VALIDATION OF A SEMI-TRAILER STEERING MODEL

Brian Jujnovich and David Cebon

University of Cambridge, Transportation Research Group
Trumpington St, Cambridge, CB2 1PZ, UK.

ABSTRACT

A 5-axle articulated vehicle, consisting of a 2-axle tractor unit and a pivotal bogie steering trailer, was subjected to a number of prescribed manoeuvres at low and high speed. The test data is compared to predictions made with a yaw-roll model of the vehicle. The performance of the trailer steering system during high and low speed manoeuvres is quantified and compared to predictions from a previous theoretical study. Conclusions are drawn about the effectiveness of the bogie steering strategy. Finally, planned future research into active trailer steering systems is outlined.

INTRODUCTION

Cambridge University's Transportation Research Group is currently undertaking research into active steering of articulated heavy vehicles. The aim of the research is to determine how active steering of the tractor and trailer wheels can improve articulated vehicle performance. The aim is to develop safer and more efficient vehicles to cope with the ever-increasing demand placed on road transport. The work is supported by the Cambridge Vehicle Dynamics Consortium (CVDC), a collaboration between Cambridge University and major industrial companies in the heavy vehicles sector (CVDC, 2003).

At the 7th International Symposium on Heavy Vehicles Weights and Dimensions in Delft, 2002 the group presented a comparison of the theoretical performance of passive semi-trailer steering systems (Jujnovich and Cebon, 2002). The study used a yaw-roll simulation model to determine how such steering systems perform under a variety of operating conditions. The study drew conclusions regarding the performance of passive semi-trailer steering systems; most notably that while they improve low speed performance they tend to degrade high speed performance.

To validate the computer model used in the above-mentioned study and verify the findings of the theoretical study, a series of vehicle tests were performed during 2003. Tests were performed on an instrumented vehicle comprising a 2-axle tractor unit and a pivotal bogie steering trailer; one of the steering systems investigated in the previous study. The tests included three high and low speed manoeuvres with the trailer bogie steering system in both locked and steering modes. This allowed the effect of the steering system to be quantified. Additional tests were conducted to determine parameters required for the simulation model. The same tests were then simulated with the updated vehicle model.

This paper presents details of the semi-trailer steering model validation exercise. Conclusions are drawn regarding both the validity of the vehicle model and the findings of the theoretical study.

VEHICLE TEST METHODOLOGY

Test vehicle

The test vehicle consisted of a 2-axle tractor unit coupled to a pivotal bogie steering trailer, as shown in Figure 1.

The test tractor was the CVDC's Volvo FH-12 tractor. This vehicle unit is fitted with a variety of sensors and a logging system to record test results. The test trailer was a 16m long tri-axle trailer, fitted with a novel rear pivotal bogie designed and built by Silvertip Design in conjunction with Don-Bur (Henderson, 2001). The pivotal bogie assembly replaces the usual fixed-axle trailer group. The bogie is mounted on a ballrace and, when unlocked, it can yaw freely relative to the chassis. The middle and rear axles of the bogie steer in fixed

Proceedings 8th International Symposium on Heavy Vehicle Weights and Dimensions
'Loads, Roads and the Information Highway'
Proceedings Produced by: Document Transformation Technologies
14th - 18th March, Johannesburg, South Africa
ISBN Number: 1-920-01730-5
Conference Organised by: Conference Planners

ratios relative to the bogie frame (see Figure 1). Further details of the steering mechanism are given in Henderson (2001).

Figure 1. The test vehicle.

By steering the whole tri-axle group the pivotal bogie system is able to minimise lateral scrubbing of the tyres in low speed corners and greatly reduce the effective wheelbase of the semi-trailer. For such a system the effective wheelbase is approximately half of the actual wheelbase, allowing it to track much better than a fixed axle trailer of the same length (Jujnovich, and Cebon, 2002). The 16m Don-Bur trailer was designed to corner within the spatial envelope usually occupied by a conventional 13.6m non-steering trailer.

The trailer incorporates a locking system that is usually used to prevent steering whilst reversing. During testing this locking system was used to simulate a long non-steering trailer. Tests were conducted both with the trailer steering and with the trailer locked. Comparing the two sets of results allowed the effect of just the steering system to be quantified.

The tests were conducted with the trailer laden to full UK legal limits, using water tanks and concrete ballast boxes. The load was distributed to make the yaw moment of inertia equivalent to a uniformly distributed load. The trailer was also fitted with outriggers to prevent rollover of the vehicle during extreme manoeuvres.

Vehicle instrumentation

The CVDC tractor unit is permanently fitted with an array of sensors to determine critical vehicle parameters. The sensors and their locations are shown in Figure 2. Trailer instrumentation is shown in Figure 3.

Digital video cameras were fitted to the front of the tractor cab and the rear of the trailer. They filmed a white line painted on the road surface. The driver attempted to follow this same line. The outputs of the cameras were sent via a ‘firewire’ (IEEE 1394) interface to the global controller computer, where the images were converted into measurements of the lateral position of the front of the tractor and the rear of the trailer, relative to the line. The measurements were corrected to remove the effect of body roll.

Lateral tyre forces are difficult and expensive to measure directly. Instead they were estimated from the measured sideslip angles, steering angles and vertical loads, using the same non-linear tyre model used in the simulations. Sideslip of each wheel was determined from the combined output of the tractor sideslip sensor, trailer yaw/roll trolleys, yaw rate sensors and wheel angle sensors.

