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Smart caravan chassis design, matching low-speed manoeuvrability with high-speed stability

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ABSTRACT

This paper analyses the behaviour of a new type of caravan chassis equipped with a nose wheel at the front, and with the centre axle shifted to the rear. In this way, the caravan carries its own weight. With vertical load transfer avoided between caravan and towing vehicle, one might hope for improved performance of the vehicle-caravan combination, both with respect to cornering limits and potential oscillatory or divergent instability. Moving the axle to the rear may have a negative effect on the vehicle-caravan yaw stability, which may be compensated by restricting the nose wheel steering. On the other hand, low speed manoeuvring requires a free steering nose wheel. Hence, some control of the nose wheel is anticipated, and the paper discusses the use of a steering damper and rotational springs for this purpose. By varying the spring stiffness, all situations between a free steering nose wheel and a nose wheel fixed to zero steering angle can be examined. This idea was adopted by the company Lusaro and analysed through experiments and model investigations in close cooperation with the HAN University. The experiments served to obtain practical evidence about design aspects and potential problems for the Lusaro caravan, as well as to identify the correct vehicle and caravan parameters for the subsequent simulation research. The simulation studies served to investigate safety and stability characteristics of the vehicle - caravan combination, with emphasis on sensitivity with respect to load configuration and axle characteristics.

Topics: vehicle dynamics and control, active safety

1. INTRODUCTION

A caravan is basically a central axle trailer, with part of the load carried by the towing car through the coupling point. A car-caravan combination in this way becomes unstable beyond a certain speed, with this speed depending critically on the caravan centre of gravity, mass, axle cornering stiffness and draw bar length. These parameters, except for the draw bar length, are a result of the weight and weight distribution, applied by the user in stowing his luggage in the caravan, resulting in considerable risk of instabilities on a trip to the sunny beaches of Italy or Spain. There have been various approaches to improve the directional stability and handling performance of articulated vehicles. One approach is through all-wheel steering, [2]. Another approach is through the use of active moment control, see [3] and [5]. In this paper, we investigate the potential of adding an additional nose wheel (caravan front axle) at the front of a caravan, and at the same time shifting the rear axle rearward. In this way, the caravan centre of gravity (COG) is located between both axles, and the performance of the car-caravan is expected to be more robust against variations in loading compared to a conventional caravan. This idea has been adopted by the company Lusaro, and investigated in cooperation with the HAN University. A first prototype of this chassis concept, for the purpose of testing is shown in figure 1.

Fig. 1.: First prototype Lusaro caravan chassis.

The nose wheel serves to carry part of the weight of the caravan in a way that no load transfer occurs between caravan and towing vehicle. But the nose wheel may also be used to deal with potential problems in handing and stability at large speeds and/or high lateral accelerations. One may think of different options, for example by applying a possibly speed dependent steering damper or rotational spring stiffness between chassis and nose wheel, by completely fixing the nose wheel steering angle at zero, by linking the steering angle of the nose wheel to the articulation angle between vehicle and caravan, etc. Such control only makes sense for speed beyond the level where large steering angles and small radii of curvature may be expected. For low speed, a high level of manoeuvring is required. A control strategy therefore should be based on an approach with the steering angle free rotating for low speed, and with some transfer to a controlled wheel rotation at higher speed. This paper will only consider the situation for large constant speed. The transfer in control from low to high speed is not considered.

The paper is structured as follows. In the next section, some further information is given on the chassis design. In section 3, the single track model for the car-caravan combination is discussed including validation through experiments. In section 4, the cornering performance is discussed, and compared with the performance for a conventional caravan with the same payload and chassis mass with the nose wheel removed. Stability is treated in section 5 for wheel shimmy and in section 6 for the total vehicle yaw response. Conclusions are drawn in section 7.

2. CHASSIS DESIGN

A schematic layout of the Lusaro caravan chassis is shown in fig. 2. The nose wheel is steerable, and suspended to the chassis with some combined spring-damper systems.

