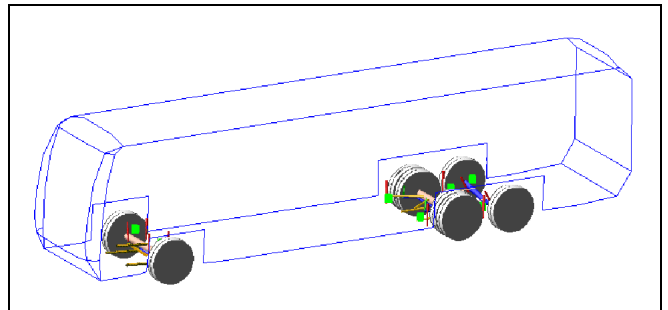


Figure 4: Full vehicle model.

For the handling analyses the Delft tire model, which makes use of the magic formula (Figure 5), according to reference [1] was used.

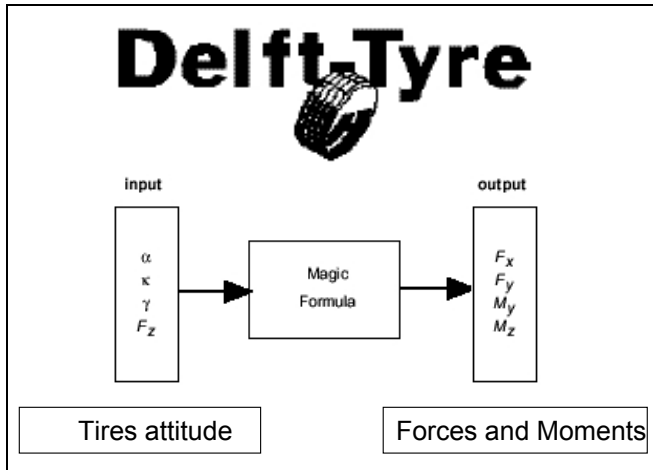


Figure 5: Delft tire model.

ANALYSES

The analyses can be divided into 4 groups: experimental validation of the full vehicle model; analyses with the 3 suspensions considered separately (Figures 1 to 3); analyses with a plane vehicle model and analyses with the complete vehicle model (Figure 4).

MODEL VALIDATION

At a first step, the results obtained with the model were compared to the results of the experimental measurements done with the vehicle prototype.

SUSPENSIONS

Spring rate

For all 3 suspensions (first, second and third axle) it was done a verification concerning the spring rate characteristics. In this vehicle, all the 3 suspensions have air springs. The objective was to obtain adequate values of vertical sprung and unsprung masses frequencies, according to client's criteria.

Shock absorber curve

It is possible, assuming a linear behavior, to optimize the damping value of the shock absorbers, targeting at minimum acceleration and displacement of the sprung mass (comfort) and minimum variation of normal load at the tires (safety), for both the loaded and unloaded vehicle. Having done this, the value of damping may be translated into a proper shock absorber design. It is also important to know how much of the optimized damping value is supplied by friction in parts of the suspension, like bushings, air springs and contact between tire and road. The shock absorbers, together with the friction damping in the suspension, should supply the optimum damping.

Roll center height

Determination of the roll center height of the 3 suspensions, in order to define the vehicle roll axis. The roll center height was determined according to reference [2].

Stabilizer bar stiffness

Adjustment of the stabilizer bar stiffnesses for the 3 axles, according to the bus manufacturer's criteria, spring rates and vehicle roll axis.

Elasto-kinematics

In this kind of analyses, the suspension is studied separately. Motions, like bounce/rebound and roll under load, are imposed to the suspensions, trying to simulate the actual suspension operation. The objective is to optimize the suspension behavior while working, both in vertical and rolling displacements and also during braking. This can be achieved by minimizing some undesirable effects, like wheel steer for example, which can lead to lateral drifting of the vehicle, mainly during braking.

PLANE VEHICLE

The plane vehicle was simulated in order to study the influence of the position of the axles in the steering characteristics of the vehicle.

COMPLETE VEHICLE

The complete vehicle model was used to perform several analyses, among them: modal, single lane change, double lane change, steering impulse and steering sweep.

RESULTS AND EVALUATION

MODEL VALIDATION

It was obtained a very good correlation, what provided confidence on the multibody vehicle model results.

SUSPENSIONS

The values of both vertical sprung and unsprung masses frequencies obtained, for all the 3 axles, were reasonable. So, it was not necessary to modify these parameters.

With respect to the shock absorber curves, it was necessary to change all of them. It is possible to see in Figure 6, for the third axle, the old shock absorber curve, in blue, and the modified one, in red.

