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MULTI-TRAILERS ON THE ROAD

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ABSTRACT

Cargo transport plays an important role in the Dutch economy. However, congestion is an increasing problem that is resulting in declining accessibility and increasing transport times and costs. To overcome these problems extensive research programmes have been set up. The Delft University of Technology is participating in several related short and long term research projects. This paper focuses on the following topics:

- It is proposed that within the Netherlands rubber tired five-trailer cargo vehicles should be used to transport containers in batches (10 TEU) on dedicated infrastructure or in dedicated lanes of public infrastructure during the quiet night hours. After an uncoupling procedure, the separate trailers could then be used for distribution.
- Dutch conditions (densely populated roads, narrow bends) are structurally different from those other countries where longer and heavier vehicles are used. The road handling of the vehicle has to be suitable for the environment. This means that the vehicle has to possess good manoeuvrability **(**minimal swept path, minimal out swing) as well as good stability at higher operating speeds.
- A multi-body simulation model has been created to study an existing track-following five-trailer vehicle that is used for internal container transport at low speeds (30 km/h) in several ports. To facilitate modification of the model, it has been set up in a parametized modular form. The simulation results have been validated by experiments.
- A relatively simple, speed-dependent steering mechanism seems to provide the desired road handling capacity. Similar mechanisms can be used in all full trailers to improve stability.

INTRODUCTION

The geographical position of the Netherlands has made it the pre-eminent transport nation of Western Europe. The transport and communications sector makes up 8 % of the GNP [5]. Some 60% of the containers moving through Rotterdam (the largest port in Europe) to the hinterland are transported by road [1]. In recent years, however, growing congestion problems have reduced the accessibility of the port of Rotterdam, and therefore threaten its 'mainport' position. As a result of this, several extensive research projects designed to improve the hinterland connections of the port of Rotterdam have been initiated. Delft University of Technology is cooperating in several such projects for both long-term and short-term transport concepts.

When looking for better ways to transport freight it must be remembered that the present large percentage of transport by road results mainly from penetration level and flexibility and from the relatively short transport distances. To facilitate door-to-door delivery, an important factor to remember when investigating alternatives is their degree of integration with the road network. Other criteria to be considered when evaluating alternatives are safety, environmental impact, cost effectiveness, the level of acceptance by society and time needed for their introduction.

The long-term studies involve automated transport systems on dedicated infrastructure (e.g. underground pipelines). A short-term solution is to increase the maximum weight and size of trucks. Experience abroad has shown that the introduction of higher capacity trucks (to replace conventional trucks) has a positive effect on all criteria mentioned above, with the exception of social acceptance.

The situation in the Netherlands is structurally different from that in large countries like Australia or Canada. The Netherlands is densely populated, which results in congested roads, while the existing infrastructure does not provide much space for off-tracking. The fact that road safety improves with increasing vehicle capacity is something few people realise. This is a result of the decreasing number of vehicles needed on the road. Of course this advantage is reduced if accidents occur as a result of the decreasing stability and/or increasing swept path of longer vehicles. All this places specific demands on the road handling performance of the vehicles.

The Department Transport Technology of the Faculty of Mechanical Engineering of Delft University of Technology is carrying out research that is intended to lead to the development of a high capacity vehicle that is suited to the Dutch situation. It is proposed that concentrated container flows should be transported by so-called 'multi-trailers'. Currently these 10 TEU capacity vehicles are used for internal transport at container terminals. The steering mechanism of the five constituent trailers has been designed in such a way that when making a turn each trailer follows the same track as its predecessor, resulting in a very small overall swept path. However, the vehicles have to be modified to meet more stringent requirements for driving on public roads. These modifications include changes in braking capacity, axle load and stability.

Research has been focussed on stability, which has proved to present the biggest problem.

TRANSPORT BY MULTI-TRAILER

History

The development of multiple trailer vehicles started at the end of the previous century because of their supposed military value. The ever-increasing capacity demands resulted in increasing overall length and therefore space requirements when making turns. To overcome this problem, the trailers were equipped with steering rear axles, in order to minimise the swept path. **Figure 1** shows a design by Ferdinand Porsche.

Because of the legislative restrictions on total vehicle length in most countries and the slightly more complex steering mechanism, this type of all-wheel steering vehicle has disappeared from public roads.

Current application

In the early 70's the Dutch container terminal operator ECT started a study designed to increase the capacity of internal transport vehicles [3]. It was necessary to alleviate the congestion caused by the number of vehicles using the terminal. To minimise the impact on the terminal layout they decided to use vehicles consisting of five all-wheel steering trailers. This so called 'Multi-trailer system' **(Figure 2)** was developed in co-operation with the Technical University of Delft.