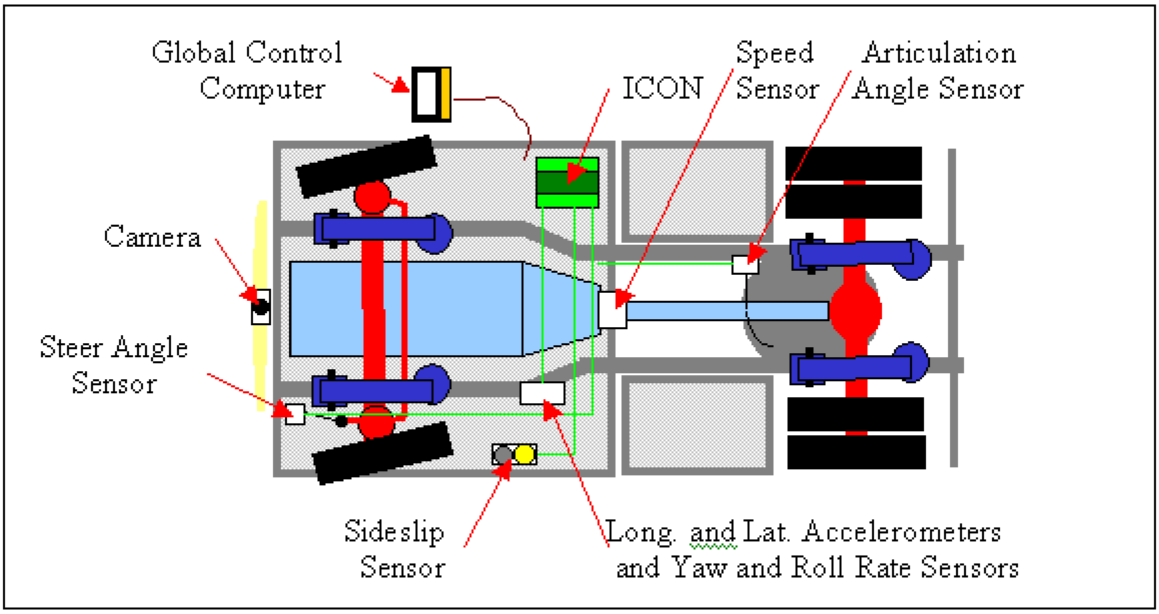


Figure 2. Plan view of tractor unit showing instrumentation.

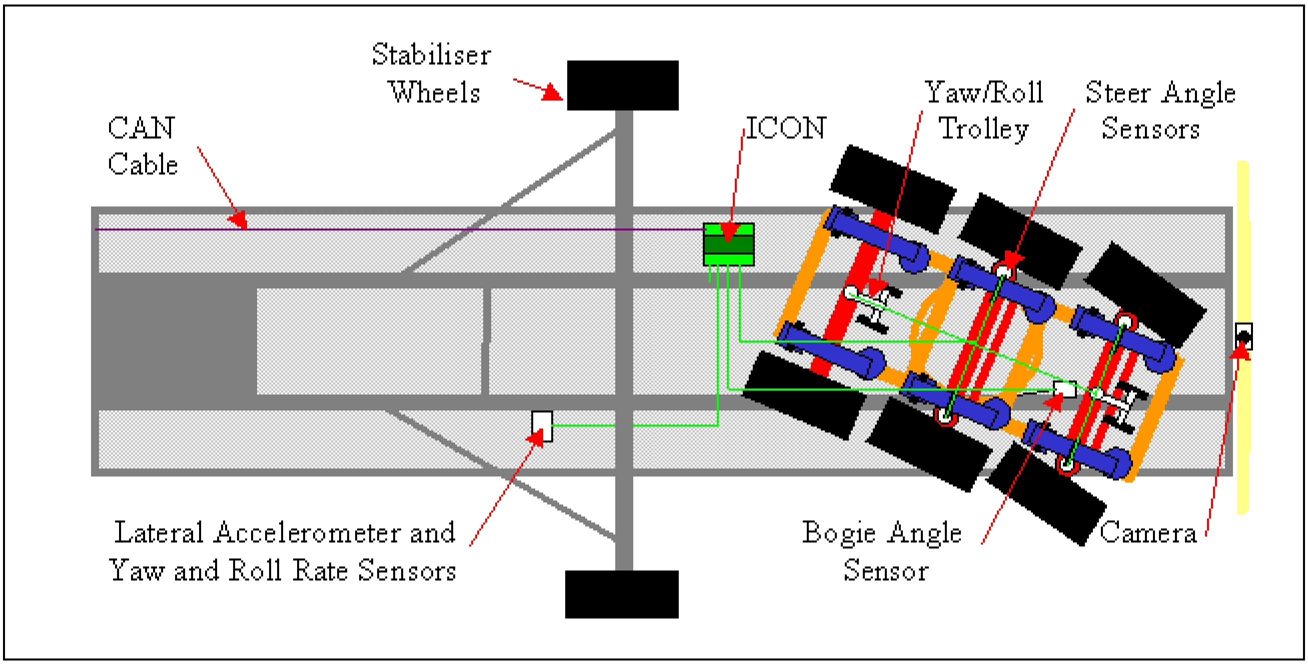


Figure 3. Plan view of trailer unit showing steering bogie and instrumentation.

All data was collected by a distributed logging system. Sensor outputs were logged by two ICON industrial computers – one on the tractor and one on the trailer. These filtered, digitised and processed the signals, before transmitting them via the vehicle's CAN network to a central 'global controller' computer, located in the tractor unit. The global controller stored the data for each run and was also used to control the logging and synchronise the data from the tractor, trailer and cameras. Further details of the logging system can be found in Jeppesen (2002).

Vehicle test procedure

Vehicle testing was conducted at the Motor Industry Research Association (MIRA) proving ground in Nuneaton, England between January and March 2003. The vehicle was subjected to three separate manoeuvres: a 90-degree corner, a steady state circle and a lane change. Different performance measures were derived from each of the tests. The manoeuvres and corresponding performance measures are outlined in Table 1. Further information about the manoeuvres are given in Jujnovich and Cebon (2002), SAE (2000) and Prem (2001).

Table 1. Manoeuvres.

MANOEUVRE	DESCRIPTION	PERFORMANCE MEASURES
Low-Speed 90º Corner	Centre of tractor steer axle follows a path with straight approaches to an 11.25 m radius 90º circular arc. Vehicle speed 10 km/h.	Lateral Tyre Forces Low-Speed Offtracking Tail Swing
Handling Test	Centre of tractor steer axle follows a circular path of radius 33 m. Vehicle speed slowly increased from 0 km/h to wheel lift speed.	Handling Quality Static Rollover Threshold
High-Speed Lane Change	Centre of the tractor axle follows a sinusoidal lane change path, with a 1.464m offset in 61m (see SAE J2179 2000). Vehicle speed 88 km/h.	High Speed Offtracking Lateral Acceleration

Each test was repeated five times for the trailer in both the locked and unlocked conditions.

SIMULATION MODEL

Model overview

In order to compare the performance of the various steering systems a roll-yaw model of the whole test vehicle was developed in Simulink. Details of the model are provided in Jujnovich and Cebon (2002). The equations of motion for the system are similar to those used in the UMTRI constant velocity yaw-roll model (Gillespie and MacAdam, 1982). Some changes were made to the model to account for system imperfections that were discovered in the testing programme.