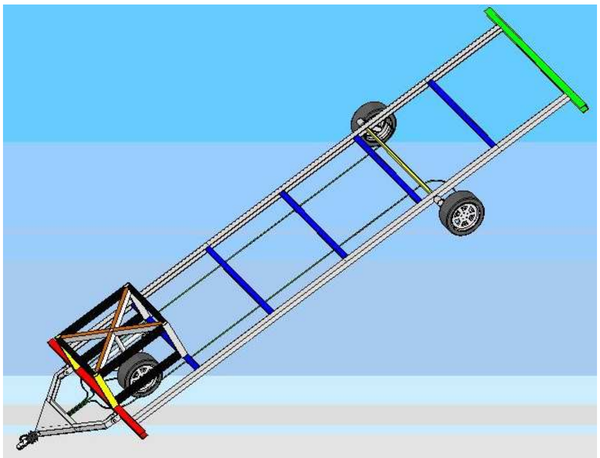

Fig 2.: Layout of the Lusaro caravan chassis

A special design is used to allow for reversing the vehicle speed direction without reversing the nose wheel direction. The side forces acting on the nose wheel result in significant reaction forces and bending moments within the chassis. In order to deal with that, a support structure was designed, corresponding to a significant mass increase at the location of the nose wheel. This has an effect on the COG-location and therefore on the caravan performance. The draw bar is connected to the caravan through simple hinges, preventing vertical load transfer at the coupling point.

3. MODEL AND VALIDATION

The Lusaro car-caravan combination has been described by MATLAB-SIMULINK in two ways, (1) with a two-track model including the axle load transfer and combined slip, and (2) with a single lateral track model. This paper discusses the single track model, for constant forward velocity u and given input steering angle $\delta_1 = \delta_1(t)$ at the car front axle. The axles have been described based on the full nonlinear Magic Formula relationships, see [4]. The model is schematically shown in fig. 3. A caravan with a single front nose wheel and a rear axle at distances c and d from the caravan COG, respectively, is connected to a car at distance f from the caravan COG. The axles in this model will be indicated as axle 1 and 2 for the towing car, and axle 3 and 4 for the caravan.

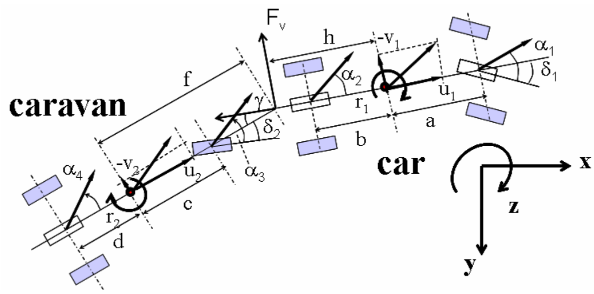

Fig. 3.: The car-caravan model

The single track bicycle model for the combination of car and caravan is given by the following equations:

$$m_1.(u.r_1 + \dot{v}_1) = F_{y1} + F_{y2} - F_v \quad (1)$$

$$m_2.(u.r_2 + \dot{v}_2) = F_{y3} + F_{y4} + F_v \quad (2)$$

$$J_1.\dot{r}_1 = a.F_{y1} - b.F_{y4} + h.F_v \quad (3)$$

$$J_2.\dot{r}_2 = c.F_{y3} - d.F_{y4} + f.F_v \quad (4)$$

$$v_1 - h.r_1 + u.\gamma = v_2 + f.r_2 \quad (5)$$

$$k_d.\dot{\delta}_2 + c_d.\delta_2 = -e.F_{y3} \quad (6)$$

for masses m_1, m_2 and moments of inertia J_1, J_2 of car and caravan, lateral axle forces F_{yi}, reaction force F_v, yaw rates r_i and lateral velocities v_i. The steering angle at the nose wheel is indicated by δ_2.

The first four equations describe the lateral and yaw behaviour of the car and caravan, the fifth equation expresses continuity of lateral velocity at the coupling point connecting both units, car and caravan. The final equation expresses the fact that the nose wheel is linked to the caravan chassis through rotational stiffness c_d and damping k_d, to be considered as the control parameters to tune the system performance. Varying c_d allows one to investigate the impact of steady state nose wheel restriction on vehicle behaviour. The damping parameter k_d serves to limit undesired oscillations of the nose wheel (e.g. shimmy) and possible excessive yaw oscillations of the caravan.

The tyre forces are described by the Magic Formula (MF) model:

$$F_{yi} = \mu.F_{zi}.\mu_{yi}.\sin(C_i.\arctan(B_i.\alpha_i - \\ - E_i(B_i\alpha_i - \arctan(B_i.\alpha_i)))) \quad (7)$$

with road friction μ, axle load F_{zi}, slip angle α_I and MF-parameters μ_{yi} (normalised tyre force), B_i, C_i and E_i all depending on F_{zi}. We neglected horizontal and vertical shifts in (7).