In the seventies the main issue was to look for an optimal balance between the *size* and *shape* of the swept path. The *shape* of the swept path is important in the first part of a turn. Off-tracking to the outside of a turn (out-swing) can result in trailers colliding with an object that the tractor has passed without a problem. This balance was accomplished by varying the kinematic transfer functions between the pull-bar and front axle rotation, and between front and rear axle rotations in a computer simulation and by measuring the track deviation of the trailers.

Future development

The benefits of multi-trailers have been demonstrated during twenty years of experience. Consideration could therefore be given to extending the operating range of these vehicles. Currently the multi-trailers cover distances of approximately 3 km.

The largest container terminal of the Netherlands is situated 40 kilometres from the centre of Rotterdam. Because the Rotterdam area is one of the main bottlenecks in the Dutch road network it is desirable that an alternative transport system should bypass the Rotterdam ring roads.

It is proposed that multi-trailers should be used to transport containers within the Dutch borders at a speed of 50 km/h [2]. To enable their introduction in the short term, with minimal investment in infrastructure, it seems feasible to reserve lanes on existing highways during the hours of night, thus creating semi-dedicated infrastructure. The reservation of the lanes could be accomplished by using signals to control the traffic. At a limited number of interchange areas the multi-trailers could be uncoupled and then distributed over the conventional road network. In a later stadium this concept can be combined with the development of automated transport on a strictly dedicated infrastructure.

The most important advantages of a system based on multi-trailers are:

1. Optimal *integration with* the current *road network*. There is no need for additional transhipment.
2. Improvement in *road safety*. Fewer vehicles are needed to perform a specific transport task because of their increased capacity. This proposal also separates passenger and freight transport by shifting freight transport to dedicated lanes during the quiet night hours.
3. Reducing *environmental impacts* of freight transport. Power consumption due to air resistance is reduced significantly because of the low speed and low drag coefficient per container. The low drag coefficient per container is a result of the small longitudinal distance between the containers. The containers 'share' the energy loss generated by the airflow turbulence at the front and rear end of the vehicle.
4. *Cost effectiveness*. Both the government and the operating companies will gain financial benefits. For the government these arise from the optimisation of the capacity of the existing road network, reducing need for investment in new infrastructure. The operating companies can also reduce both investments and operating costs. One large vehicle is cheaper than a number of conventional trucks with equivalent capacity. Operating costs are mainly related to the costs fuel and maintenance and the salary of the driver. A reduction can be expected in all these areas.

5. The possibility *of introduction in the short term.* It is not necessary to create new infrastructure, and the vehicle is mainly based on existing technology.

There is some concern about the social acceptability of the proposed road multi-trailer concept. The public is already concerned about the dimensions of conventional trucks, and recently much attention has been given to rollover accidents by the media. This is one of the main reasons why the road handling capacity of the vehicle is at the centre of attention.

The multi-trailer is currently operated at a speed of 30 km/h. The track following characteristics provide a degree of manoeuvrability that is also desirable for the future road multi-trailer. The main problem is to ensure the stability of the 80 m combination at a speed of 50 km/h. Stability problems were expected because they are strongly related to speed, the number of trailers and the degree of track following characteristics.

Computer simulation played a major part in the study of the vehicle's road handling capacity.

VEHICLE SIMULATION

When the current multi-trailer was developed some twenty years ago, a computer program was used to minimise the track deviation of the centre of gravity of the trailers (COG) as compared to that of the COG of the tractor when making turns. This program was basically a primitive two-dimensional model of the vehicle, including inertia and limited tire dynamics.

In the project "Multi-trailer on the road", initially a computer model based on the equations of the above mentioned program was produced in Matlab/Simulink. It was soon discovered that some of the assumed parameters were not exact enough for dynamic calculations at higher speeds. After the correction of parameters the results were still not satisfying and it was decided that a two dimensional model would not give sufficient accuracy.

Modelling the vehicle by using multi-body techniques seemed a promising alternative. When modelling a mechanical system every part that can move (that has at least one degree of freedom) in relation to another part or to the ground is incorporated separately. The kinematics is established by indicating the possible motions that parts can describe in relation to each other. Allocation of mass, inertia, centre of gravity, angular speed of parts and external forces ensures the representation of dynamics. The internal deformation of the parts is neglected.

The particular program used was ADAMS (Automatic Dynamic Analysis of Mechanical Systems) and it provided in the following advantages:

1. The model was three-dimensional so the effects of load transfer on cornering characteristics, and the non-linearity of the steering mechanism were taken into account.
2. The visualisation of the vehicle motion could be lifelike.
3. Modelling on a virtual prototype basis provided a tool for a wide variety of situations (e.g., calculating swept paths as well as dynamic stability in several manoeuvres).
4. A very important feature was the availability of tire-models.

Modelling structure

A representation of one trailer and the tractor is given in **Figure 3**.