The main difference between this model and a conventional articulated vehicle model is the way in which the semi-trailer axle group is modelled. In this model the axles are steerable and connected to a ballrace-mounted bogie assembly, which can yaw relative to the trailer body.

The steering input to the trailer axles can be varied to suit the type of steering system being modelled. For a fixed axle system the steering input is zero and the axles and bogie are locked. For a pivotal bogie system the steering input is the bogie articulation angle, multiplied by the lever ratio of the linkages, and the bogie is free to rotate. Thus by choosing the steering input and locking or releasing the bogie the steering systems investigated in this paper can be modelled.

Self-steering and command-steering systems can also be simulated with this model. See Jujnovich and Cebon (2002) for further details.

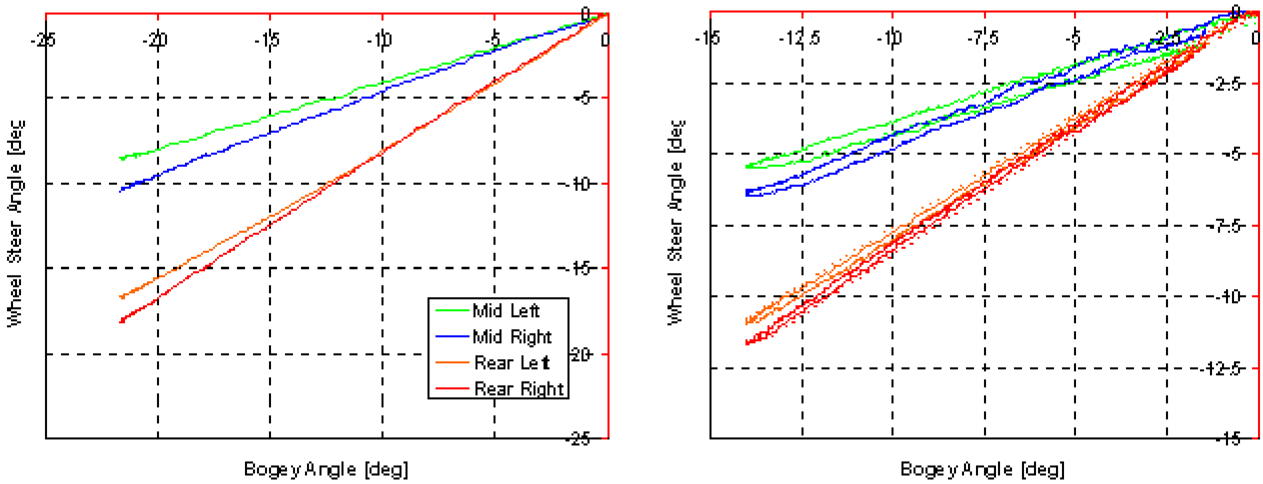
Model parameters

To model the particular vehicle used in the tests, the main vehicle parameters first needed to be determined. Dimensional parameters, such as the wheelbase, rear overhang, track, axle spread and spring spacing were measured from the vehicle. The laden weight and axle loads were measured on a static weigh bridge. These were combined with a materials takeoff to determine the required inertias of the tractor and trailer. Spring stiffnesses, damping rates and chassis compliance values were obtained from manufacturers' data or previous tests on the vehicle. Tyre parameters were estimated from tyre test data provided by the manufacturer whilst the coefficient of friction between the tyre and road was chosen based on the road surface and weather conditions.

One set of parameters that required careful measurement were the bogey to trailer wheel steering ratios. The ratios were determined by lifting the bogie clear of the ground and rotating it whilst simultaneously measuring the bogie and wheel angles. A graph of wheel angles vs. bogie angle is shown in Figure 4a. This data was used to determine the relevant steering ratios.

Any backlash in the trailer steering system affects the steering ratios achieved during normal operation. To determine the amount of steering system backlash dynamic steering tests were performed. The truck was driven down a road and weaved from side to side whilst recording the bogie and wheel angles. The results, presented in Figure 4b, show different steering ratios for clockwise and anticlockwise rotation as expected for a system with backlash. This backlash was modelled in the simulation program using a standard Simulink "backlash" block.

In addition to the backlash in the steering system a small amount of play was found in the bogie locking mechanism. On the trailer the bogie was locked by engaging two parallel pins between the chassis and bogie. It was found that even with the pins engaged the bogie could rotate a few degrees.



a) Static Steering Ratios

b) Dynamic Steering Ratios

Figure 4. Bogie steering behaviour.

To account for this play, the simulated bogie was allowed to steer a limited amount in locked mode (instead of being completely locked). Changing from locked to steering mode was achieved simply by removing these steering limits

Under certain conditions the bogie was found to contact a rubbing block on the trailer chassis. To model this effect dry friction between the bogie and chassis was included in the simulation model. The vertical load and coefficient of friction for the rubbing block were estimated.

COMPARISON BETWEEN TEST AND SIMULATION RESULTS

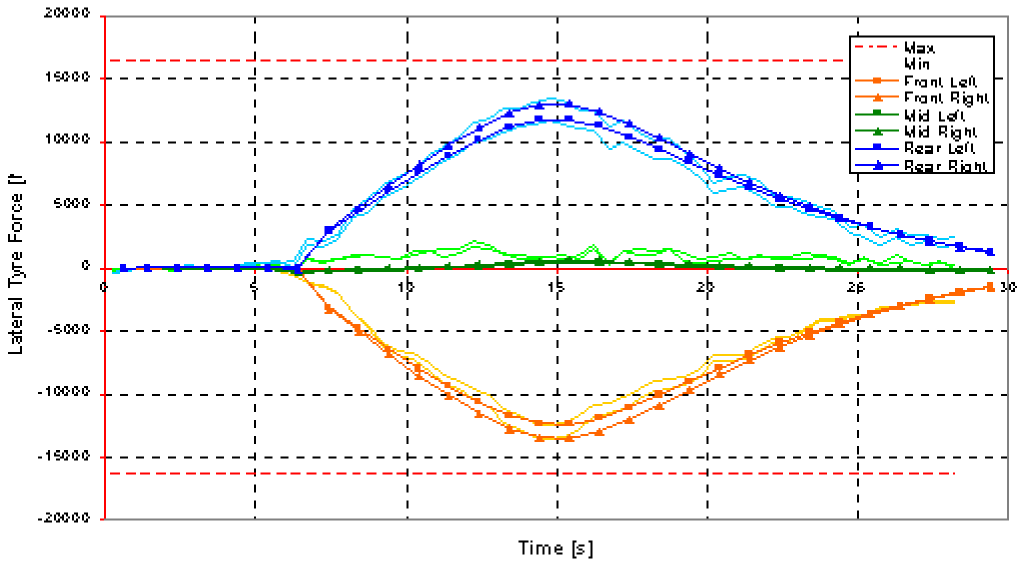
Low speed 90° corner

A low speed cornering test was used to determine lateral tyre forces, offtracking and tail swing. High lateral tyre forces during low speed manoeuvres are of concern since they can lead to severe contact patch deformation and scrubbing. This can reduce the life of the tyre and damage the road surface.

