Dynamic handling of an extremely fast bus: criteria and control

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In order to limit traffic congestion, initiatives are taken to improve the public transport. Such initiatives may include high speed travelling of a special bus on specially designed lanes, with speeds up to 250 km/hr, combining fast travelling with an effective door-to-door service. Conditions to establish a safe and comfortable dynamic performance of such vehicles are usually defined in terms of weights and dimensions, low speed manoeuvrability, body eigenfrequency, automotive detection system etc. but not in terms of dynamic performance of the bus itself. It is envisaged that there still may be situations where safety relies on the driver response to undesired and potentially dangerous conditions. In addition, these vehicles are unique, with unique operation conditions and non-standard traffic circumstances. This makes it difficult to demonstrate safe performance on the basis of experience with existing alternative transport modes. It therefore makes sense to establish safety related performance based handling criteria for these vehicles, to be fulfilled with full account taken of the driver control. Such criteria are suggested in this paper. They are verified by simulation. It is shown that some additional vehicle control and driver assistance measures are successful to improve the driver-vehicle dynamic performance, to satisfy these criteria.

Topics / 1: Vehicle Dynamics, 6: Vehicle Control, 10: Direct Yaw Control

1. INTRODUCTION

In order to stop the traffic infarct, being a daily experience in most of the countries of the world, initiatives are taken to improve the public transport. Such initiatives may include high speed travelling of a special bus, combining fast travelling with an effective door-to-door service.

In the Netherlands, such an initiative has been taken, with speed between 150 and 250 km/hr, see [1]. The bus will use the high speed on specially designed lanes. Lower speeds will be used closer to the desired destiny. A maximum number of about 25 passenger is assumed. A schematic picture is shown in figure 1.

In the design process, criteria for the dynamic safety properties are usually set in terms of natural frequency (ride comfort), dimensions, low speed manoeuvrability (rear axle steering), weights and wheel loads. With safety critical conditions in mind, such as cornering and obstacle avoidance manoeuvres, low road friction and severe cross-wind gust loading, additional quantitative criteria are required, and these criteria are presented in this paper. The research is carried out for arbitrary fast bus design.

With a bus travelling at extremely high speed (250 km/hr), this may pose a special risk in terms of

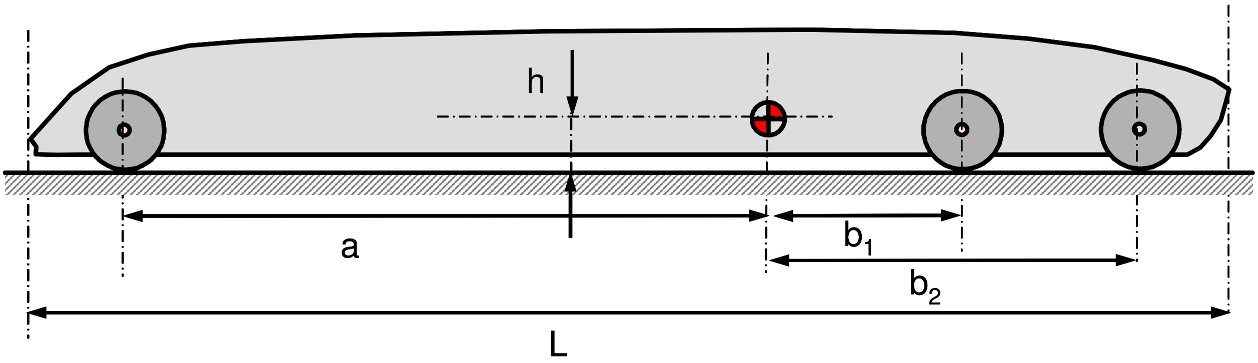


Fig. 1.: Schematic layout

excessive path deviations, possible unstable behaviour, highly nonlinear tyre-road conditions leading to loss of control by the driver, etc. In theory, partial loading conditions may occur, with most of the passengers located at the front or the rear of the vehicle, and this will change the vehicle understeer characteristics. As a result, partial payload conditions may be more critical than the situation with maximum payload.

