A TRAILER STEERING STRATEGY FOR THE B-DOUBLE COMBINATION

A.Prati,
MSc, PhD student at
Eindhoven University of
Technology

I.J.M.Besselink,
MSc, PhD, assistant
professor at Eindhoven
University of Technology

H.Nijmeijer,
MSc, PhD, Professor and
Chair of Dynamics and
Control group at Eindhoven
University of Technology

Alberto Prati, Igo Besselink, Henk Nijmeijer
Department of Mechanical Engineering
Eindhoven University of Technology

PO BOX 513, 5600 MB Eindhoven, The Netherlands
Phone: +31 40 247 28 11
Email: a.prati@tue.nl

Abstract

This paper describes a new trailer steering strategy called Virtual Rigid Axle Command Steering (VRACS). This strategy is implemented in a B-double model. This combination is composed from a tractor, a B-dolly carriage unit -known as first semi-trailer - and a standard semi-trailer and it was selected for its poor swept path performance. The VRACS strategy is developed observing the results obtained from a path following strategy and command steering system. It works seamlessly at all speeds using existing and reliable sensors on articulation angle and on vehicle speed. It improves both low-speed manoeuvrability and high-speed stability.

Keywords: LHVs, B-Double, Steering System

1. Introduction

Freight transport is currently responsible for one fifth of total CO_2 emissions in Europe [1]. In the years ahead, it is anticipated that road transport will continue to grow [2], leading to an increase in traffic congestion, in the use of infrastructure and in the level of GHG emissions. The European Commission has set targets [3] for reducing greenhouse gas emissions and the transport sector can play a strategic role in this.

The HTAS-EMS research project, which involves two academic institutes (TUE/e and HAN) and major heavy truck industry players, was established to identify the requirements for designing the future commercial vehicle concepts for the years 2020+, [4]. The European Modular System (EMS) is a concept that allows existing loading units (modules) to be combined into longer and sometimes heavier vehicle combinations (LHV), resulting in fewer vehicles needed to transport the same amount of goods. New futuristic vehicle concepts (Figure 1) should evolve from the current longer and heavier vehicle combinations (LHV) and should be designed to be both modular and intermodal using interchangeable loading units, in order to optimize the logistic process.

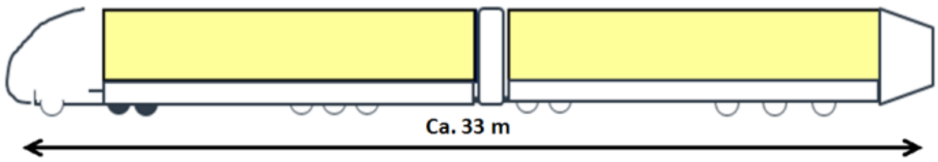

Figure 1. Example of a vehicle concept for 2020+

Some European countries allow LHVs on specific roads regulating both the maximum weight at 60 tons and the maximum length at 25.25 meters. Considering the new aerodynamic devices (longer cabin, boat tail) and the trend to use longer loading units such as the new standardized 45ft-container (13.7 meters long), recently approved by ACEA [5], the future commercial vehicle may easily exceed this maximum length. Since the existing European road infrastructure will not be modified to host these vehicles, a trailer steering system needs to be developed in order to improve low-speed manoeuvrability and high-speed stability.

Existing trailer steering systems include self-steering axles, command steering systems and pivotal bogie systems. All these systems improve low-speed performance but exhibit low yaw stability at high speed; for this reason passive steering systems are automatically locked at high speeds.

The self-steering axles provide steering action in response to the lateral forces developed at the tyre-road interface. The command steering system forces the trailer axles to steer proportionally to the articulation angle between the tractor and semi-trailer and based on Ackermann’s angle by means of a mechanical linkage, a hydraulic or an electrical system. A pivotal bogie system is a command steering system which steers only the last two rear axles in relation to the angle between the chassis and the pivotal bogie, which connects the tri-axle group to the trailer.

Since the articulation angle can be sensed and transmitted electronically, a flexible and reliable control strategy can easily be implemented in the command steering system. Active steering systems, which are available on the market, operate only at low speeds and are automatically locked at high speeds (above 55 km/h) to provide the same stability as a fixed-axle trailer [6].

Several researchers have focused on developing steering control strategies in order to improve both high speed stability and low speed manoeuvrability, trying to achieve perfect path following of the front of the vehicle by the vehicle’s rear.