We have carried out a large number of tests for various speeds and payload configurations, including lane changes, impulse response tests, step-steer response tests and braking in a turn.

The tests have been carried out for the caravan prototype as shown in fig. 1, with a chassis which appeared to be rather flexible. The total mass for the unloaded caravan in the test was 480 kg, a large part of which (over 120 kg) could be attributed to the nose wheel and the nose wheel support structure. As a consequence, the caravan COG is located quite some distance away from the rear axle, increasing the reaction force F_v between car and caravan. A future improved design should allow for further mass reduction and therefore also a better control on the value of d. The nose wheel was connected to the caravan chassis with two shock absorbers, corresponding to a rotational damping value k_d = 277 Nms. No springs were applied (c_d = 0 Nm) during the tests. Three payload positions were considered during testing, at 2, 3 and 4 meter from the front edge of the caravan prototype.

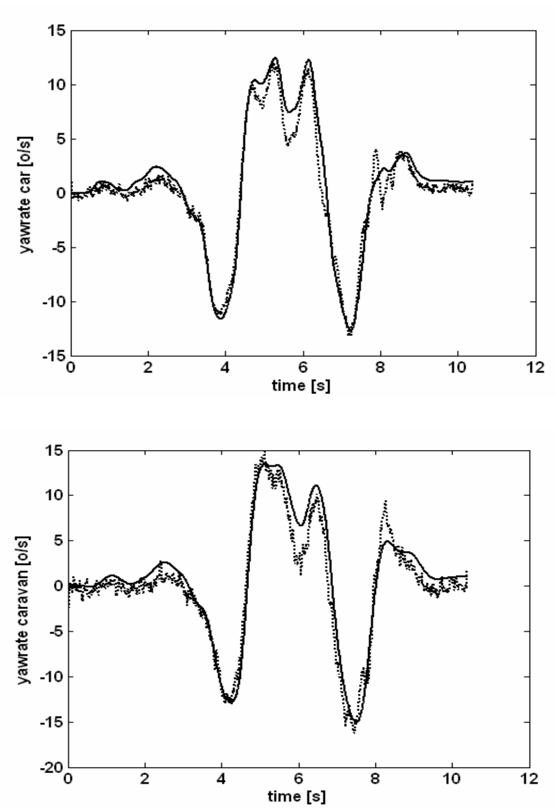

Fig. 4.: Yaw rate results, simulation vs. experiments.

The validation of the model depends critically on the choice of MF-parameters and therefore also on the road- and weather conditions. Part of the experiments was carried out just following a period of rain and snow. In addition, the front tyres of the towing vehicle (a Mercedes C180 Combi) showed a strongly unsymmetrical wear pattern. For these reasons, a 30 % lower friction level was assumed plus a vehicle front axle normalised cornering stiffness being 40 % lower than the vehicle rear axle normalised cornering stiffness, in order to match experiments with the model. It is assumed that the asymmetric wear pattern of the front tyres affects the tyre performance, especially for small tyre loads, suggesting a lower axle stiffness taking into account the load transfer between left and right tyres during manoeuvring. Some results (yawrate for towing car and caravan) as obtained using the model and from the experiments are shown in figures 4 for a lane change with about 85 km/h vehicle speed and with a payload of 768 kg located at the centre position. The investigations in the remaining part of this paper are carried out for the same friction level (0.9) at all axles, plus a more realistic normalised cornering stiffness of the vehicle front axle (about 30 % less then the vehicle rear axle stiffness). The additional payload has been shifted slightly rearward (0.5 meter) out of the centre of the caravan. We shall refer to this situation as the reference configuration.

4. COMPARISON WITH A CONVENTIONAL CARAVAN

Let us first consider the steady state performance of the Lusaro caravan for a fixed lateral acceleration and vehicle speed. For this analysis, linear axle characteristics are chosen, with the cornering stiffnesses based on the nonlinear MF-descriptions. With the other loading conditions and damping value k_d unchanged, we have calculated the steady state normalised axle forces (lateral friction coefficient μ_{yi}) for varying stiffness value c_d, see fig. 5. The vehicle is thereby driving at 100 km/h with a lateral acceleration of 0.6 g. At the left side of the figure, the nose wheel is free to rotate and will not transfer any tyre force to the road. In this case, the rear caravan axle force corresponds to a yaw moment, acting around the caravan COG. This has to be balanced by the lateral reaction force acting at the coupling point, leading to an increased lateral force at the car rear axle.