In this paper, safety related handling criteria are suggested. With these new types of public transport, with newly designed vehicles, with unique operational conditions with no comparison with any other known transport mode, these criteria are completely open and will be under discussion. It is therefore not so much the severity of the criteria which is important (one may agree to change this), but the fact that there is an understanding about the existence and the type of criteria.

Judging vehicle dynamic performance, one requires agreement on the following issues:

- Type of manoeuvres, the bus is expected to carry out (straight on, cornering, lane change,..)
- External conditions (road, weather, obstacles,..) including possible disturbances under which the bus has to function (road friction, forces and moments due to cross-wind,..)
- Service conditions that may occur in terms of speed, payload, run-flat conditions, etc.

Criteria are then based on combinations of these three, with first an indication of the type (maximum path deviation, stability, damping,..), and second a specification of the quantitative limits.

With the criteria defined, the vehicle handling performance is examined against these criteria. We use a model approach, accounting for the various loading conditions (cornering, cross-wind).

Handling safety with the driver in the loop is clearly related to the driver feed-back control on the vehicle handling disturbances. For some manoeuvres, we therefore use a simplified driver model to obtain an understanding of the vehicle-driver response. We have varied the driver model parameters (gain, delay time) to verify the sensitivity of these model parameters to the system response, and to explore steering assistance.

Next we have run simulation studies to verify the criteria. The various simulation models, derived for this analysis, can be used for any manoeuvres, road friction conditions, gust loading. That means that possible other criteria can be verified without much effort. It turns out that for most relevant conditions, the reference vehicle will remain stable, i.e. the tyre-road conditions are not saturated. However, especially in case of low road friction and unfavourable payload conditions, the path deviations become rather large. Among other things, this is influenced by the driver parameters. A low gain will keep the vehicle-driver system stable but leads to significant path deviation overshoot, whereas a high gain leads to severe course oscillations for the vehicle, and possible unstable behaviour.

This suggests an active front axle steering control or steering assistance with varying gain, supplemented by an approach to stabilize the vehicle. For that, we have selected the following approaches:

1. active rear axle steering (RWS)
2. direct yaw moment control (DYM)

It turns out that the combination of varying steering gain with RWS and/or DYM may lead to significant lower (and acceptable) path deviations.

2. PERFORMANCE BASED HANDLING CRITERIA.

For the vehicle, four different loading categories are distinguished:

1. fully loaded
2. half loaded, with all the payload located at the front half of the passenger compartment
3. half loaded, with all the payload located at the rear half of the passenger compartment
4. empty, i.e. zero payload.

The bus is designed such that under full loading conditions, the axle loads are almost identical. In case of a partial load, the different axle loads may lead to a different wheel slip distribution, with a lower critical lateral acceleration. This motivates the choice of the two partial loading conditions.

The vehicle is subjected to the following reference manoeuvres and conditions:

- step steer response at maximum speed (250 km/h) with a reference curve radius of 1600 m.
- a single lane change with a maximum lateral displacement of 3.5 m within a longitudinal distance of 75 m. This distance is chosen larger (tripled) then the distance for a normal lane change, because of the extreme high speed.
- a realistic wind gust, while driving straight on or in combination with a steady state turn. The wind gust is derived from 15 m/s wind speed, resulting in a design loading of about 5000 N side force and 12000 Nm yaw moment.

In contrast to the ISO single lane change test [3], we are primarily interested in the path deviation while 'tracking' the single lane change path. The driver is assumed to carry out this manoeuvre with a preview distance of 75 m.

These handling conditions are considered for the four payload categories, with possible variation of road friction between 1.2 and 0.5. For lower friction levels (snow, ice), the vehicle is assumed not to be allowed to drive at maximum speed, and adequate precautions are expected to be taken.

The criteria for the judgement of safe handling behaviour are selected as follows:

A. The friction limits at any of the three axles will not be exceeded under each of these reference manoeuvres, for any payload conditions, in any combination with changes in wind gust and/or road friction.
B. When we account for a realistic driver response or driver steering assistance to possible lateral disturbances (such as wind gust and/or changing road friction during cornering), the deviation from the intended vehicle path (single lane change) should not exceed 0.8 meter.