Recently, Cebon and Jujnovich from the University of Cambridge [7] have proposed a path-following steering control strategy where the controller steers the axles of the semi-trailer so that the rear end of the trailer follows the path of the fifth wheel coupling for all paths and at all speeds. This strategy which is known as ‘Conventional Tractor-Active Trailer’ (CT-AT), improves low-speed manoeuvrability, eliminates tail swing, reduces rearward amplification and the propensity to roll over in high-speed transient manoeuvres.

Since the CT-AT strategy uses expensive sensors (i.e. yaw rate and side slip sensors) and employs two separate low and high-speed controllers, which need to switch based on the forward velocity, it was observed that there is room for researching a new steering strategy. The aim of this paper is to arrive at a steering strategy which is suitable for all speeds, simple, easy to implement and able to improve both high and low-speed performance of multiple articulated commercial vehicles.

A new Virtual Rigid Axle Command Steering strategy (VRACS) was developed for a B-double combination [8]. This combination is composed from a tractor, a B-dolly unit and a standard semi-trailer. Comparing the performance of the B-double combination with other LHVs, it completes a 90° intersection with the greatest swept path, which is an indicator of poor low-speed manoeuvrability.

The European Directive (96/53/EC, point 1.5) prescribes that any vehicle combination must be able “*to turn within a swept circle having the outer radius of 12.50 m and the inner radius of 5.30 m*”. This leads to a maximum width of swept path of 7.2 meters, which is definitely a difficult requirement to achieve for a longer vehicle, highlighting even more the urgent need for a suitable steering system.

The new strategy we are proposing operates seamlessly at all speeds with the same controller using a minimal set of existing and reliable sensors, such as vehicle speed and articulation angle.

2. Research method

As first step, it was decided to compare various existing steering systems by means of computer simulations. The B-double combination with conventional non-steered trailers was modelled in the multi-body domain by means of the “TU/e - Commercial Vehicle Library’’, which is a generic library of truck, trailers and components, developed in MATLAB-Simulink/SimMechanics by the Eindhoven University of Technology.

The structure of these models is modular in order to give the user freedom to create and develop many different types of combination just connecting the sub-models. At the same time, the user has the great flexibility to easily customize all the components through the central library and distribute this modification to the linked models. The purpose of the library is to be maximally generic and avoid all the details in order to represent overall dynamical behaviour of vehicle combination with sufficient accuracy and reasonable calculation time. For modelling the tyres, which are critical for vehicle dynamics simulation, the TNO Delft Tyre Toolbox was selected and implemented. The model employs Pacejka’s Magic Formula [9] for evaluating the vertical, lateral and longitudinal operating forces of the tyres. For increasing the credibility of the library, two LHVs (D- and B- combinations) were subjected to several experimental tests and the obtained measurement data was used for a models validation process [10].

For the purpose of our research, the command steering system based on the articulation angles was modelled and applied to each trailer axles of the B-double; likewise, the controller of the CT-AT strategy was adapted and implemented to the B-double model. The steering behaviour is analysed in detail for different test scenarios.

3. Virtual Rigid Axle Command steering strategy – Low speed

When a vehicle combination makes a turn, it always needs more space than the width of the combination, since the rear axles cannot follow the path of the front axle and part of the vehicle sweeps inside the trajectory of the front wheel. The space required for performing a turn is called the swept path and this is a good indicator for evaluating low-speed manoeuvrability. According to the European directive 96/53, the maximum swept path is 7.2 m on a 12.5 m outer radius. However, the Dutch regulations for LHVs prescribe a maximum swept path of 8 m on a 14.5 m outer radius. For this reason, it was decided to evaluate the low-speed performance of the B-double combination with different steering systems, simulating the driving around this circle in a steady state condition. During this manoeuvre, it can be noticed that both command and path following steering strategy (CT-AT) apply the same steer angle values on the trailer axles for steady state circular driving, as figures 2 and 3 show.

