Analysis of lateral dynamics and ride performance of the Superbus

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ABSTRACT

Vehicle handling and stability are very important at high speeds especially when the vehicle has a weight of about 6 times a normal luxury passenger car as in the case of the Superbus which travels at 250kph.

In this paper the high speed performance of the Superbus will be analyzed. First the model will be discussed. Then, a number of the several analyses that were carried out will be discussed. These include single lane change and steering impulse. The simulations were done with a complete multibody model made in ADAMS, which accounts for all the major non-linearity’s of the actual vehicle, such as air springs and shock curves, suspension bump stops and Pacjeka tire model [1]. The results of these analyses show that the Superbus is a safe vehicle to drive at high speeds and still can be very comfortable.

INTRODUCTION

There should be a solution to the continuous traffic increase and related pollution. One possible solution for this is the Superbus. The Superbus is a new concept vehicle [2] which is fully electric, operates at 250 kilometers per hour cruising speed and it is aimed at increasing public transportation with respect to private mobility. The Superbus travels at high speeds on specially designated roads (namely the supertracks) and at lower speeds on existing roads. This constitutes a significant novelty in public transport as passengers will not have to change transportation means from departure point to arrival point. The Superbus can transport 23 persons safely and comfortably at high speeds. It has three axles, for a total of six rubber-tired wheels. With a length of 15 meters and a width of 2.5 meters, the Superbus has similar dimensions to a conventional bus but the height is just 1.6 meters. This is due to reduce frontal area for aerodynamic performance, to lower the center of gravity for vehicle stability and to define more individual and comfortable personal areas. The low frontal area combined with a highly streamlined body shape has allowed obtaining a low coefficient of aerodynamic drag so to optimize energy consumption. The vehicle has 16 doors, 8 placed along both sides of the vehicle to allow direct access to all seats. The Superbus will be operated by the combined use of a driver and vehicle electronic guidance. Indeed, the vehicle is equipped by a sophisticated navigation, obstacle detection and adaptive cruise control systems. The road surface of the dedicated concrete supertracks will be heated during winter, to prevent the formation of icing, using solar heat stored in the summer. This eliminates the chance of slippery and unsafe road conditions.

Figure 1: The Superbus

In the winter of 2005/2006 the possibilities for application of the Superbus on the Zuiderzeelijn were investigated. The Zuiderzeelijn is the intended fast connection between the West and the North of the Netherlands. In this investigation the Superbus was compared to other means of high speed public transport like the magnetic levitation train, fast intercity services and high speed
trains. The Superbus was found to be the best in comparison to other means of transport. Therefore the Dutch government decided upon a research and development program for the Superbus. The first phase [3], which is partly funded by the Dutch government, is aimed at the realization of a fully functioning demonstration vehicle to be launched at the Olympics 2008 in Beijing. The Superbus is a joint project of a number of faculties within the Delft University of Technology in the Netherlands (including Aerospace Engineering, Industrial Design Engineering, Electrical Engineering, Mechanical Engineering, Civil Engineering) a number of institutes and of companies for a total of 36 groups.

This paper concentrates on the modeling of the suspension system of the Superbus and the analyses carried out through the design phase. The suspension is one of the most important parts of a vehicle because it contributes to the safety and to the comfort. The novelty of the Superbus vehicle has required a tailored suspension system to account for the various operational conditions. Indeed, especially at high speeds, the vehicle has to operate in a comfortable way but also perform a good handling in emergency scenarios.

MODEL

PRINCIPAL ASPECTS OF THE SUSPENSION SYSTEM

The Superbus has three axles, one axle in the front and two driven axles in the rear. All axles have independent double wishbone suspension. All wheels can be steered up to 40 deg to allow the vehicle to perform a turning circle of less than 12.5 meters – as requested by the European road regulations. The rear wheel steering system will only be used at low speed.

The Superbus ground clearance can vary from 60mm to 400mm. This is done through the use of the custom made VB-Airsuspension system and of a hydraulic lifting system between subframes and body. The vehicle will travel at the lowest ground clearance on the supertrack, when running at height speed, and in some circumstances when loading the passengers. However, to avoid road bumps in the city center or other obstacles, the Superbus will be raised up to 400mm, see Figure 2. Needless to say, the adjustable ground clearance will also allow the alignment with any platform so to enhance accessibility. The variable vehicle height is obtained as follows. Starting from the lowest ground clearance of 60mm, the use of air-springs will allow the ground clearance to be increased by an additional 60 mm. From 120mm, the hydraulic lifting system will increase the ground clearance of an additional 280 mm to reach a total ground clearance of 400mm.

The dampers implemented in the vehicle are supplied by KONI and are frequency selective. These frequency selective dampers (FSD) have different damper characteristics for low and high frequencies which give them a stiffer handling at cornering and a softer comfort at bad quality roads, see Figure 3.