All relevant values have been parameterised. By incorporating all separate elements of the steering mechanism the steering angles can be accurately represented. The rear axle is not sprung (as it is in the real vehicle), and the front axle is fitted with a suspension. To be able to use the sprung axle component in future models it is also equipped with roll-stiffness.

The front axle of the tractor is equipped with an Ackermann steering mechanism. The steering signal is applied by stipulating the steering rotation of the wheels.

The tire characteristics are partly based on Willeke [6]. A major problem was presented by the heavy axle loads in the vehicle. These can exceed 30 tons. We found neither tire measurements nor test equipment available in that range. Therefore some estimates have been made in consultation with C.H. Verheul of SayField International and Professor H.B. Pacejka, Professor of Vehicle Dynamics, Delft University of Technology.

Performance indicators

Stability was investigated by having the modelled vehicle execute an ISO double lane change manoeuvre (**Figure 4**). In the USA passenger-cars have to be able to accomplish this at a speed of 80 km/h for acceptance to the public road [7]. This manoeuvre is very extreme for any truck combination. However, it was deliberately chosen in order to detect instability.

The chosen performance indicators were:

1. The maximum speed at which the lane changes could be executed without a trailer rolling over.
2. The relation of the maximum lateral acceleration of the fifth and the first trailer (rearward amplification).
3. The track deviation of the fifth trailer compared to the first trailer.

The indicators were used in a qualitative sense.

EXPERIMENTS AND MODEL VALIDATION

The constructed model is capable of performing a wide variety of manoeuvres. When validating the model, it had to be taken into account that it is most important to model the influence of speed on the road handling correctly. The test runs used for validation were therefore carried out at the highest possible speed. However, because of the large total vehicle weight (270 tons), and the limited tractor power (300 kW), the speed could not exceed 38 km/h. The tests were executed at the ECT terminal (Figure 2), which is paved with concrete blocks. The weather conditions were poor: rainy and heavy winds (Beaufort 8).

Model validation

Figure 5 shows a comparison of the modelled and real vehicle. A double lane change manoeuvre was carried out. Before and after the manoeuvre the left side of the tractor was in line with the line on the road surface and during the manoeuvre it experienced a lateral displacement of 2 meters to the left.

The decreased stability of the system can be discerned from both the representations of the system, considering the fifth trailers rather large lateral displacement to the *right* (about a double tire width) before executing the actual lane change to the *left*. The fact that the lateral displacement in the model is consistent with that of the real vehicle validates the model results. It should be noted that the comparison of the complete manoeuvre is available on videotape.

Test runs have also been executed with unloaded trailers. In these cases speeds of 50 km/h were reached. In extreme sinus shape excitations the lateral displacement of the fifth trailer was about 2.5 times that of the first one. A comparison between modelled and real vehicle again provided gratifying results.

RESULTS

Researched modifications

The road multi-trailer will have to display the same favourable manoeuvrability at low speeds as the current multi-trailer. However, several studies in vehicle dynamics have indicated that in most cases optimal behaviour in relation to manoeuvrability and stability demands conflicting vehicle parameters [4]. In accordance with this we have already concluded that the stability of the current multi-trailer is not acceptable at higher speeds.

To achieve acceptable behaviour in both cases two main options are considered:

1. To improve stability by making adjustments that will not influence the manoeuvrability.
2. To use a steering mechanism that is dependent on the state of the vehicle. In fact manoeuvrability is most important at low speeds, and stability is necessary at higher speeds. Introducing a speed related steering mechanism therefore seems desirable.

Ad 1. Modifications that improve stability without influencing manoeuvrability are:

- Reducing the height of the combined centre of gravity. This was accomplished by lowering the loading platform.
- The application of roll coupling is a known stability improving measure. To apply this the rotational freedom about the longitudinal axis was removed at three positions: tractor – trailer 1, trailer 2 - trailer 3 and trailer 4 - trailer 5.

Ad 2. Speed dependent steering mechanisms can be applied as follows:

- By decreasing the amount of steering on the rear axle with increasing speed.
- By using a so-called four-bar mechanism. The top view of the mechanism is displayed in **Figure 6**. In the standard multi-trailer the rotation of pull bar A and steering arm B are rigidly coupled. In the four-bar mechanism the rotations of pull bar A and steering arm B are uncoupled and replaced by a steering bar C is added. The end, D, of steering bar C can be shifted over sliding mechanism on the rear end of the first vehicle as a function of the speed. In the low speed condition A, B and C form a rigid triangle, thereby giving the same steering characteristic as the standard multi-trailer. In the high-speed condition the steering signal is influenced by the *angle between the vehicles*. This results in the elimination of the disturbing effect of the hitch moving in the wrong lateral direction before making a turn. In addition, the steering signal is passed on earlier.

Simulation results

The simulation results of two modifications that were investigated are described below. The results of the standard multi-trailer are compared to the best stability improving measures, these being three-times roll coupling and the four- bar steering mechanism.