In order not to interfere with road barriers along the road or to leave the road undesired, the value of 0.8 m has been chosen. For comparison, for high-speed off-tracking for 25 m road trains in Australia, one also selects 0.8 meter as a maximum value, see [4].

3. THE VEHICLE MODEL.

The model, schematically shown in fig. 1, is subjected to a number of assumptions and simplifications:

- The effect of roll is taken into account through lateral load transfer. The effect of roll acceleration on lateral and yaw performance is neglected.
- A two-track model is used.
- The model allows lateral handling behaviour (lateral speed, yaw) as well as variation in forward speed.
- The possibility of high-speed steering control for one or more axles (originally mainly for reasons of low-speed manoeuvrability) is included.
- The model allows for separate braking per wheel. Brake forces are considered as input to the model.
- Separate tyre-road friction levels are accepted by the model.
- Tyre camber effects are neglected.
- Nonlinear tyre characteristics (Pacejka model, see [6]) are accounted for.

The vehicle behaviour is described by standard two-track equations (see [2]), in lateral direction, yaw direction and forward direction, respectively, taking into account aerodynamic forces (lateral, down force) and aerodynamic yaw moment.
Both rear axles (indicated with 2 and 3) are assumed to be steerable, with steering angles coupled to the front axle steering angle:

$$\delta_3 = K_{32}.\delta_2 = K_{32}.K_{21}.\delta_1 \tag{1}$$

Under initial non-cornering conditions, the tyre loads are given by the static values, with the down force added. Speed variations are assumed to be small. Therefore, variation in down force is neglected.
With axle loads G_i for axle i, and neglecting coupling of pitch and roll, and suspension dynamics, equilibrium of moment in y-direction around the front axle ground contact point leads to the following equation:

$$\begin{aligned}(a+b_1).G_2 + (a+b_2).G_3 &+ \\ -h.m.\dot{V} - (m.g + F_{zd,total}).a &= 0\end{aligned} \tag{2}$$

with total mass m, and total down force $F_{zd,total}$ over all axles, which is assumed to act at the Centre of Gravity.
Clearly

$$G_1 + G_2 + G_3 = m.g + F_{zd,total} \tag{3}$$

The axle loads can be determined from the suspension characteristics, and neglecting differences in damper deflections. We assume identical vertical stiffnesses for all three axles. This leads to:

$$\begin{aligned}&\begin{pmatrix} b_2 - b_1 & -(a+b_2) & a+b_1 \\ 1 & 1 & 1 \\ 0 & a+b_1 & a+b_2 \end{pmatrix} . \begin{pmatrix} G_1 \\ G_2 \\ G_3 \end{pmatrix} = \\ &= \begin{pmatrix} 0 \\ m.g + F_{zd,total} \\ (m.g + F_{zd,total}).a + h.m.\dot{V} \end{pmatrix}\end{aligned} \tag{4}$$

for forward speed $\dot{V}$ and total down force $F_{zd,total}$.
Wheel loads are obtained from lateral load transfer in terms of the lateral acceleration a_y.

With a cross-wind gust of 15 m/s (strong wind) perpendicular to the orientation of the vehicle speed with magnitude of 250 km/h one obtains a relative wind speed of V_r = 71.05 m/s, and an angle β_{wind} between vehicle orientation and wind direction of 21°. From the data in [2], we have derived some representative drag coefficients, and estimated side force and yaw moment due to wind gusts in the order of F_{aero} = 4300 N and M_{aero} = 12000 Nm.

Closed loop performance is described through a simplified driver tracking control model as follows:

$$\frac{\delta_1}{u} = -K_d.\frac{1}{1+\tau.s} \tag{5}$$

with front axle steering angle δ_1, path deviation u at preview distance L = 75 m (corresponding to about 1 s preview time), delay time τ and gain K_D (see [2]). The gain K_d is determined such that a proper balance is achieved between stable behaviour and accurate path-tracking.