Graphs of the lateral tyre forces in the locked and steering modes are shown in Figures 5 and 6 respectively. The darker simulation results are shown overlaying the lighter test results. The simulation results were output from the simulation model whilst the test results were estimated from the measured body sideslip angles, steering angles and vertical loads, using the same non-linear tyre model. Comparison of tyre forces in this manner is analogous to comparing sideslip. However it is much easier to interpret and gives an indication of the magnitude of the forces involved relative to the maximum possible.

The lateral forces from the simulation model were found to compare favourably with the test results. This indicates that the tyre model and parameters used in the simulation were accurate, even at relatively high levels of side slip.

Both the simulation and test results show that when the steering system is locked (Figure 5) the front and rear trailer axles are subjected to very large lateral tyre forces. These forces approach the maximum possible friction force (shown as dashed horizontal lines in the figures). The large forces are due to the front and rear axles' lateral forces opposing one another throughout the turn.



Note: Dashed red lines indicate force generated when the tyre's contact patch is fully sliding

Figure 5. Locked trailer lateral tyre forces- cornering.

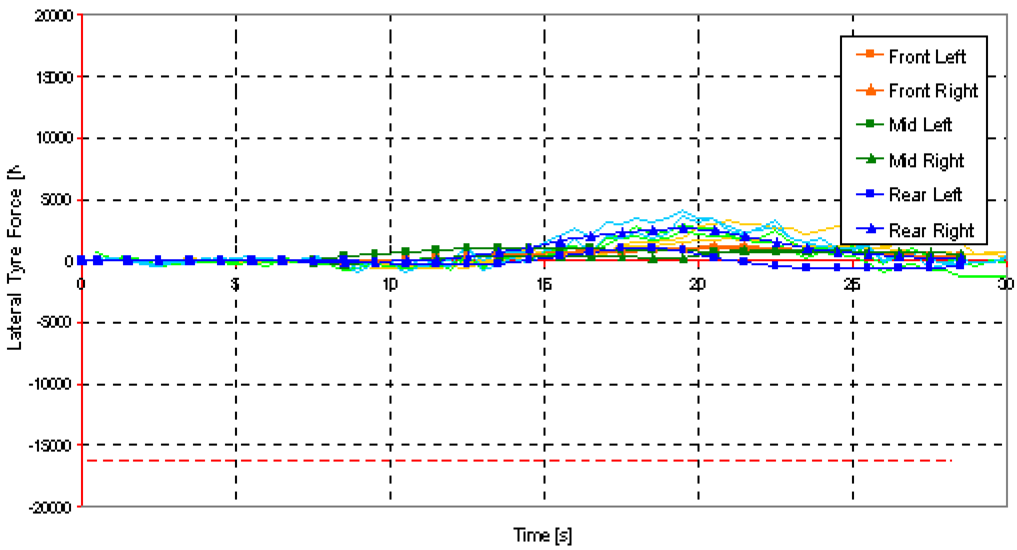


Figure 6. Steering trailer lateral tyre forces- cornering.

Figure 6 shows the lateral tyre forces with the trailer bogie allowed to steer. Both the simulation and test results show that the forces are much lower and more evenly shared between wheels than when the steering is locked. The reduction in lateral tyre forces is a result of the steering system directing each wheel so that its normal approximately passes through the centre of the turn. This reduction in lateral tyre forces at low speeds is one of the main advantages of this particular passive trailer steering system.

The path tracking performance was measured during the tests using the camera system that recorded the lateral offset of the trailer from the desired path. This was compared to the lateral offset determined from the simulation program. Figure 7 shows the lateral offset of the trailer in both locked and steering modes. Both the testing and simulation produced similar levels of cut-in and tail swing. This not only helps to validate the steering model but also demonstrates the accuracy of the camera system used on the vehicle.

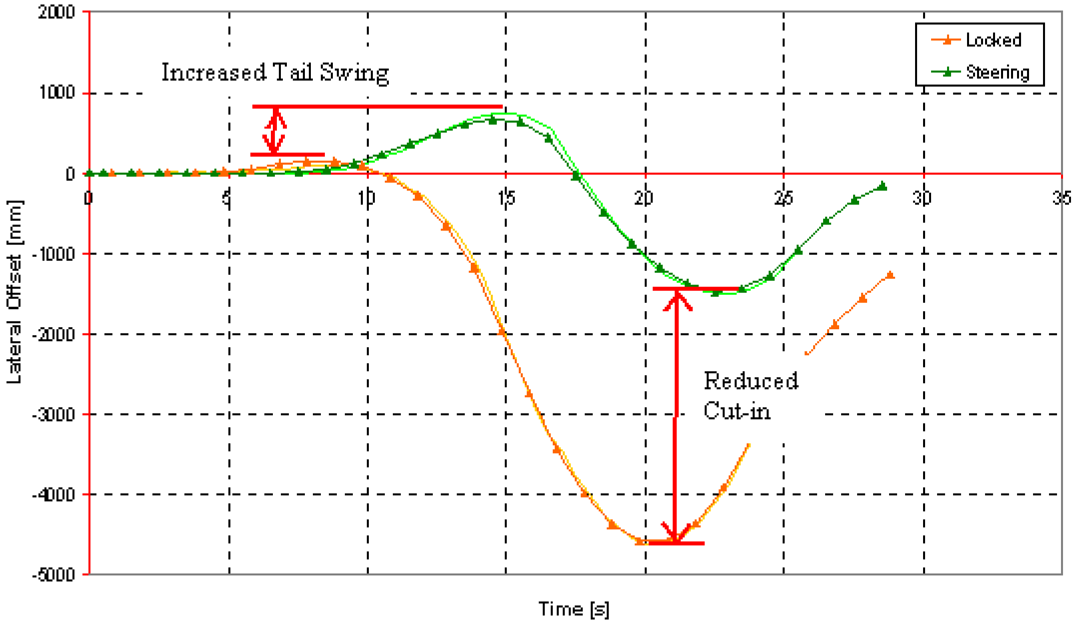


Figure 7. Lateral offset at the rear of the trailer- cornering.