The standard multi-trailer was not able to negotiate the lane change manoeuvre at 50 km/h (**Figure 7**).

When roll coupling was applied the vehicle did not roll over at 50 km/h. However, **Figure 8** shows that the rearward amplification was approximately 2 (relation between the maximum values of the fifth and first trailers lateral acceleration).

The track deviation of the fifth trailer was also rather large (**Figure 9**).
The multi-trailer with three-times roll coupling rolled over at a speed of 60 km/h.

The multi-trailer with a four-bar mechanism in every trailer gave much better results. The vehicle accomplished the manoeuvre, and had a rearward amplification of less than one (**Figure 10**).

Simulation has demonstrated that by changing the position of the connecting point D (Figure 6) of the steering bar on the sliding mechanism on the rear end of the first trailer it is possible to achieve the desired rearward amplification. In the near future experiments with a physical prototype are expected to provide more detailed information on this subject.

In further experiments the vehicle proved able to accomplish the lane change at speeds up to speed of 72 km/h. At a higher speed, it was the first trailer, not the fifth, which rolled over. This means that the stability of multiple-trailer vehicles equipped with this steering mechanism is mainly determined by the rollover stability of a single trailer, namely the first.

There are several major differences between the two stability-improving modifications.

From the constructional point of view, applying roll coupling to a full trailer is difficult. The maximum torque found in the hitch and pull bar mechanism proved to be around 400 kNm. To be able to cope with this a pull-bar would have to be approximately 0.5 meters in diameter, while the dimensions of the coupling mechanism would be even more. In the four-bar mechanism the pulling and steering functions of the original pull bar are separated. The steering bar only has to convey the steering force so the connecting point D (Figure 6) shifting mechanism can be a light construction.

More important is that the four-bar mechanism gives a much greater improvement in stability. Applying roll coupling only reduces the effects of rearward amplification; it does not eliminate it while the four bar mechanism can prevent the occurrence of rearward amplification.

It should be noted that the speed dependency of the four-bar mechanism results in a *passive* stability improvement. The condition of the mechanism is continuously updated to the vehicle speed. This minimises the chance of failure of the system in the case of an accident.

CONCLUDING REMARKS

A concept based on multi-trailer road vehicles offers an interesting option for container transport within the Dutch borders. The concept offers the following advantages: optimal integration with the road network, improvement of road safety, diminution of environmental impacts, improvement of cost effectiveness and the possibility of its introduction in the short term.

When equipped with a speed-dependent four-bar steering mechanism, the road handling of a road multi-trailer displays favourable behaviour at both low speed (small swept path) and at high speed (stability).

To improve stability similar mechanisms can be applied to all full trailers.

Stability-improving steering mechanisms have rarely been applied to truck combinations, mainly because of their complexity and high costs. The biggest advantages of the proposed four-bar mechanism are that it is simple, reliable and cheap.

A physical prototype is currently under development.

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REFERENCES

1. CTT, “Masterplan Incomaas.” Rotterdam: CTT, 1996.
2. Drenth, K.F., “Wegmultitrailers (een bijdrage ter vermindering van congestie op de weg)”(Road multi-trailers, a contribution to reducing congestion on the road). Delft: TU Delft, 1996.
3. Rijsenbrij, J.C.,”ECT Delta terminal: strategy through to 2000 and beyond”. Rotterdam: ECT, 1983.
4. Roos, G., “Vierwielbesturing: bepaling van een optimale strategie voor de besturing van de achterwielen van personenwagens”(Four wheel steering: determination of an optimal strategy for steering of the rear wheels of a passenger car). Eindhoven: TU Eindhoven, 1990.
5. Transport en Logistiek Nederland, Transport in cijfers editie 1995 (Transport in statistics edition 1995).
6. Willeke, H.G., “Messung und modellierung der Fürungseigenschaften von Nutzfahrzeug-reifen.” Hannover: Universität Hannover (Measuring and modelling the driving behaviour of truck tires), 1996.
7. Zoest, P. van, “Beoordeling van lane-change-manoeuvres van vrachtwagens. (Evaluating lane- change manoeuvres by trucks)” Delft: TU Delft, 1988.

AUTHOR BIOGRAPHIES

Arjan Boezeman was born in Amersfoort, the Netherlands, on February 25, 1971. After completing his secondary education at the Christelijk Lyceum Zeist in May 1990, he entered Delft University of Technology. He studied Mechanical Engineering, graduating in July 1997. His thesis was devoted to the dynamics of multi- trailer concepts. While studying he worked as a bus driver, thereby obtaining practical experience of the road behaviour of large vehicles. Subsequently, he continued his research into this subject at Delft University of Technology. He is currently developing a physical prototype of a trailer with a stability-improving steering mechanism in co-operation with the trailer manufacturer Buiscar B.V. He is also supervising the research of three graduate students who are working on vehicle dynamics related subjects.