4. RESULTS, UNCONTROLLED.

4.1. Single lane change.

We have carried out simulations for two different frictions (μ=1.2 and μ=0.5), and with the bus fully loaded (loading category 1). The gain K_d was chosen such that the deviation from the path is minimal in rms (root mean square), resulting in K_d = 0.009 rad/m. The maximum lateral acceleration appeared to be 0.4 g (high friction) and < 0.3 g (low friction). Results for the position of the vehicle CoG and of the front and rear end of the bus (for low friction) are shown in figure 2.

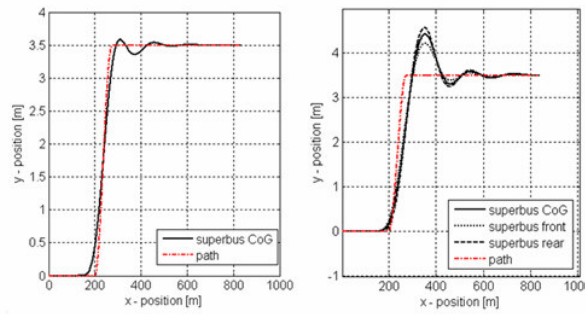
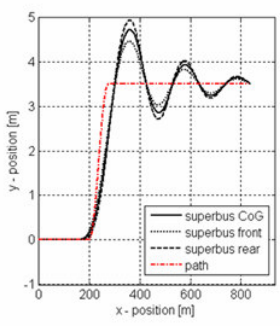


Fig.2: Simulation results for μ=1.2 (left) and μ=0.5, bus fully loaded

For high friction, the deviation from the path for the vehicle CoG is very small (< 10 cm), increasing to 106 cm for the rear end of the bus for low friction, i.e. exceeding the allowable value of 80 cm.

By increasing the gain K_d, one may be able to follow the lane change more closely but at the cost of more oscillations, and the risk of losing control (system of driver and vehicle becomes unstable). For K_d = 0.012 rad/m the vehicle path is shown in fig. 3. A rear swing of 84 cm is obtained. Increasing K_d further, the vehicle-driver system becomes unstable for K_d = 0.015 rad/m, with an optimal path deviation of 71 cm. It is clear that this rear swing will never be reached, due to the extremely unsteady lateral behaviour of the vehicle.



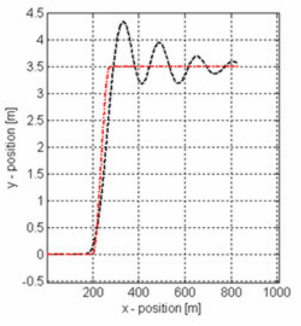


Fig. 3. Results for μ=0.5, for 50 % max. payload at rear

Fig. 4.: Rear end position or μ=0.5, adjusted K_d

Next, we have carried out the same analysis for the payload configuration 3, i.e. with half of the maximum payload located in the rear half of the bus, see fig. 4. We observe a less damped response with a larger deviation from path (144 cm) at the rear (rear swing). This is due to the increased load transfer at the rear axle, leading to reduced understeer. The steering is less effective due to the reduced first axle load, which means that more steering is required for the lane change.

4.2. Cross-wind loading.

The fully loaded bus is subjected to a cross-wind gust during 2 sec., with a resulting side force and yaw moment as introduced earlier. We have considered again both frictions of 1.2 (fully loaded) and 0.5 (50 % payload at rear), for the driver model cf. (5). Path deviations appeared to vary from 29 cm (dry road) to over 1 m (slippery road).

The front axle steering input increases from 0.15° to 0.6° and more dynamic steering is required for low friction in combination with partial loading in the rear half of the bus, see fig. 5.

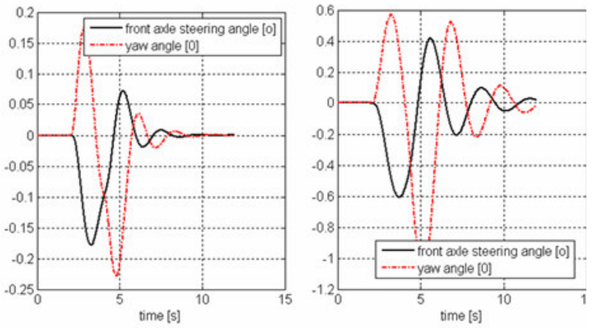


Fig.5.: Gust response, fully loaded, μ=1.2 (left) and partially loaded (category 3), μ=0.5 (right)

We have varied both the driver gain and the length of the cross-wind gust, to analyse the possible effect on the path deviation, see fig. 6.