As a consequence, large values of the normalised axle forces at the rear axles (2, 4) are obtained (compared to the latac-value of 0.6, also being the normalised axle force value for a conventional central trailer caravan). This indicates friction limits to be exceeded at the vehicle or caravan rear axle for low lateral acceleration, depending on the steady state axle slip angles.

These slip angles are shown in fig. 6, showing that the rear axle side force is likely the first axle force to saturate, due to large slip. In addition, the reaction force leads to an increased yaw motion of the leading vehicle, reinforcing the vehicle yaw response. Hence, the yaw gain is increased compared to a conventional caravan. To be more specific, for a conventional caravan one finds δ_1 = 2.00° whereas for the Lusaro caravan, one finds δ_1 = 0.95°. The steering angle at the nose wheel was found to be δ_2 = -2.71°. The minus sign indicates the nose wheel to follow the local lateral speed orientation.

With increasing c_d, a lateral force is built up at the nose wheel, reducing the axle forces of axles 2 and 4. At the right side of the figure, the rear axle normalised forces are still slightly larger then the conventional caravan value. The slip angle α_4 is reduced. Consequently, increasing c_d is expected to lead to a reduction of he risk of skidding.

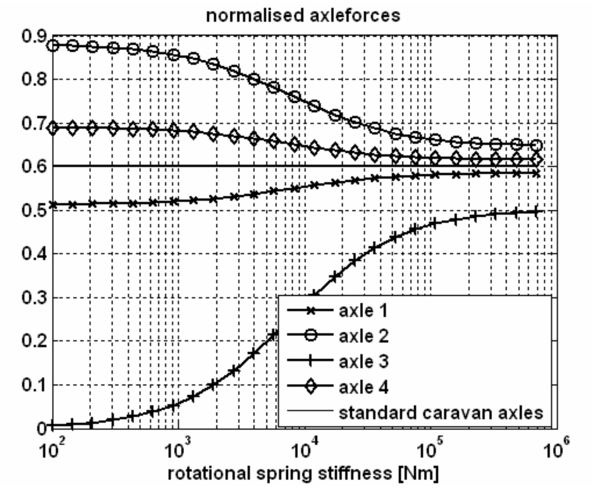

Fig. 5.: Normalised axle forces under steady state conditions, for varying rotational spring stiffness, linearised model.

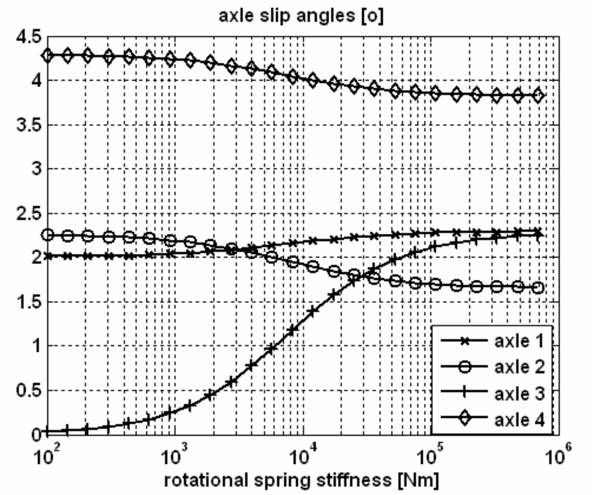

Fig. 6.: Axle slip angles for varying rotational spring stiffness, linearised model

In order to investigate this effect for the case of realistic nonlinear axle characteristics, we have carried out ramp steer response analyses for both the Lusaro caravan (with rotational spring stiffness $c_d = 10^4$ [Nm]) and a conventional caravan with COG located above the caravan axle and with the same payload (distributed equally along the caravan), but with the nose wheel mass neglected. Both analyses have been performed for a steady state lateral acceleration of 0.5 g. and vehicle speed of 80 km/h. In fig. 7 we have depicted the slip angles at the different axles for both cases. From these figures, it is clear that the conventional caravan shows larger average slip angles at the caravan rear angle, as well as significant oscillations leading to overshoot of these slip angles, well in the nonlinear range. We conclude that the Lusaro caravan improves the car-caravan performance.