From the graph it is apparent that the steering system is able to greatly reduce the offset of the trailer and hence the vehicle's swept path. The steering system reduced the maximum cut-in of the trailer by approximately 67%. This is a consequence of the steering system reducing the effective length of the vehicle by almost half. Less cut-in is advantageous when operating on narrow or winding roads or when manoeuvring around small roundabouts. Such conditions are typical in the inner city areas of the United Kingdom.

While the steering system was found to improve cut-in, it was found to substantially increase the amount of the tail swing (Figure 7). Increased tail swing can be a major problem since it can lead to the rear of the trailer colliding with curb side objects such as parked cars, pedestrians or lamp posts. The problem is compounded since the outside rear corner of the trailer is in the driver's blind spot during the turn.

The increased tail swing associated with a passive trailer steering system is also a result of reducing the effective length of the vehicle, because this increases the effective rear overhang. The best strategy for avoiding excessive tail swing is to make the actual rear overhang as short as possible, as employed in the design of the trailer tested. This trade off between cut-in and tail swing cannot be avoided in current passive trailer steering systems.

Handing test

The handling test was performed by driving the test vehicle in a 33m circle and slowly increasing the speed up to the point of wheel lift. Unfortunately due to rain, the test was conducted on a wet track which reduced the available coefficient of friction. The coefficient of friction used in the model was adjusted accordingly. Due to the rain the results are not typical of normal dry road operation. However, they can still be used to compare the performance of the steering trailer to a fixed trailer and verify the accuracy of the simulation model.

Figures 8 and 9 show the variation in the lateral forces generated by the left (outer) tyres of the three trailer axles, with the trailer steering system locked and free to steer respectively. When locked (Figure 8), the simulation model produced similar forces to the tests. When free to steer (Figure 9), the simulated forces were slightly overestimated but still of acceptable accuracy.

At low speeds both sets of results agreed well with those from the cornering tests. In the locked mode (Figure 8) the tyre forces were large due to wheels opposing one another while in the unlocked mode (Figure 9) the forces were fairly equal.

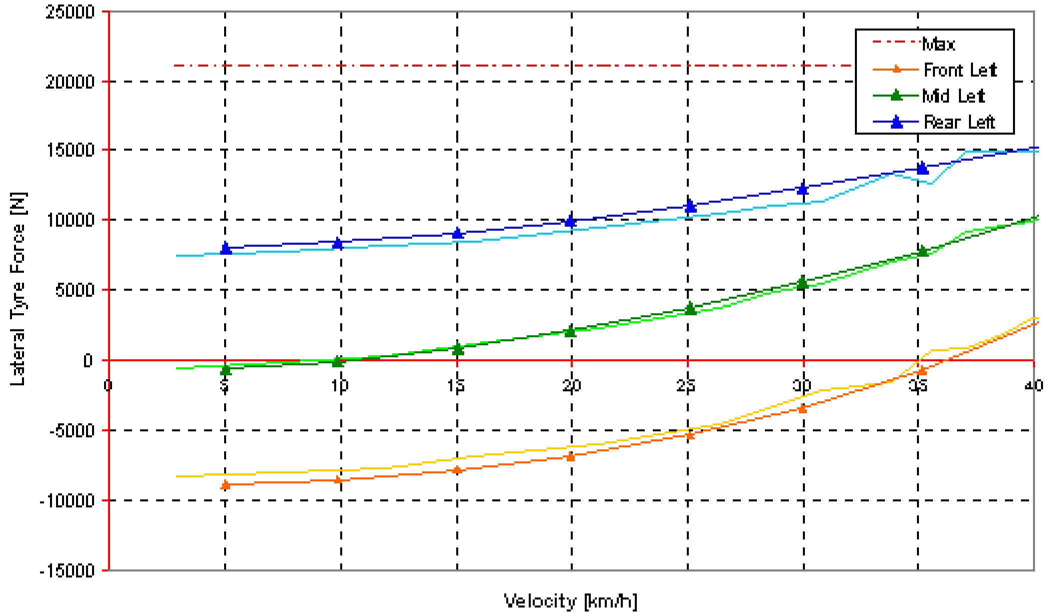


Figure 8. Lateral tyre forces on the three outer trailer tyres, handling test, locked steering.

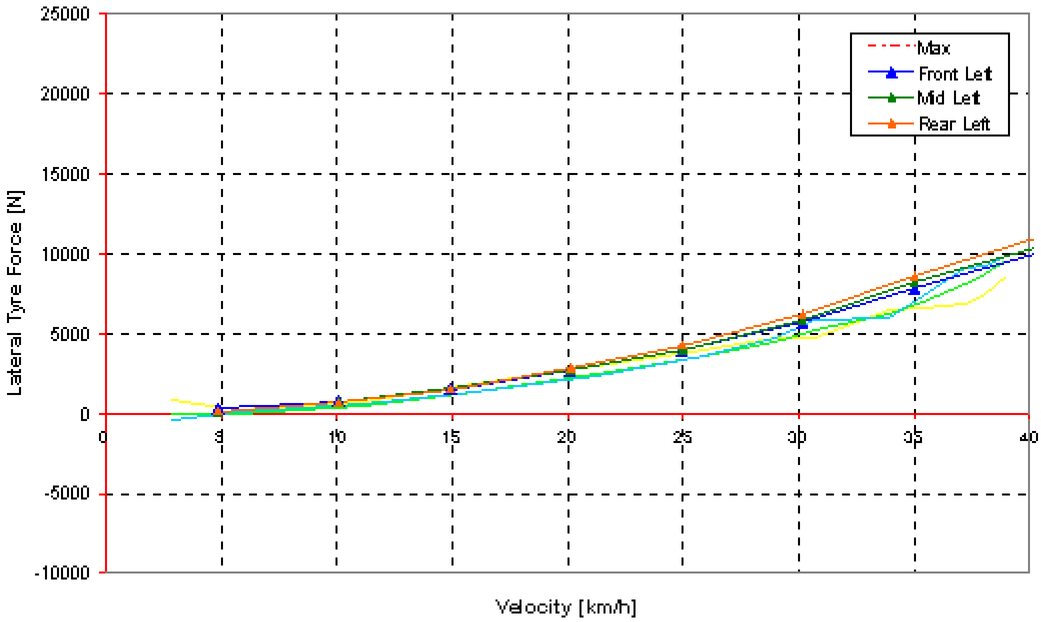


Figure 9. Lateral tyre forces on the three outer trailer tyres, handling test, free steering.