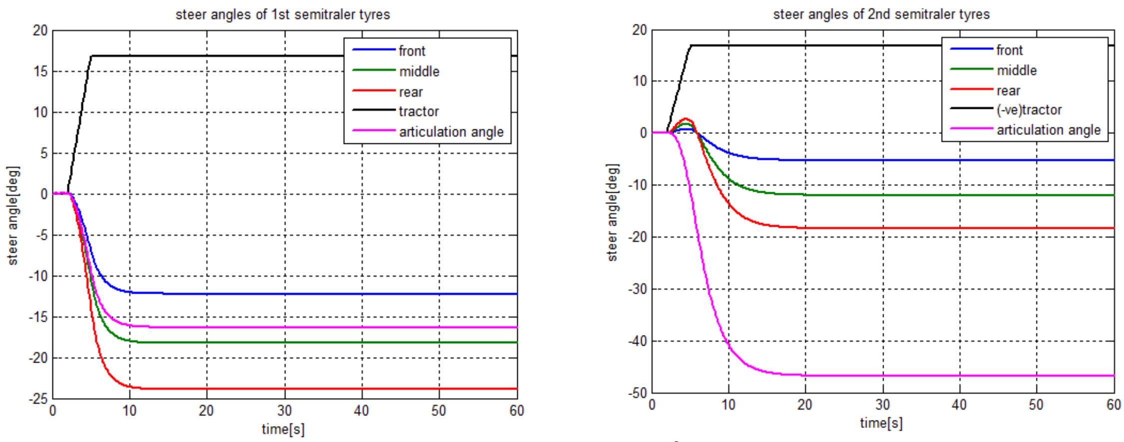

Figure 2. Steering angles of the axles of 1st and 2nd semi-trailers– Command steering

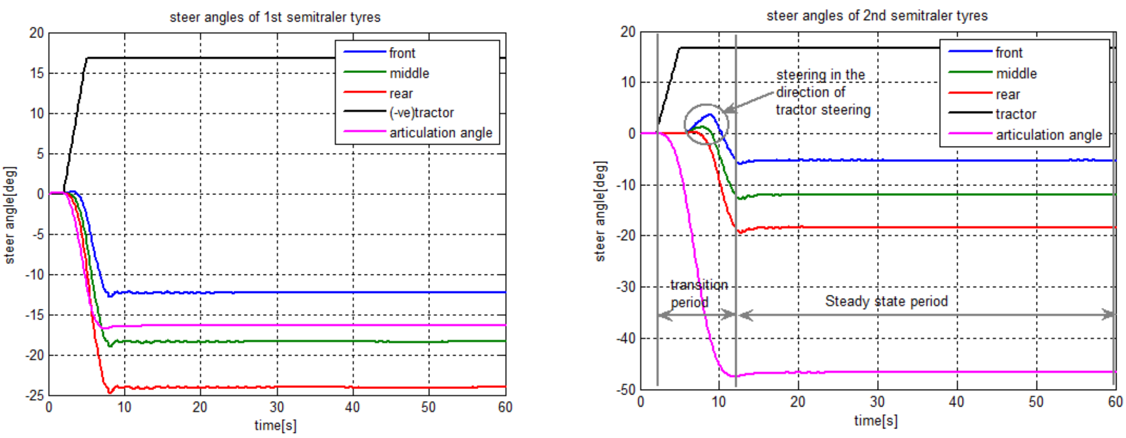

Figure 3. Steering angles of the axles of 1st and 2nd semi-trailers – Path following strategy

Based on the geometry of the articulated vehicle in steady state condition, the steering equations can be easily derived. In order to reduce the slip angles and therefore, the lateral forces, the trailer axles need to be steered so that their normal passes through the same centre as the midpoint between the two 5th wheel couplings of the first trailer and the midpoint between the 5th wheel coupling and the rear end of the second semi-trailer (Figure 4).

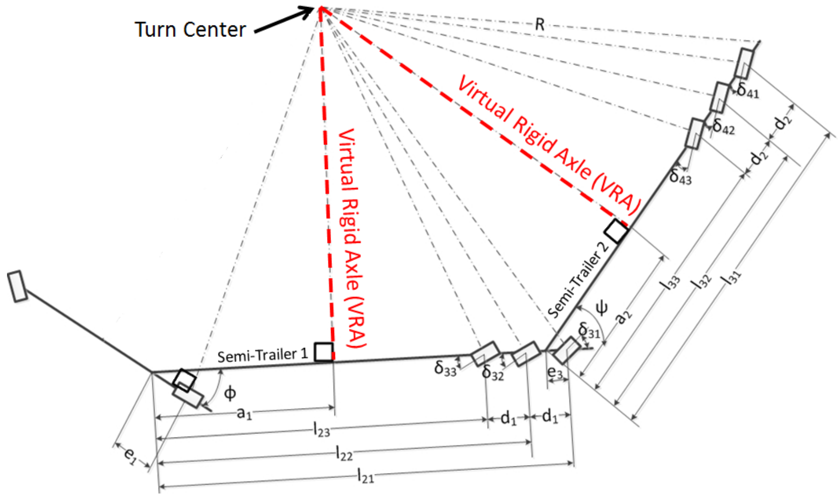

Figure 4: Schematic of a B-double with trailer steering at low speed.