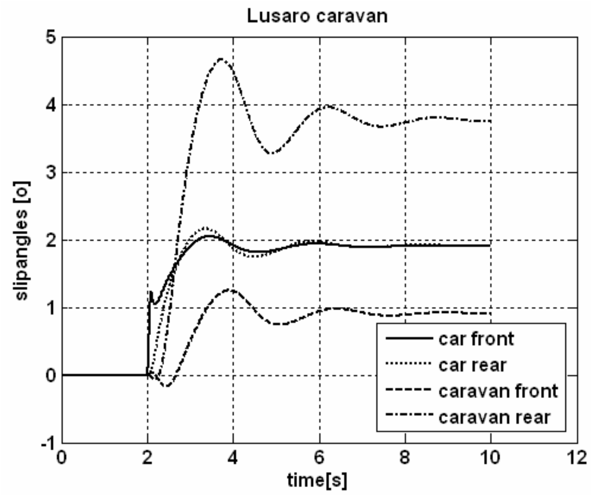

Fig. 7.:Axle slip angles, Lusaro caravan.

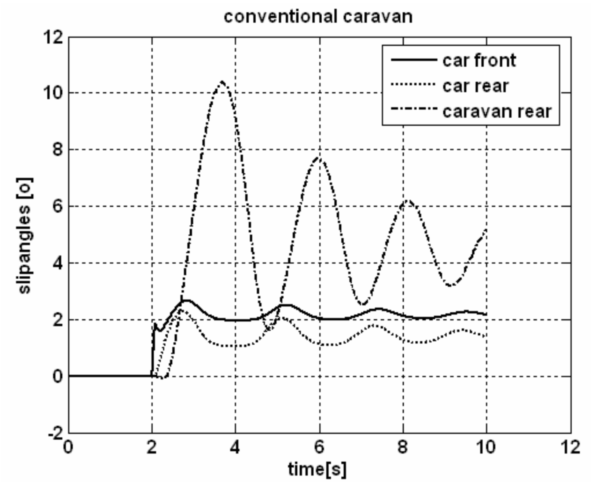

Fig. 8.: Axle slip angles, conventional caravan.

We have carried out some further investigations for varying parameters of the Lusaro caravan.

(i) Reduction of the payload with 400 kg (leading to a total caravan mass of 848 kg, and different position of the COG) leads to a maximum slip angle at the caravan rear axle of 2.7^o (instead of 3.7^o in fig. 7), and almost complete absence of the caravan oscillations following the step steer input.
(ii) Increasing the rotational spring stiffness with a factor 10 (i.e. the nose wheel is almost fixed at zero steering angle), the maximum slip angle is slightly reduced to 3.6^o, but it shows a much stronger oscillation (reduced damping).
(iii) We have reduced the axle stiffnesses C_{yi} for each of the axles separately with 25 %, and considered the caravan rear axle slip angle as well as the type of performance (oscillatory, or a small overshoot only). The results are summarized in table 1.

The results in table 1 indicate that especially for a reduced cornering stiffness at the caravan rear axle, saturation of the axle force is reached earlier, compared to the reference case.

	δ_1 (°)	α_4 (°)	Oscillations
Reference	1.6	3.7	Strong
C_{y1} reduced	2.2	3.8	Strong
C_{y2} reduced	0.9	3.8	No
C_{y3} reduced	1.4	3.8	No
C_{y4} reduced	1.8	4.8	Very strong

Table 1.: Ramp steer results with 25 % reduced axle stiffnesses

In all other cases, the design is robust with respect to variation in tyre cornering stiffness, at least as far as cornering potential of the vehicle combination is concerned. Reducing the cornering stiffnesses of the intermediate axles (2, 3) leads to almost absence of the oscillatory behaviour following the ramp input. Apparently, these lower stiffnesses lead to more interaction in lateral behaviour between caravan and towing vehicle, allowing the caravan to follow the smoother vehicle response more compared to the other two cases.

5. SHIMMY

For certain conditions, such as for low speed in order to guarantee manoeuvrability, the nose wheel is free to rotate, and therefore might show shimmy oscillations.