As the speed increases the wheels need to generate more centripetal force to counteract the lateral acceleration of the vehicle. This results in higher lateral tyre forces. Both the locked and steering modes showed a similar parabolic rate of increase of force (Figures 8 and 9). However, the rear wheels on the locked trailer (Figure 8) were closer to saturating due to the added force opposing the front axle. In locked mode the rear tyre generated 33% more force at 40 km/h than in the unlocked case (Figure 9). In both modes the vehicle began to roll over before full saturation of the tyres occurred, which is typical for a heavy goods vehicle with a high centre of gravity.

Figure 10 shows the variation of the lateral displacement offset of the rear of the trailer with speed in a constant radius circle (measured by the cameras described in section 2.2). The simulated responses are within 100mm of the test results and show a similar trend with speed. In the steering mode the trailer tracked nearly perfectly at low to medium speeds. At higher speeds, however, the trailer began to track outwards of the radius driven by the tractor. By 40km/h, this off-tracking is approximately 1m. This is a consequence of the tyres needing more side slip angle to generate greater lateral forces at higher speeds.

In locked mode the trailer 'cut the corner' by approximately 2.2m at low speed. As speed increased, the radius of the path followed by the trailer wheels increased (and the 'cut-in' reduced) in a similar way to the unlocked axles.

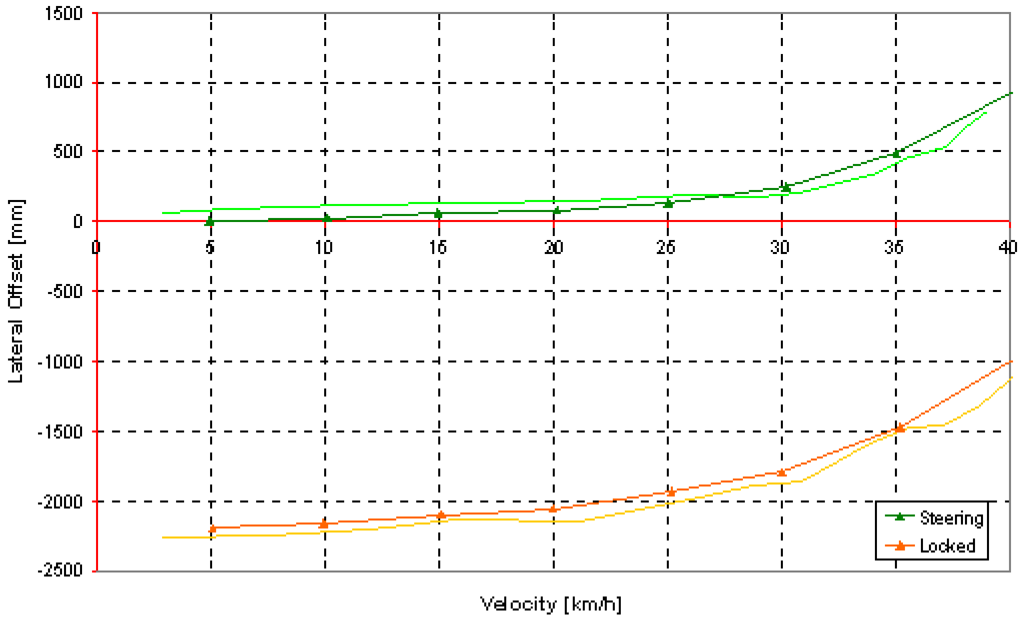


Figure 10. Lateral offset at the rear of the trailer-handling simulation.

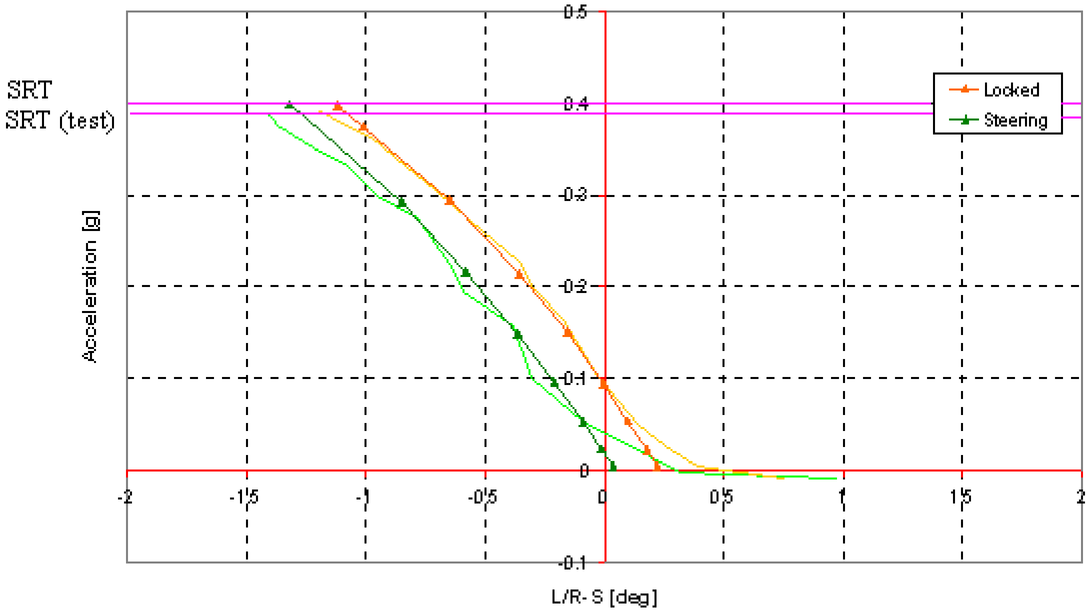


Figure 11. Tractor handling diagram- handling test.