Karel F Drenth was born in The Hague, the Netherlands on October 10, 1946. He studied mechanical engineering and then process control technique at the College of Advanced Technology in The Hague.
From 1969 till 1972 he worked as a design engineer in the field of NC machines. In 1972 he joined the staff of the Faculty of Mechanical Engineering of Delft University of Technology from which he graduated in Mechanical Engineering in 1983. The subject of his degree thesis was the design of a continuous ship unloader for bulk cargo.

Since that time he has lectured in mechanical engineering and transport related problems at several education institutes, including Delft University of Technology, The Erasmus University School of Economics, Rotterdam, The Business School Rotterdam and the College of Advanced Technology, The Hague. He also acts as a consultant from time to time. He designed the Multi-trailer for ECT, which is now produced by Buiscar.

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Figure 1. Five-trailer all wheel steering vehicle (1911).

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Figure 2. Multi-trailers at the port of Rotterdam

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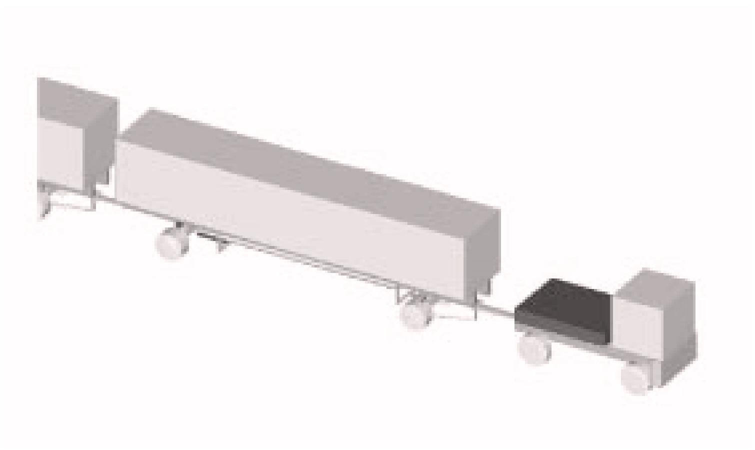

Figure 3. Model of the tractor and a trailer.

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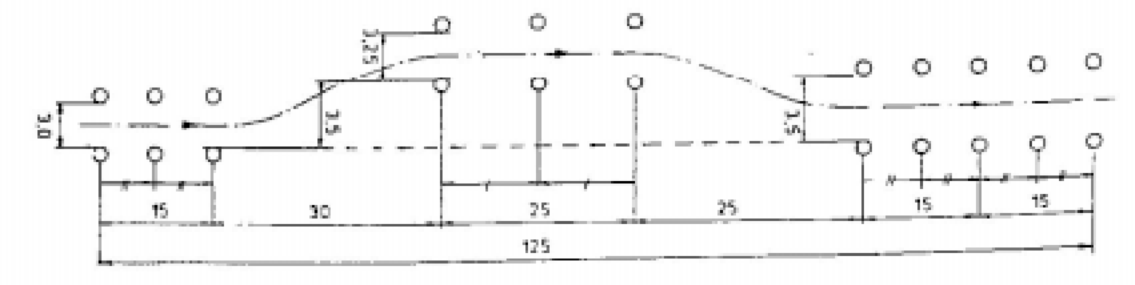

Figure 4. The ISO double lane change manoeuvre.