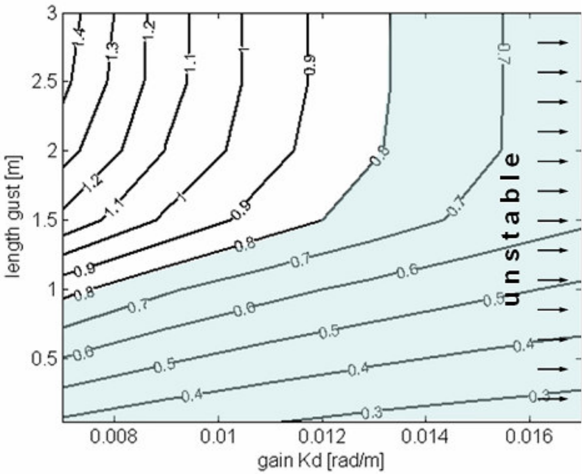


Fig.6.: Effect gain and gust length on path deviation

We have performed this analysis for the unfavourable payload, located at the rear. The gust length of 2 meter appears to be properly chosen in the sense that the path deviation hardly changes for larger gust length. For gust length of 2 meter, and up to a gain of about K_d = 0.013 rad/m, the path deviation exceeds the critical level of 80

cm. It is concluded that the fast bus for partial rear payload conditions will not meet the deviation criterion.
With increasing preview length, the path deviation may be reduced with about 20 to 30 %, but we don't feel that to be representative for all possible realistic situations, and we maintain the conservative assumption of a preview length of 75 m (being about 1 sec. preview time).

4.3. Step-steer response and steady state cornering

We start with the fully laden bus, driving straight on a dry road, until the front axle steering angle is suddenly changed to a value corresponding to a steady state manoeuvre with lateral acceleration of $a_y = 0.31$ g. This transition of the steering angle takes place within 0.2 sec. (ramp steer). Calculations have been repeated for a slippery road ($\mu = 0.5$), with partial load at the rear half of the bus. Finally, we assume a cross-wind gust, to occur while cornering. In all cases, the driver is passive, i.e. does not respond to path deviations. Results for the yaw rate for low friction are shown in fig 7.
Without cross-wind, one observes a larger overshoot of the yaw rate, indicating large understeer. The axle slip angles appear to have been increased compared to the high-friction case, but the vehicle is still stable. Adding the cross-wind gust pushes the yaw rate up and the vehicle becomes unstable.

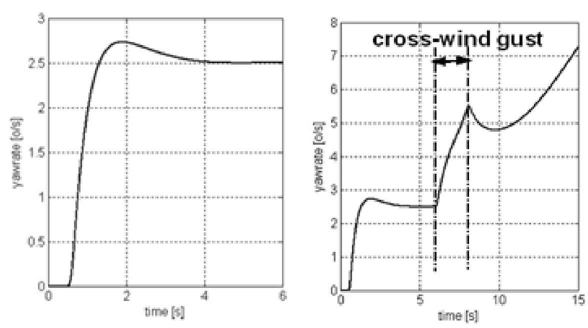


Fig.7.: yaw rate for μ=0.5, 50 % payload (rear) without (left) and with (right) cross-wind gust.

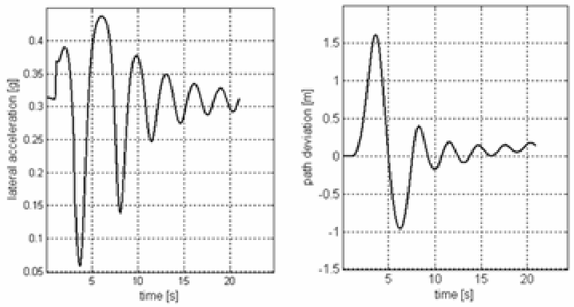


Fig. 8.: Lateral acceleration and path deviation for a 2 sec. cross-wind gust disturbance, accounting for driver steering feedback, with road friction μ=0.5, and 50 % payload at rear.