The constant radius handling test also enabled a handling diagram to be constructed for the tractor unit. The handling diagram is often used to characterise the "feel" of the vehicle and how it varies with lateral acceleration. The handling diagram for the locked and steering modes is shown in Figure 11.

The handling diagram shows good correlation between the simulation and test results, except at near zero lateral acceleration. The difference in this region is most likely due to backlash in the tractor steering system that was not included in the simulation model. The general agreement between the test results and simulation indicates that the model correctly included the main non-linearities that influence the handling behaviour. The simulated static rollover threshold (SRT) was also close to the value found through testing.

The locked and unlocked curves have nearly the same gradient, indicating a similar level of understeer. The main difference is that the steering curve is offset to the right of the locked curve, which results from the lateral force applied to the 5th wheel by the trailer. When the steering system is locked, the lateral forces generated by the trailer axles (Figure 8) generate a large yaw moment, which is reacted by the tractor at the fifth wheel. This pushes the rear of the tractor outwards. In the unlocked case, this yawing moment disappears. Consequently, with less lateral force, the tractor cuts in a little more and requires slightly more steering angle to keep the tractor on the path.

The steering system was found to have little effect on the static rollover threshold (SRT) of the vehicle. The vehicle experienced a very similar level of lateral acceleration before wheel lift occurred in both steering modes, as expected.

Lane change

The final manoeuvre performed was an SAE J2179 lane change. This is a very mild lane change at 88 km/h where the vehicle moves 1.464 m laterally in 61 m of travel along the road (SAE, 2000).

Unfortunately, the mildness of the manoeuvre made it difficult to compare the performance of the trailer in locked and steering modes. In the steering mode the manoeuvre did not generate much trailer steering at all. Furthermore, in the locked mode a certain degree of steering was still introduced due to backlash in the locking pins. Hence the difference between steering and locked modes was not as pronounced as initially expected. Nonetheless, the lane change test did allow the transient performance of the steering trailer simulation model to be validated. It also highlighted some important points regarding the high-speed performance of passive trailer steering systems.

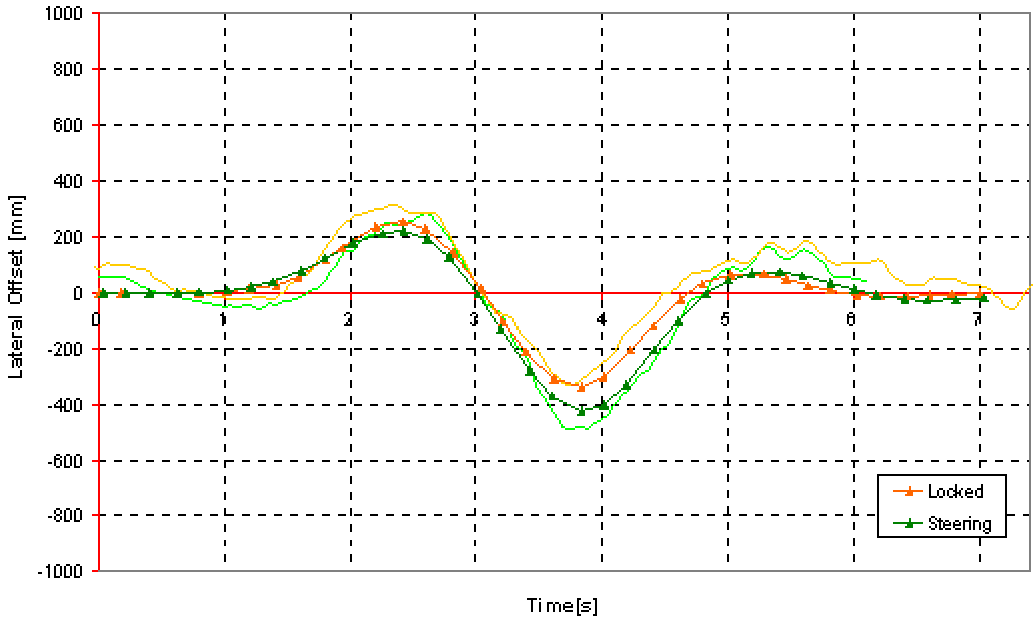


Figure 12. Lateral offset at the rear of the trailer-lane change.

Figure 12 shows the lateral offset of the rear of the trailer in both locked and steering modes. The simulated results follow the test results quite well. There is a small difference at the start and end of the test, most likely due to the driver not quite following the same line as the simulation model on the approach and exit.

In the locked mode the lateral offset was found to be approximately sinusoidal. The trailer cut-in at the start of the lane change, as indicated by the increased positive offset at 2.4s, and overshot at the end, as indicated by the large negative offset at 3.8s. Afterwards the trailer gradually settled into line with the tractor.

Steering the trailer was found to slightly decrease the amount of initial cut-in. The trailer's steering system effectively delayed turning the wheels, allowing the trailer to better track the path of the tractor unit. While this delay helped to reduce the amount of cut-in it increased the amount of overshoot at the end of the manoeuvre by almost 150 mm. Excessive overshoot during a lane change manoeuvre can be a significant problem. In the worst case it can lead to the trailer coming into contact with other vehicles or the crash barrier.

The reason for this behaviour is that the steering system reduces the effective length of the trailer without changing its yaw moment of inertia. The reduced effective length causes the vehicle to track better at low speeds, but it also reduces the yaw moment generated by the tyres at high speeds. This reduces yaw stability.

Figure 13 shows the lateral acceleration of the trailer CG in locked and unlocked modes. Lateral acceleration is important since high levels can lead to vehicle rollover. The ratios of the peak lateral accelerations in locked and unlocked modes is proportional to the ratios of the rearward amplification. A higher lateral acceleration indicates greater rearward amplification.

Again there was good correlation between the test and simulation results. There were slight discrepancies at the initial and final peaks in the curve but these could be due to the driver correcting the steering input to better follow the curve.

From the graph it can be seen that the steering system reduced the magnitude of the first acceleration peak but increased the magnitude of the second acceleration peak. It is the second peak that usually results in vehicle rollover and hence is the more critical. Overall, the steering system increased the rearward amplification of the trailer by 20% making it more susceptible to rollover at high speeds.