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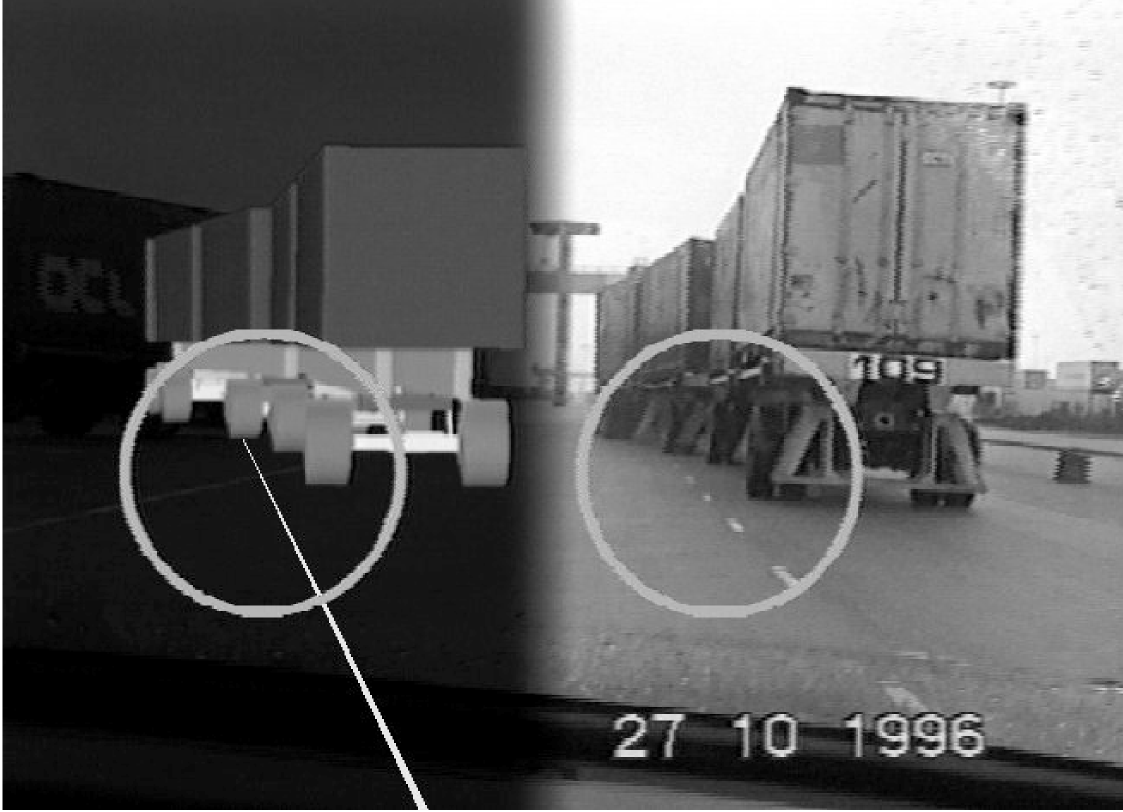

Figure 5. Modelled vehicle in comparison with real vehicle.

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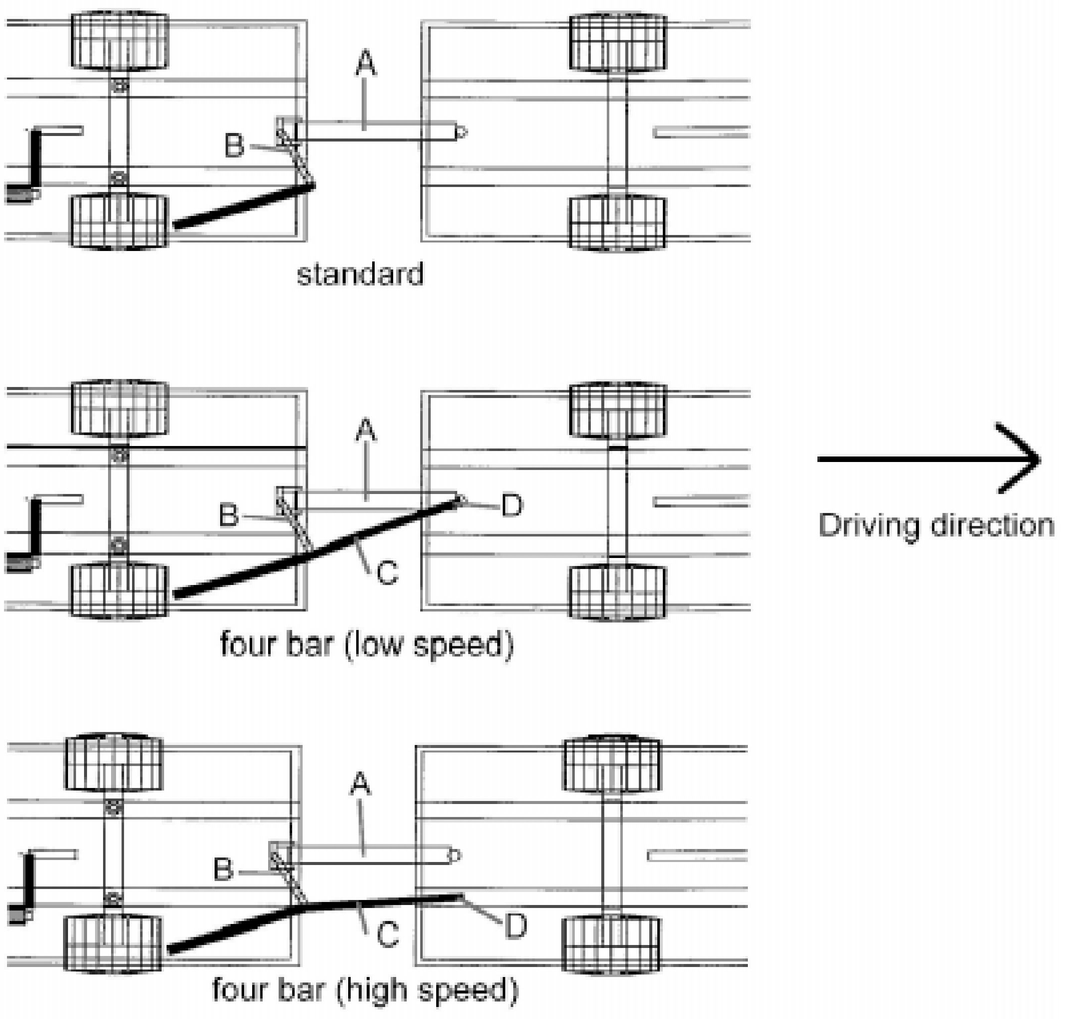

Figure 6. Explanation of the four bar steering mechanism.