These midpoints represent the positions of the virtual rigid axles (VRA) at low speed along the semi-trailer bodies. The virtual rigid axle is defined as the virtual non-steered axle, placed at the point where the turn centre and the vehicle body meet perpendicularly. Their locations play a strategic role in determining the steering gain for each trailer axle, as the steering equations show.

For the 1st semi-trailer axles:

$$\delta_{3i} = tan^{-1}\frac{(l_{2i}-a_1)sin(\Phi)}{(a_1 cos(\Phi)-e_1)} \tag{1.1}$$

For the 2nd semi-trailer axles:

$$\delta_{4i} = \tan^{-1}\frac{(l_{3i}-a_2)\sin(\delta_{33}-\Psi)}{(e_3\cos(\delta_{33})-a_2\cos(\delta_{33}-\Psi))} \tag{1.2}$$

Where:

i = number of the axle of the semi-trailer (i.e.: 1=last axle of semi-trailer);
Φ = Articulation angle between the tractor and the 1st semi-trailer;
Ψ = Articulation angle between the 1st and the 2nd semi-trailers;
a_1 and a_2= Virtual Rigid Axle positions along respectively the 1st and the 2nd semi-trailer;
e_1 = distance from the first 5th wheel coupling to the rear axle of the tractor;
e_3 = distance from the second 5th wheel coupling to last axle of the 1st semi-trailer;
l_{2i} = distance from the first 5th wheel coupling to the i-axle of the 1st semi-trailer;
l_{3i} = distance from the second 5th wheel coupling to the i-axle of the 2nd semi-trailer;
δ_{3i} = steer angle of the i-axle of the first semi-trailer;
δ_{4i} = steer angle of the i-axle of the second semi-trailer.

During the transition period, the entry and the exit of the circle, both the path following strategy and the command steering systems steer all trailer axles towards the same direction as the tractor steering before moving to the opposite direction until a steady-state condition is reached (Figure 2, Figure 3 and Figure 5). Analysing the steering behaviour, it is evident especially for the second semi-trailer axles, that the command steering starts to steer immediately, see Figure 2, while the path following strategy works only after some delay (Figure 5). For this reason the CT-AT strategy eliminates any kind of tail swing during the manoeuvre. It is also clear that, in the steering behaviour of the path following strategy, the rate of change of the steer angles at the trailer axles is approximately equal to the rate of change of the articulation angle at the coupling point (Figure 5).

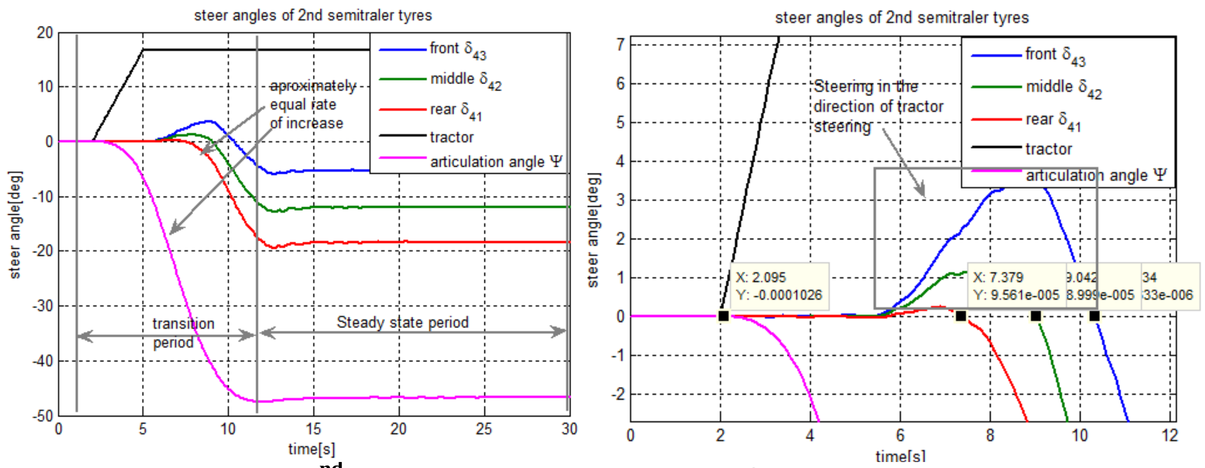

Figure 5: 2nd semi-trailer steering angles of CT-AT and Zoom Area.