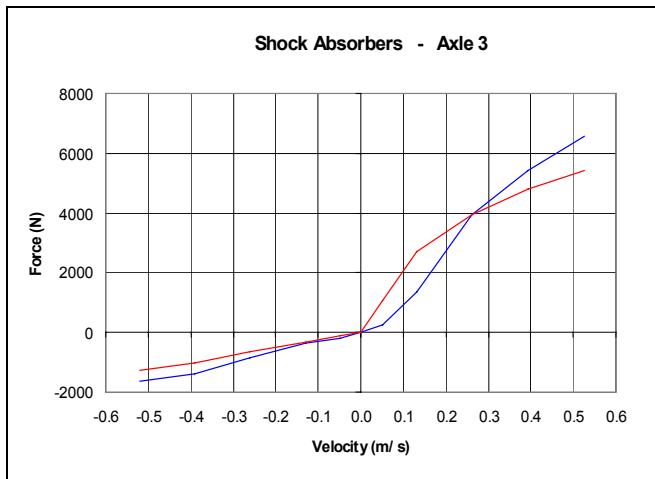


Figure 6: Shock absorber curve for the third axle.

The roll center height of the third axle was a little bit out of the roll axis defined by the first and second axle roll centers, so this was kept in mind during the handling analyses.

All the stabilizer bars were also changed, according to bus manufacturer's criteria. This criterion assumes a defined permissible roll angle due to a defined lateral acceleration (4 m/s^2).

With respect to elasto-kinematics, all the 3 suspensions showed good results, both in vertical and rolling displacements and also during braking. So, no modifications were necessary with respect to this topic.

PLANE VEHICLE

The results of the plane vehicle showed that it was not necessary to change the position of the axles. The vehicle presented a behavior represented by an under-steering characteristic (Figure 7).

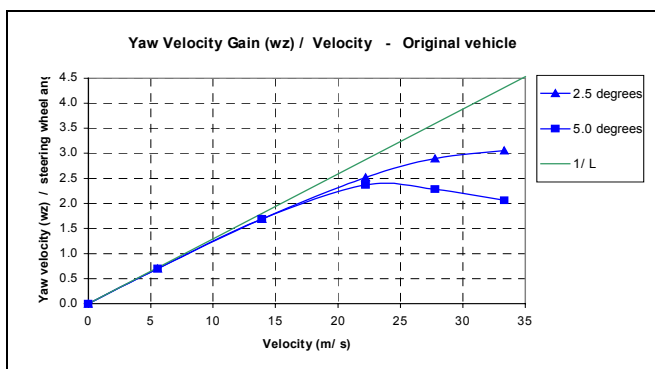


Figure 7. Yaw velocity gain.

COMPLETE VEHICLE

The major analysis with the complete vehicle was the single lane change maneuver, which is described in

Figure 8. The vehicle was simulated at 50 km/h, according to client's criteria.

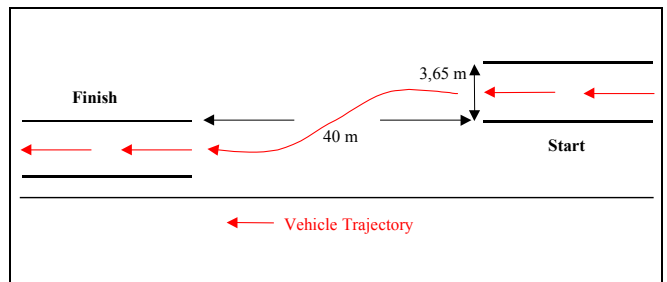


Figure 8: Single lane change maneuver description.

In Figure 9 it is shown vehicle lateral acceleration obtained at the single lane change maneuver. The maximum acceleration was about 1850 mm/s^2 ($0,19 \text{ g}$). The acceleration was measured at vehicle CG (Center of gravity).

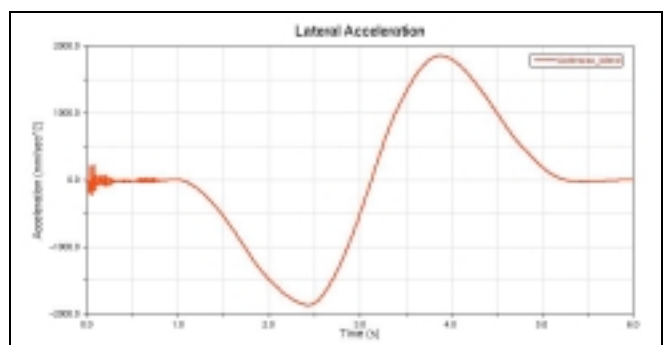


Figure 9: Vehicle lateral acceleration.

In Figure 10 is showed the vehicle roll angle obtained at the single lane change maneuver. The maximum roll angle was about 2.5° (0.044 rad).

Through a linear extrapolation, it can be showed that the manufacturer's criteria was satisfied. For a lateral acceleration about $0,19 \text{ g}$, the vehicle roll angle was 2.5° . So, for a lateral acceleration about $0,4 \text{ g}$, the vehicle roll angle would be 5° , satisfying the criteria.

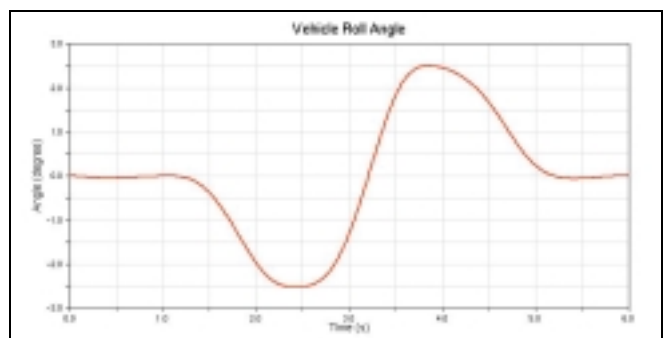


Figure 10: Vehicle roll angle.