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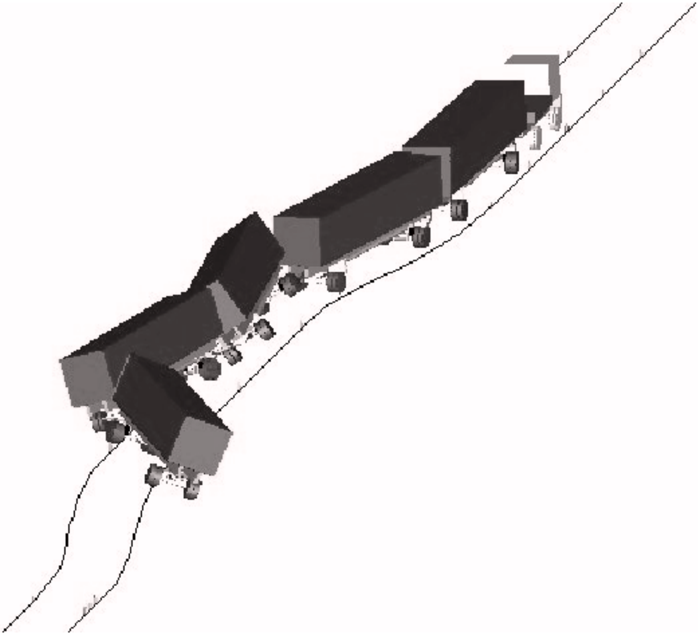

Figure 7. Standard multi-trailer in 50 km/h lane change.

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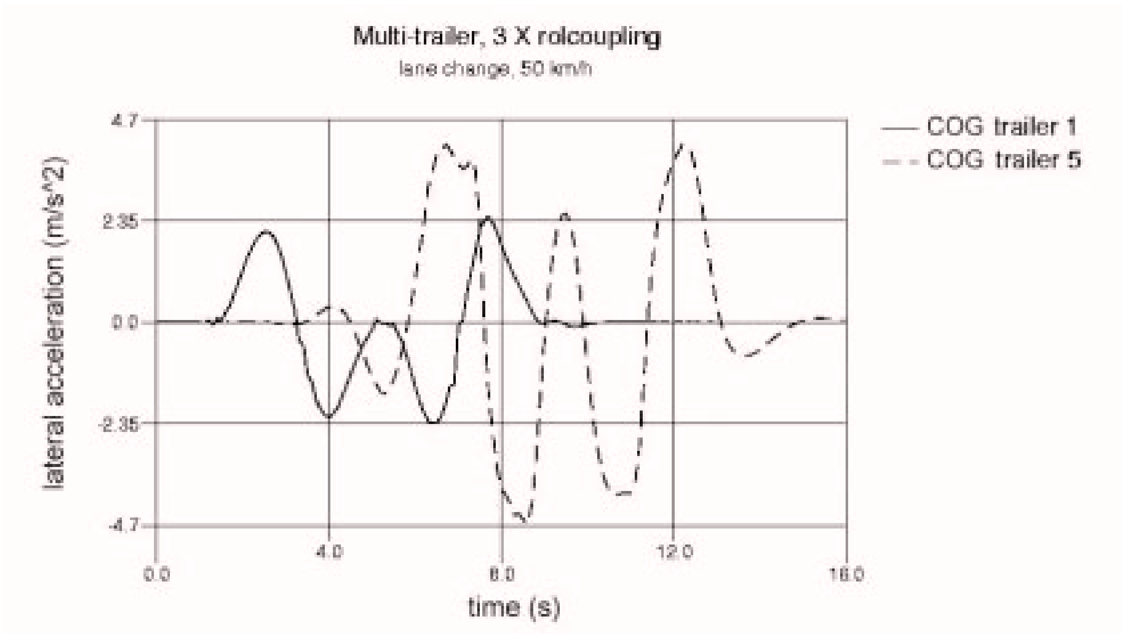

Figure 8. Lateral acceleration of a multi-trailer with 3 x roll coupling.