The tires are custom developed by Vredestein and are 315/50-22 tires. Due to the operational characteristics of the Superbus, it was chosen not to implement run flat tyre technology mainly for weight and comfort penalties. The wheel-rims are custom developed by Dymag and will have a magnesium hart and a carbon rim to keep the total weight under 16kg and able to withstand a static load of 1600kg, see Figure 4. The braking systems components will be as well lightweight due to the use of carbon-ceramic brake discs, which will also make it possible to brake up to 1.2g. As a result of the use of custom developed lightweight tires, wheels, and braking system the overall unsprung weight is less than 150kg.
The chassis, bodywork and glazing are made from different light composite materials to keep the total weight of the Superbus under 9 tons (including 23 passengers and luggage) and designed for a torsional stiffness of more than 30kN/deg which is comparable with a Ferrari F50.

**ADAMS MODEL**

The superbus simulation model is made with the multibody dynamics program ADAMS/Car which allows the simulation of the full suspension system.

The Superbus model is a full-vehicle model and includes all the movable parts and connections from the suspension system like an upper and lower arm, knuckle carrier and knuckle as can be seen in Figure 6. Bushings are used as connections just as in the real system. The tires are modeled with Pacjeka 2002 models[1].

**SIMULATIONS**

The Superbus ADAMS model has been used through the design phase and suspension system components selection. A number of simulations were performed through the various stages of system optimization.

The most relevant simulations related to the high speed performances of the Superbus are first described then analyzed below.

The simulations are:

- Step steer response to steady state cornering at maximum speed of 250 kph with a reference radius of 1600 m. This is the smallest corner that the vehicle must be able to drive at 250 kph without excessive path deviations.

- Small radius cornering with increasing lateral acceleration. At high lateral accelerations the stability still has to be ensured.

- A single lane change with a lateral displacement of 2.5m within a longitudinal distance of 150 m. The Superbus will be equipped with the latest radar systems.
technology that is able to detect an object on the road several hundred meters in advance. To ensure the avoidance of such objects the Superbus has to be able to brake within this distance or drive around it if the road is wide enough. The vehicle has to follow a smooth path without excessive overshoot of the rear axles and without getting into a high lateral acceleration. These criteria have to be met on both dry and wet roads.

- A sudden lateral wind gust of 15m/s while driving straight at 250 kph. The Superbus will have to pass this test without large path deviations or instability. Both dry and wet asphalt will be simulated.

- Comfort at 250kph. The vehicle will drive over an ISO road class C and E [5]. Class C is a stochastic road profile that can be compared to a good quality highway. Class E can be compared with a low quality highway. The results can be compared to the ISO 2631 criteria [4],[6] which show how long a human been can withstand a certain acceleration frequency.

SIMULATION RESULTS

1600m cornering at 250kph

Driving on a 1600m radius corner at 250kph results in a lateral acceleration of 0.31 g. This can be reached with a steering-wheel input from 0 to 3.4 degrees in 1 seconds. The results are shown in Figure 7.

Figure 7: 1600m radius cornering

As expected, the side slip angle is small and well within the linear range of the axle characteristics. Thus, the vehicle will be able to drive at cruising speed on a 1600 m radius corner without excessive path deviations or over or understeer.

Small radius cornering with increasing lateral acceleration

For this simulation, a small corner of 80 m radius is chosen for which a steering wheel angle of 60 degree is needed. The lateral acceleration is increased until extreme over or understeer is detected. The result can be seen as the blue line in Figure 8.

The result shows an oversteer moment at a lateral acceleration of 0.85 g. This value of lateral acceleration will never be reached in normal driving conditions. Indeed, the normal driven condition will be limited to approximate 0.35 g. However, larger accelerations need to be accounted for in case of the occurrence of extreme external conditions to ensure the avoidance of dangerous situations. For this an anti-roll-bar will be included in the design. The function of anti roll bar is to tune the high g / limit understeer behavior of the vehicle. The limit understeer behavior is tuned by changing the proportion of the total roll stiffness that comes from the front and rear axles. Increasing the proportion of roll stiffness at the front will increase the proportion of the total weight transfer that the front axle reacts and decrease the proportion that the rear axle reacts. This will cause the outer front wheel to run at a higher slip angle, and the outer rear wheel to run at a lower slip angle, which is an understeer effect. The result, when using the ARB in de Superbus model can be seen as the red line in Figure 8.

The results show that the implementation of the ARB significantly changes the behavior of the vehicle which will have slowly increasing understeer at very high lateral accelerations instead of a sudden oversteer reaction which can be dangerous.

Single lane change/ Avoidance maneuver

The radar system used by the Superbus will be able to detect obstacles on the road up to a distance of 260m. This will give the adaptive cruise control the ability to stop the vehicle in time. In case of a failure of one of the systems the requirement is for the vehicle to be able to drive around it. For the single lane change maneuver simulation the driver has to follow a path that has a lateral deviation of 2.5m in a longitudinal displacement of about 150m. The analysis is done on a dry road with a road friction coefficient of 1.2 but also on wet road conditions with a mu of 0.7 and 0.5. The results are shown in Figure 9.
The results show a fast response with an overshoot of only 0.4 m. Even on a wet road the performance will stay reasonable although the overshoot will get a bit larger. Thereby, for these analysis it is expected that the Superbus will be able to smoothly avoid an obstacle when driving 250 kph.