A simple way to improve the system's high-speed performance (employed by many passive trailer steering manufacturers) is to lock the steering mechanism at high speed.

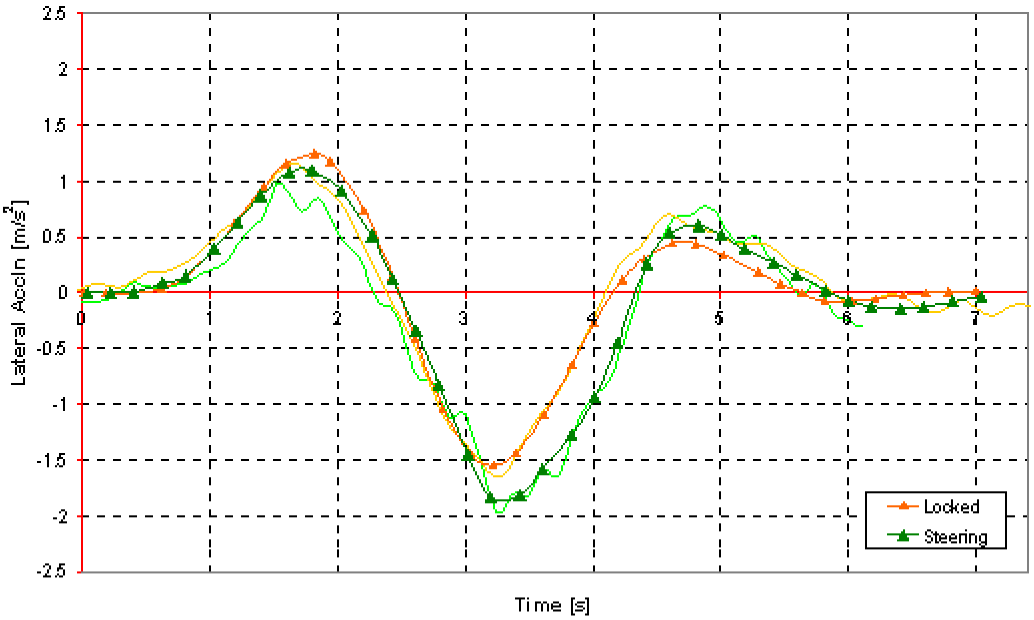


Figure 13. Trailer lateral acceleration- lane change.

The findings above agree well with those from the comparative study of trailer steering systems (Jujnovich and Cebon, 2002). The values of the performance measures are not directly comparable between the two studies, since the comparative study was based on a shorter (13.6m) length trailer. Nonetheless, the results show similar trends and relative changes. The test results therefore both validate the model used in the comparative study and verify the previous study's findings.

CONCLUSIONS

- A pivotal bogie steering trailer was fitted with numerous sensors and subjected to three separate manoeuvres to test the full range of normal vehicle operation, with the steering system both locked and unlocked.

- The parameters of a yaw-roll simulation model were updated with those from the test vehicle and the model was modified to include small non-linear effects that were previously ignored.
- The model results agreed well with the test results in both the high and low speed manoeuvres.
- The test results and simulation both showed that the steering system was generally beneficial to low speed performance. It greatly reduced the amount of cut-in and the lateral tyre forces whilst cornering. However this was at the expense of increased tail swing.
- The results also showed that the steering system was detrimental to high speed performance. It increased high-speed offtracking and led to higher lateral acceleration levels on the trailer.
- The findings agreed well with those published in the theoretical comparative study of semi-trailer steering systems. Hence the test results verify the study's findings.

FURTHER WORK

The comparative study and vehicle tests have illustrated that when using passive trailer steering systems there is a fundamental trade off between high and low speed performance. Such steering systems generally improve low speed performance but reduce high speed performance. This trade off can be avoided by employing an active steering system.

Further work is being done on active steering of articulated vehicles by the Cambridge Vehicle Dynamics Consortium. New steering strategies are being developed which vary the steering ratio and effective length of the vehicle according to its operating conditions. Preliminary simulations of an active steering vehicle have shown that such strategies can improve nearly all areas of high and low speed performance.

To test the active steering strategies a prototype active steering articulated vehicle is under construction by the Consortium. When completed the vehicle will have the ability to steer the tractor drive and trailer axles in addition to the usual front tractor axle. Steering is achieved by individual hydraulic actuators on each axle that are controlled electronically.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the following individuals and organizations for their assistance with this project:
- Silvertip Design and Don-Bur Trailers
- CVDC Members (especially MIRA, Fluid Power Design, Qinetiq, ArvinMeritor and Volvo)
- CVDC Researchers (Frank Kienhofer, Richard Roebuck, Edd Stone and Arnaud Miege)
- CUED Technicians

Brian Jujnovich would also like to thank the Cambridge Commonwealth Trust for funding his postgraduate studies.

At the time of writing, the Cambridge Vehicle Dynamics Consortium has the following industrial members: Tinsley Bridge Ltd, ArvinMeritor, Koni BV, Qinetiq, Shell UK Ltd, Volvo Global Trucks, FM Engineering, Firestone Industrial Products, Haldex Brake Products, MIRA Limited, Mektronika Systems and Fluid Power Design.

REFERENCES

1. Cambridge Vehicle Dynamics Consortium, 2003. "Cambridge Vehicle Dynamics Consortium Homepage". www.cvdc.org.
2. Gillespie, T. D., and MacAdam, C. C., 1982. "Constant Velocity Yaw/Roll Program User's Manual". University of Michigan Transportation Research Institute. Report No. UMTRE-82-39.
3. Henderson, C., 2001. "An Investigation into the Dynamic Stability and Road Friendliness of a Pivotal Bogie Semi-Trailer". MSc Thesis. University of Northumbria.
4. Jeppesen, B. P., 2002. "Enhancing Safety in Active Suspension Systems". PhD Thesis. Cambridge University Engineering Department.

5. Jujnovich, B., and Cebon, D., 2002. "Comparative Performance of Semi-Trailer Steering Systems". Proc. 7th Int. Symp. Heavy Vehicle Weights and Dimensions. Delft, The Netherlands.
6. Prem, H. et al., 2001. "Definition of Potential Performance Measures and Initial Standards". Discussion Paper. National Road Transport Commission, Australia.
7. SAE, 2000. "J2179 : A Test for Evaluating the Rearward Amplification of Multi-Articulated Vehicles". Society of Automotive Engineers.