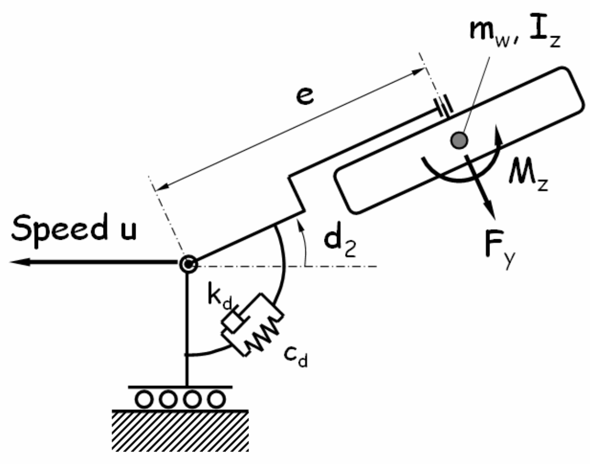

Fig. 9.: Model for shimmy analysis

This suggests that some divergent instability might occur for this new type of caravan. To analyse this, we have determined the eigenvalues of the vehicle model, for linearised axle characteristics.

To investigate this phenomenon, we have used the simplified approach as treated in [4], leading to conservative results according to Besselink [1] and based on a model as shown in fig. 9 (trailing wheel system). The tyre in fig. 9 is modelled through the intersecting contact line of the deformed wheel centre plane with the road plane, based on the straight tangent approximation. Shimmy analysis requires tyre data such as half the contact length, moment of inertia, mass, pneumatic trail. These data have been estimated on the basis of data given by [1] and [7]. The mechanical trail is given by e = 0.2 m

Results of the shimmy stability analysis according to [4] are shown in fig. 10 for different values of the damping value k_d [Nms]. Dark parts of the four diagrams are related to instability. Hence, shimmy stability is guaranteed for our choice of k_d = 277 Nms.

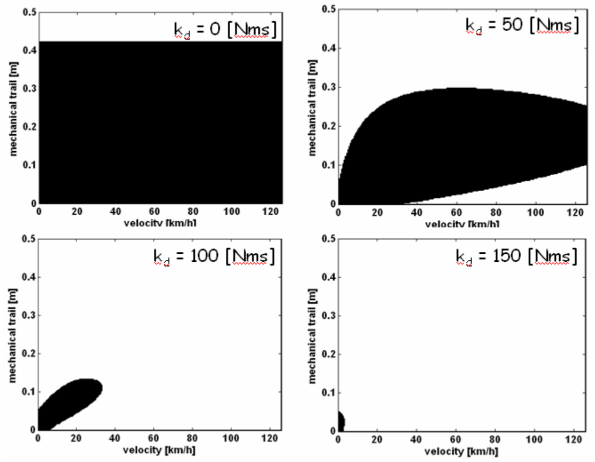

Fig. 10.: Areas of instability for the wheel system of fig. 9.

6. ANALYSIS OF LINEAR STABILITY

We finally discuss potential yaw instability of the Lusaro caravan, which may be expected in correspondence to a conventional caravan. It is known that a conventional caravan will become oscillatory unstable for sufficiently large vehicle velocity. We refer to ISO 9815 for a description of the lateral stability test to analyse this stability for passenger car and trailer combinations. According to Pacejka [4], a second divergent type of instability may occur if the portion of the weight of the caravan carried by the coupling point becomes too large. This additional weight leads to less understeer (or more oversteer) of the towing vehicle. For a free rotating nose wheel, we have observed before that the Lusaro caravan design results into an additional sideforce acting on the towing vehicle rear axle, i.e. to more oversteer as well..

Note that the stability results in this section not fully explain the time history results of section 4, with the axle performance for the caravan rear axle being close to saturation limits. It gives an interpretation of our findings, especially concerning the sensitivity with respect to towing vehicle and caravan parameters.

For our reference vehicle-caravan combination (no rotational stiffness at the nose wheel), the areas of instability are shown in fig. 11, for varying velocity and position of caravan cog with respect to the rear axle. The distance between nose wheel and rear axle is kept constant at 3.54 m. The black area indicates oscillatory instability and the gray area is related to divergent instability. The first type of instability occurs if the caravan COG is located close to the position of the rear axle when the nose wheel and coupling point are almost unloaded vertically. Hence, this situation can be interpreted as the case of a conventional caravan of which we know that oscillatory instability will occur for high speed.