A simpler technique can be devised to be used during the transition period until the steady state is reached, where the steady state steering angle values are according to the command steer equations (1.1) and (1.2). For an efficient tracking and following behaviour of the new strategy, it was decided to eliminate any steering of trailer axles in the same direction of the tractor steering and to begin to steer after a pre-determined delay, obtained by relating it to distance travelled and dimensions of the vehicle itself (Figure 6).

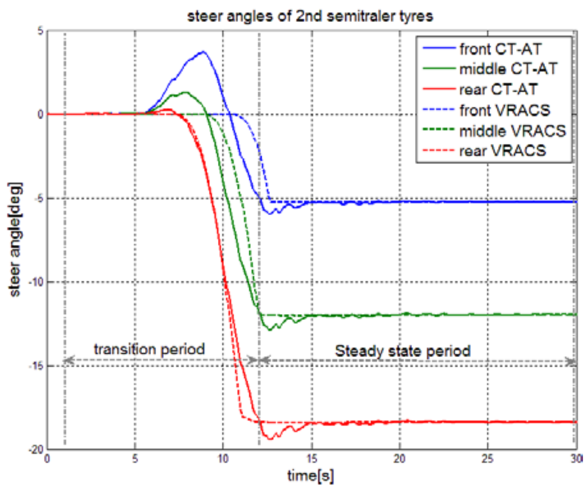

Figure 6: Comparison of steering angles of CT-AT and VRACS strategies.

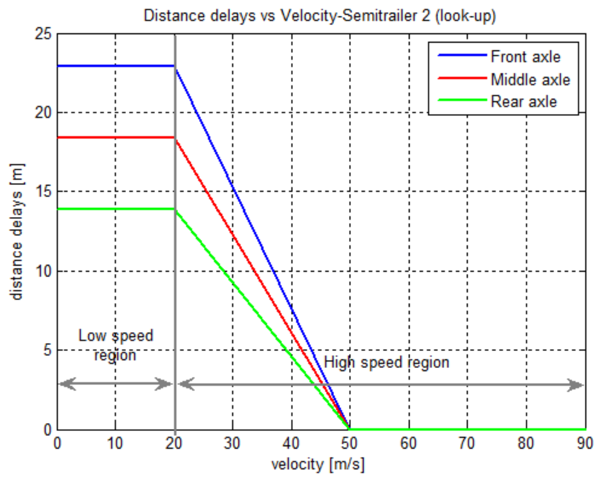

Figure 7: Look up table for distance delays of 2nd semi-trailer.

Knowing the delays, the articulation angle could be directly used as input, a time-delayed feed-forward signal, to steer the trailer axles until the steady state values are obtained (equation (1.1) and (1.2)); these define the limits up to which the trailer axles must be steered.

Tests in different manoeuvres (steady state circle and 90° intersection) and at different speeds from 0 to 20 km/h showed that the distance delays of the path following strategy remain unchanged. Based on this, a look-up table is used to delay the steering of the trailer axles (Figure 7); the range from the 20 to 50 km/h is chosen arbitrarily for linear decreases of the delays in order to ensure continuous use of the strategy at all speeds.

4. Virtual Rigid Axle Command steering strategy – High speed

The CT-AT strategy uses a different controller at high speeds which uses a velocity dependent gain and gradually eliminates the effect of the low speed controller. The new VRACS system doesn't require switching between controlling strategies, but removes the delays and uses only the command steering equations to steer the axles.

As already explained, proportionally with the velocity, the steering delays are reduced linearly to zero in the range from 20 to 50 km/h (Figure 7). Simultaneously, the strategy starts to steer the trailer wheels in the same direction as the tractor front wheels, in a similar way to what happens with four-wheel steering passenger cars, which steer all of the wheels in the same direction at high speeds (Figure 8). This leads to a gradual increase in the effective wheel base by shifting the position of the virtual rigid axles backwards. Changing the position of the VRA means choosing the instant centre of rotation (Figure 8).