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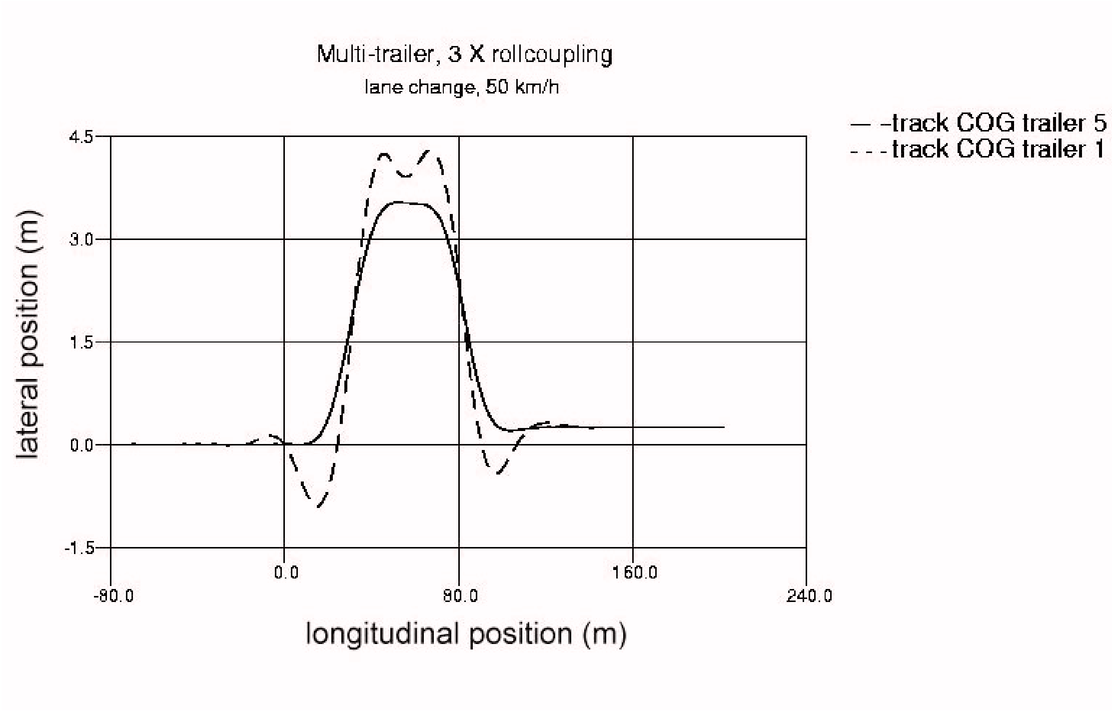

Figure 9. Track deviation of a multi-trailer with 3 x roll coupling.

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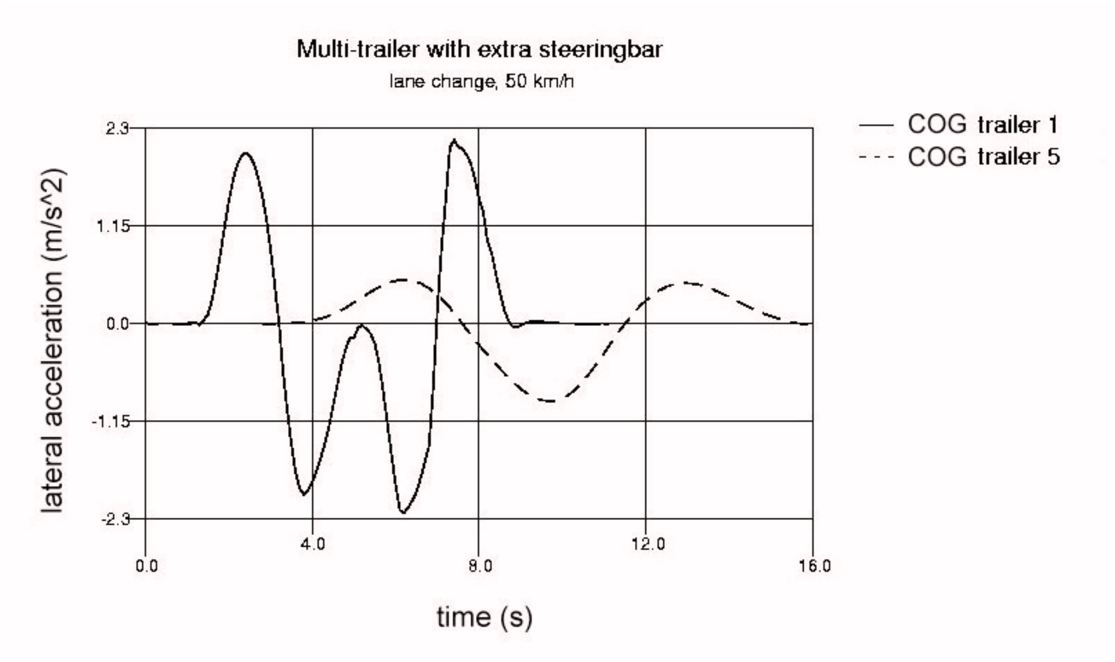

Figure 10. Lateral acceleration of a multi-trailer with a four bar mechanism.

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