We have repeated the calculation, now accounting for the simplified driver model (5). We have used the same driver parameters, i.e. preview length of 75 m, reaction time 0.2 sec. and a gain $K_d = 0.009$ rad/m.
In this way, the vehicle may be kept under control but probably at the cost of large oscillations and excessive axle slip angles (entering the nonlinear range).
Results are shown in fig. 8 for the lateral acceleration and the deviation of the vehicle CoG from the undisturbed vehicle path. A maximum lateral acceleration of almost 0.45 g is reached (tyre characteristics close to the limit) and a maximum lateral path-deviation exceeding 1.5 meter. One may improve stability by reducing the gain K_d but that will result in a larger path-deviation.

Consequently, in case of low road friction and unfavourable payload conditions, the fast bus is still within safe limits during sudden steering variation and steady state conditions. When these low friction conditions are combined with cross-wind gust loading, either the friction limits are exceeded if the driver does not interfere, or the path deviation grows up to more than 1.5 meter with driver feedback.

5. THE POTENTIAL OF CONTROL MEASURES

In this section, we explore the potential of using vehicle control and driver assistance measures to improve the fast bus handling performance on a slippery road, possibly in combination with cross-wind.
Based on the earlier observations, increasing the gain K_d may be a way to support the driver or control the front axle steering. This approach will lead to lower stability, and a successful application can only be expected if the stability of the bus is maintained with other means. Improving the stability may be achieved by both active rear axle steering (proportional to the front axle steering, and having the same sign), direct yaw moment control and possible combinations.
For the lane change, we have chosen the third axle steering angle to be 10 % larger than the second axle steering angle, with the last being equal to 20 % of the front axle steering angle. A braking torque is applied to two rear wheels at one side of the bus, when the yaw rate r exceeds $r_{crit} = 1.72$ ^{o}/s. Beyond this value, the correcting yaw moment (resulting from the two wheels under braking torque) is chosen to be linearly increasing in $(r - r_{crit})$ with gain $1.5.10^5$ Nm/rad. With the maximum yaw-rate being about 0.07 rad/s (based on the calculations), this leads to a maximum correcting yaw moment of 6000 Nm. With track width of 2.15 meter, this corresponds to a brake force at each of the two wheels of 2790 N being slightly more than 20 % of the maximum wheel load. With a brake force of 2 x 2790 = 5580 N, the vehicle is slowing down with deceleration of 0.76 m/s^2. It is assumed that this DYM control will only last some seconds. As a result, the effect on vehicle speed is small.
The driver gain K_d (assistance or actively controlled) is chosen initially equal to 0.015 rad/m to track the single lane change path as good as possible. In order to keep the oscillations down, and the vehicle stable, this gain is linearly reduced to the original value of 0.009 m/rad

within 1 sec. (from t = 4.5 sec to t = 5.5 sec.), and kept at this level from that moment on.

The resulting rear end position for the bus for the cases of only driver tracking control (previous sections) and in combination with rear axle and yaw moment control is shown in fig. 9. Initially, the vehicle is able to follow the lane change path more closely with a maximum rear swing (rear end path deviation) of 68 cm, compared to the previous 144 cm, i.e. a reduction with 53 %.

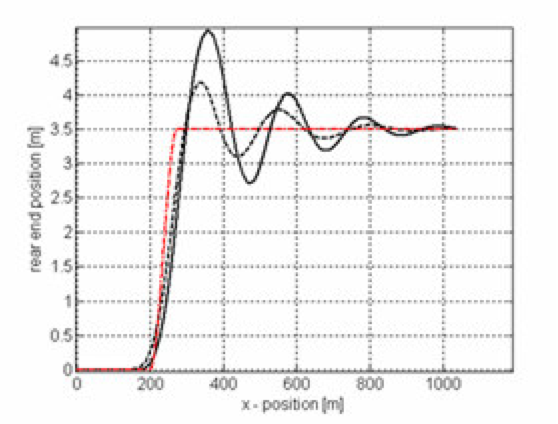


Fig. 9.: Lane change rear swing without control (solid) and with control (dashed)

When we apply the same control for a cross-wind gust loading, the rear swing appears to drop from 110 cm to 54 cm, with a faster response, followed by a more damped behaviour following the cross-wind gust loading.