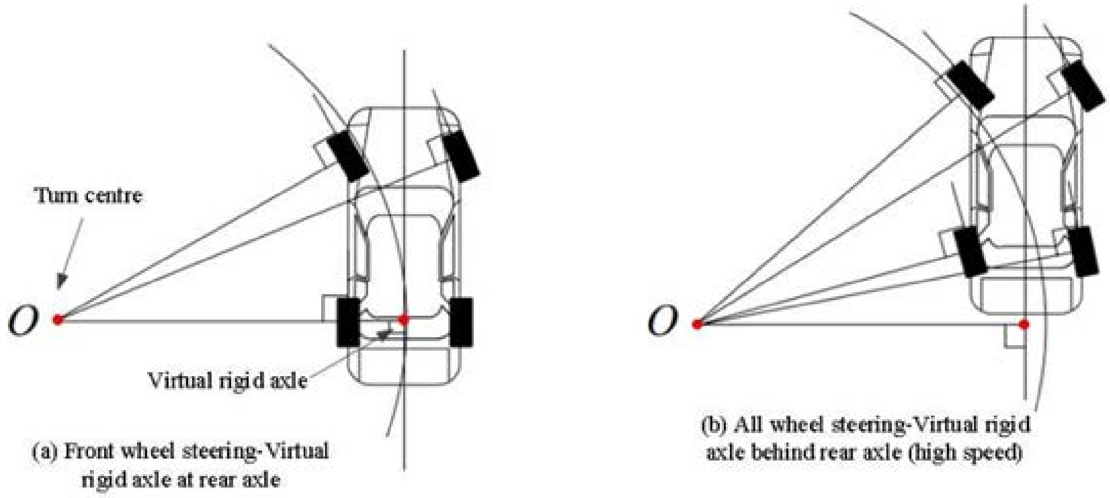

Figure 8: Illustration of virtual rigid axles and turn centre [11].

In other words, as the speed of the vehicle increase the strategy reduces the delays to zero and gradually shifts the position of the virtual rigid axle (VRA) backwards. Deciding the new positions of the virtual rigid axle is challenging. To find the best position, we decided to adopt an iterative approach. We shifted the VRA position backwards by a distance equal to "*k*" times the "original position" used at low speed, which is the "midpoint" of the semi-trailers (Figure 3), and, for different values of *k*, we simulated a single lane change manoeuvre at 90 km/h, which is the maximum speed limit in Europe for commercial vehicles (Figure 9).

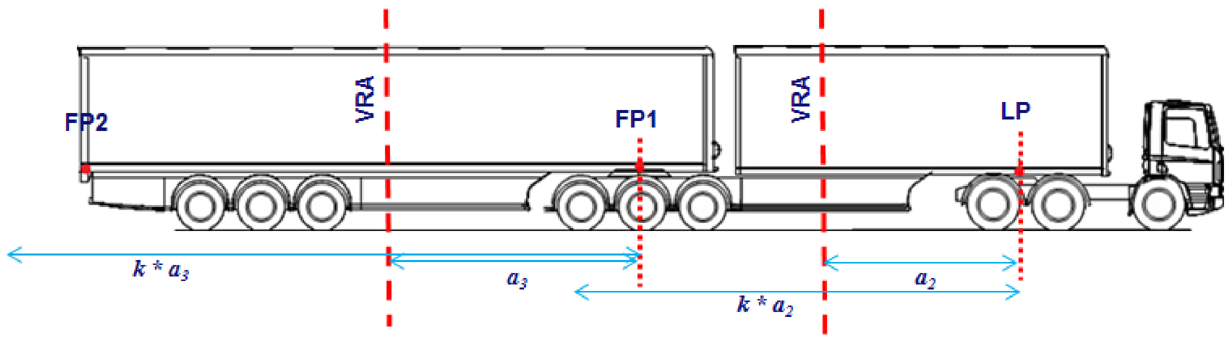

Figure 9: The position of the Virtual Rigid Axle shifted backward at high speeds.

The ideal position of VRA is established once the amount of undershoot and overshoot during the entry and exit of the manoeuvre is minimised to zero and the rearward amplification (RA) is reduced within allowed levels (Figure 10). Both these performance key indicators were calculated using the formula prescribed by the Australian Performance Based Standards [12].