Side wind gust

The wind gust forces have been estimated at 5,000 N side force and 12,000 Nm yaw torque for a 15 m/s side wind gust. This force and torque are applied for two seconds with a smooth transition as in Figure 10.

As can be seen from Figure 11, the Superbus has a maximum lateral deviation of just over 0.1 m. For this analysis, the effect of a low road friction coefficient is negligible. This can be explained by the slip angles which stay well below non-linear characteristics of the tires as can be seen in Figure 12. This means the tire forces are hardly affected by the road coefficient of friction. Thus the Superbus is capable of dealing with side wind gusts even on a wet road.

Comfort at 250kph

The Superbus will have a very low unsprung mass with respect to the overall system, which will give a favorable wheel hop frequency. The wheel hop frequency can be estimated as follows:

$$f_2 \approx \frac{1}{2\pi} \sqrt{\frac{K_1 + K_2}{m_2}}$$  \hspace{1cm} (1)

Where $K_1$ is the suspension spring coefficient, $K_2$ is the tire spring coefficient and $m_2$ is the unsprung mass.

Based on this formula, the Superbus wheel hop frequency lies around 10 Hz. This is good as the human body is sensitive to accelerations in the frequency region of 4 to 8 Hz [4] [6], which is why it is important to keep the unsprung mass low to get a wheel hop frequency above this sensitive region.

The comfort level can also be investigated in more details with ADAMS. The simulations were done for an ISO class C and E road [5]. The road class C is comparable with a smooth highway (which is similar to the high speed supertrack). The road class E is comparable with a low quality highway.

The vibration total value of the weighted RMS acceleration, determined from vibration in orthogonal coordinates, is calculated as follows [4]:

Figure 9: Single lane change/ avoidance maneuver

Figure 10. Aerodynamic wind gust forces

Figure 11. Path deviation with wind gust

Figure 12. Slip angles at 250 kph with wind gust.
\[ a_i = \left( k_x^2 a_{x}^2 + k_y^2 a_{y}^2 + k_z^2 a_{z}^2 \right)^{\frac{1}{2}} \] (2)

Where \( k_x \), \( k_y \), and \( k_z \) are 1 for seated persons in comfort studies.

Acceptable values of vibration magnitude for comfort depend on many factors which vary with each application. Therefore a limit is not defined in ISO 2631. Approximate indications state that vibrations will start to feel a little uncomfortable above 0.315 m/s\(^2\) and very uncomfortable above 1.25 m/s\(^2\).

The vibration total values calculated from data generated with ADAMS are shown in Table 1.

<table>
<thead>
<tr>
<th>ISO road class</th>
<th>At 50 kph</th>
<th>At 250 kph</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type C, smooth highway</td>
<td>0.011 m/s(^2)</td>
<td>0.012 m/s(^2)</td>
</tr>
<tr>
<td>Type E, low quality highway</td>
<td>0.099 m/s(^2)</td>
<td>0.105 m/s(^2)</td>
</tr>
</tbody>
</table>

Table 1: RMS acceleration values

From this table above it can be seen that the r.m.s. values of the accelerations are well below the 0.315 m/s\(^2\) that was stated before. These results were also analyzed with respect to the ISO 2631 diagram as can be seen in Figure 13 [6].

The accelerations inside the vehicle can be compared with the 24 hour line in Figure 13. Even in the case of a low quality highway road the Superbus shows to be very comfortable.

Although the road profiles used are very realistic, the r.m.s. accelerations are only measured for driving a straight line. No potholes or other deterministic disturbances are included in the road profiles. The indicated r.m.s. values are relative to the center of gravity of the vehicle, therefore if a passenger sits nearby an axle the accelerations will be twice as big. On the other hand, these simulations do not contain the soft seats and the special KONI FSD dampers which will make the ride even more comfortable.

CONCLUSION

Simulations are performed with ADAMS/Car to investigate the handling and comfort of the new vehicle Superbus. The results show that the Superbus will be stable and safe in normal driving conditions. In extreme situations like a high lateral acceleration the vehicle will behave as most passenger cars, with a slowly increasing understeer effect where the vehicle will still be controllable. In case of an obstacle on the road the Superbus will be able to stop in a short distance and is also able to avoid an obstacle on the road with a fast steering maneuver, even at a wet surface. In case of a side wind gust of 15m/s the Superbus will still be very stable on the road as the path deviation will be very small. This concludes that the Superbus will be safe to drive at high speeds.

The Superbus has a favorable low unsprung mass which result in a comfortable ride. The calculated r.m.s. values of different road profiles indicate that the Superbus will be comfortable, even at lower quality roads.

Other simulations are undergoing, such as braking performance with ABS and other stability control systems. Alongside that, correlation of the model to the vehicle will be done throughout testing.

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