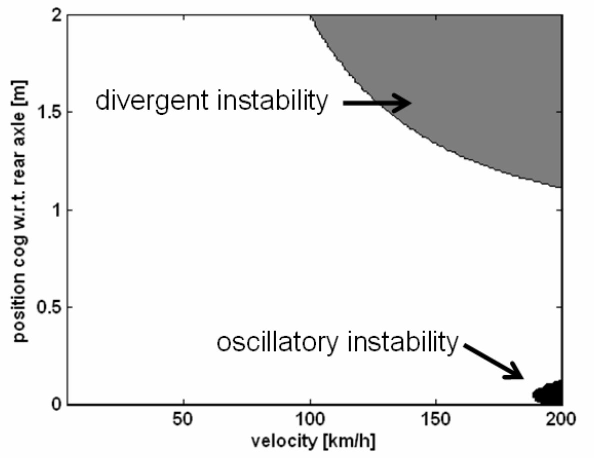

Fig. 11.: Areas of instability for the vehicle-caravan system

It appears that there is a region for d between 0.2 and 1.1 meter where stability (at least for the linearised vehicle-caravan system) is guaranteed. With the COG too far in front of the rear axle, divergent instability occurs. This means that loading of the caravan too much to the front should be avoided, just as a too heavy nose wheel (including the support structure).
With increased rotational stiffness value c_d, the divergent instability area disappears and the areas of oscillatory instability increase.

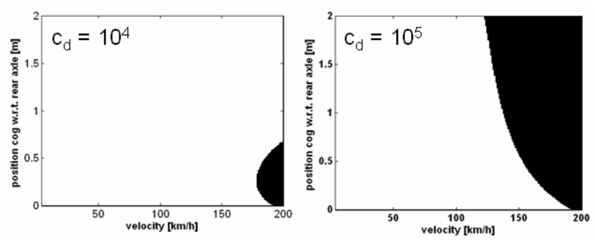

Fig. 12.: Areas of instability of different values of c_d.

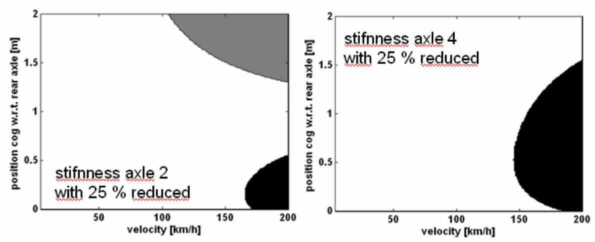

Fig. 13.: Areas of instability for adjusted axle stiffnesses, $c_d = 10^4$ Nm

Please remember our earlier observation that increasing c_d results in stronger (less damped) oscillations in axle slip angles, following a step-steer response. Comparing fig. 12 with fig. 11, one may conclude that the risk of divergent instability is cancelled, at the cost of a slight increase of the risk of oscillatory instability.
We have also considered the impact of reduced axle cornering stiffness on the linear stability. For axles 1 and 3, this results in improved stability. It also means that the prototype being used for experiments was relatively stable. The linear stability consequences for reduced cornering stiffness of axle 2 and 4 are shown in fig. 15. In both cases, the area of oscillatory instability has increased, especially for reduced caravan rear axle stiffness, confirming the results of table 1.

7. CONCLUDING REMARKS

We have discussed a caravan chassis consisting of a single nose wheel at the front and a rear axle such that no vertical load transfer exists between both articulations. The nose wheel may be controlled in steering using a steering damper and/or a rotational spring stiffness between nose wheel and chassis.
This two-axle caravan shows improved cornering response compared to a conventional caravan, in case the nose wheel is connected to the chassis with a rotational spring. Depending on the position of the caravan COG with respect to both axles, stability may be improved as well, where both oscillatory and divergent instabilities should be taken into account. With a small distance between COG and caravan rear axle, oscillatory instability may occur (similar to the conventional caravan). A very large distance may lead to divergent instability. Yaw stability depends strongly on the rear axle cornering stiffness of both vehicle and caravan. The rotational spring stiffness between nose wheel and caravan chassis should not be chosen too high, in order to prevent oscillatory instability, and not too small in order to prevent divergent instability. Wheel shimmy can be avoided by adding a steering damper. Summarizing, the Lusaro caravan shows better safety properties than the conventional centre axle caravan, and may be considered as a promising step towards a new type of caravan which matches low-speed manoeuvrability with high-speed safety and stability

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