The vehicle showed a good handling behavior, according to client's criteria, already taking into consideration the primary suspension optimizations,

like the curves of the shock absorbers and also the stiffnesses of the stabilizer bars.

VEHICLE IMPROVEMENT

In order to get an improvement of the vehicle handling behavior, were carried out an alignment of all the 3 suspensions roll centers, allowing the vehicle to have a unique roll axis. This can be seen in Figure 11.

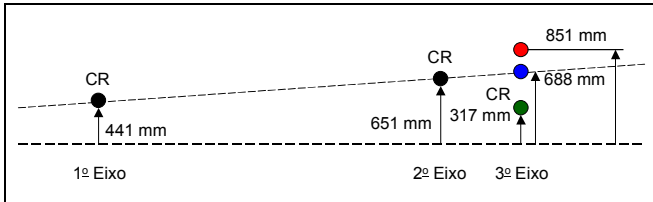


Figure 11: Roll centers of the 3 suspensions.

In Figure 11, in green, it is showed the roll center height of the third axle suspension. This third axle suspension roll center is misaligned about 371 mm (688 mm – 317 mm) from the vehicle roll axis, which is formed by the line that links the roll centers of the first and second axle suspensions.

In the same Figure, in blue, it is showed the roll center height of the third axle suspension, which would done it to be perfectly aligned with the roll centers of the first and second axle suspensions. Unfortunately, this is not a functional mounting, because of the vehicle cardan axle.

So, in the same figure, in red, it is shown the most possible alignment of the roll centers of the 3 axle suspensions. In this configuration, the third axle suspension roll center is misaligned about 163 mm (851 mm – 688 mm) from the vehicle geometric roll axis.

ANALYSES

Analyses with the complete vehicle model were carried out in order to verify the improvement, in handling behavior, obtained with the alignment of the roll centers of the 3 suspensions.

Modal analysis

In the modal analysis, it can be verified that when the 3 roll centers are not aligned (green configuration), in the vehicle roll mode, around 0.7 Hz, the third axle doesn't move in phase with the other 2 axles. This can be seen in Figure 12, in which the second and the third axles are showed.

When the 3 roll centers are aligned (blue and red configuration), the third axle moves in phase with the

other 2 axles

Single lane change maneuver

The results of the vehicle side-slip angle can be seen in Figure 13. In this Figure it is possible to see that the alignment of the suspension roll centers (blue and red configuration) eliminates the undesirable behavior detected in the vehicle prototype, which is showed by the arrows in Figure 13.

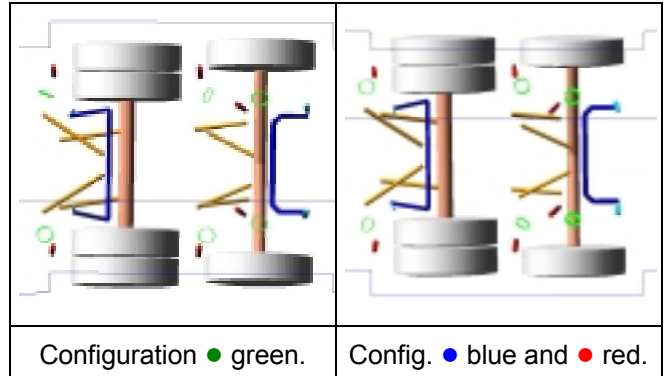


Figure 12: Vehicle roll mode.

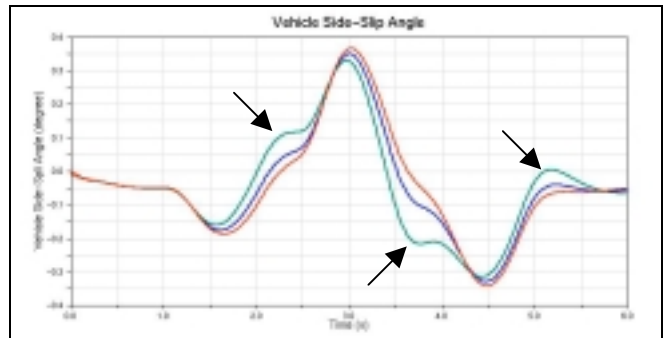


Figure 13: Vehicle side-slip angle.

EXPERIMENTAL VALIDATION

Meanwhile, subjective evaluation have confirmed the improvement on the bus handling behavior due to the modification indicated by the multibody model results.

CONCLUSION

The intention of eliminating the undesirable behavior detected in the vehicle prototype was the major reason for the client asking us this handling study. Fortunately, this was reached.

As a conclusion, it can be stated that it was possible to improve the handling behavior of a three-axle bus using a virtual prototype in a multibody system environment, through a variety of modifications in vehicle suspension elements in a short time, therefore, reducing vehicle development time and costs.

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