Finally, we consider the cross-wind loading during a steady state turn. The impacts of DYM and Rear Axle Steering on stabilization of the vehicle behaviour are considered separately. The driver gain is chosen large, as 0.02 rad/m. Starting with DYM, we now choose r_{crit} = 0.04 rad/s. With a steady state yaw rate between 0.04 and 0.05, the DYM control is active during the entire steady state run, with a corrective brake force per wheel of about 350 N, i.e very low. This control is just sufficient to stabilize the vehicle such that a driver gain of K_d = 0.02 rad/m does not lead to instability. With DYM removed, the driver-vehicle system becomes unstable.

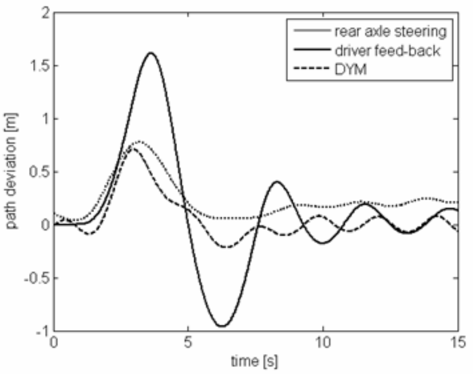


Fig. 10.: Cross-wind gust during cornering

Omitting DYM but chosing Rear Axle Steering instead (with the same ratios between the various steering angles as chosen before), this turns out to be also sufficient to allow a large gain such as K_d = 0.02 rad/m. See figure 10 for results. Each of the deviations has dropped below 0.8 m. This does not mean that the tyre forces have dropped. It is merely that the balance of the different tyre forces has changed.

6. CONCLUSIONS.

We have suggested safety related handling performance based criteria for an extremely fast bus to fulfil in order to guarantee that the bus will not enter into critical conditions, losing control at one of the axles, and path deviations during obstacle avoidance and cross-wind disturbances are restricted to safe limits.

Based on the analyses in this paper, the following conclusions can be drawn:

- The combination of high speed, low friction, cross-wind gusts, for certain loading conditions can be very critical for an extremely fast driving bus, resulting in excessive path deviations or loss of stability.
- Adapting the front axle steering gain (driver support), the vehicle may be kept within deviation limits but at the cost of large oscillations and excessive lateral slip (risk of instability).
- The criteria as introduced in Section 2, can all be satisfied with additional appropriate vehicle control and driver assistance measures, such as rear axle steering and direct yaw moment control. It is advised (as a minimum requirement) to equip these fast buses with ESC (Electronic Stability Control). The design of the vehicle control and/or driver support measures (adapting the steering gain), and/or the successful use of existing, commercially available control systems requires further analysis.

REFERENCES

[1]. W.J. Ockels, A. Terzi, J.A. Melkert.: *Superbus Preliminary Design Review* (December 2006), Delft University of Technology.

[2]. G. Genta.: *Motor Vehicle Dynamics*, *Modelling and Simulations*, World Scientific Publishers (2003), Singapore

[3]. *ISO 3888-2:2002 passenger cars – test track for a severe lane change manoeuvre – part 2: Obstacle avoidance* (2002)

[4]. P. Sweatman (ed.).: *PBS Explained, Performance Based Standards for road transport vehicles.* ARTSA (Australian Road Transport Suppliers Association), September 2003.

[5]. J.P. Pauwelussen.: *Superbus dynamic handling: criteria and control.* Private note (2007)

[6]. H.B. Pacejka.: *Tyre and Vehicle Dynamics*, Butterworth and Heinemann (2002)