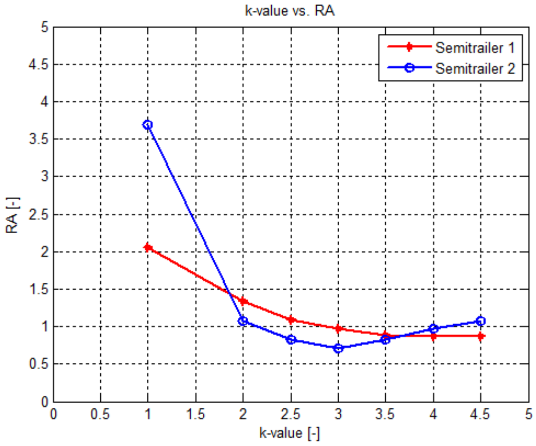

Figure 10: RA values corresponding to different "*k*" values at 90 km/h.

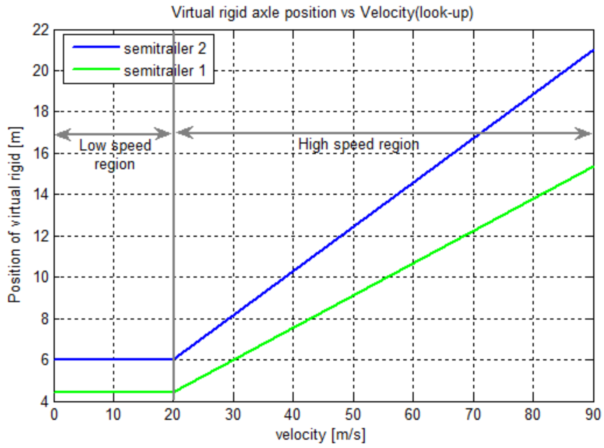

Figure 11: Look-up table for virtual rigid axle position.

To get more insight in choosing the ideal position of the virtual rigid axle, a state space model of the steerable B-double was created starting from the un-steered version made by M.F.J. Luijten [13], which was developed by using the linear bicycle model with multiple articulations. To identify the best position of the virtual rigid axle, we applied the same approach used previously in the multi-body model simulation. Based on the Rearward Amplification values, calculated in the frequency domain, it was discovered that the ideal location of the virtual rigid axle is 3.35 times the "original position" at low speeds; as explained before, for low speeds, the virtual rigid axle is placed close to the "midpoint" between the lead and follow points of each semi-trailer (Figure 4).

Also a single lane change manoeuvre at different speeds has been analysed. It was noticed that the value of RA reduces with the decrease in the speed and the rate of decrease in RA is not related to the position of the VRA. Changing the position of the virtual rigid axle behind the follow point improves high-speed performance, but after a certain point (k=3.35), the value of RA increases again. All these results are completely in agreement with the outcome of the multi-body simulations, as shown in Figure 10.

Finally a look-up table (Figure 11) is used for positioning the virtual rigid axle in the VRACS steering strategy. Up to 20 km/h, the location of the VRA is fixed, then it shifts backwards in a linear fashion with the speed up to 90 km/h, when achieves the final ideal value (k=3.35).

5. Performance evaluation according to PBS Standards

The performance of the B-Double using the VRACS system is evaluated with the help of some indicators prescribed by the Australian PBS [12]. For comparison, the same test scenarios are also executed with the un-steered B-double model, with the command steering version and with the B-Double equipped with an adapted version of the CT-AT strategy.
A summary of main tests done using various steering strategies is listed in the Table 1.

	Unsteered	Command steer	CT-AT [1]	VRACS [2]	Allowed limit
Swept path	11.39 m	4.31 m	4.20 m	4.27 m	< 8 m
Tail swing	0 m	0.55 m	0 m	0.19 m	< 0.5 m
Rearward amplification (RA)	1.59	3.69	Not tested	0.89	< 2
High speed off-tracking	0 m (entry) 0.11 m (exit)	0.15 m (entry) 0.15 m (exit)	Not tested	0 m (entry) 0 m (exit)	< 0.6

Table 1: Summary of tests results

It can be seen that the Virtual Rigid Axle Command Steering strategy satisfies all performance requirements and evidently performs much better in comparison with the un-steered trailer axles and command steered axles, while the CT-AT strategy has the best performance at low speeds.

The main advantage of the VRACS strategy is that is able to achieve acceptable levels for both high and low speed performance (reducing the RA and swept path, eliminating high-speed off-tracking); it works with one controller at all speeds by shifting the virtual rigid axle and it only uses the existing vehicle speed and articulation angle sensors. Finally, the strategy is simple to understand and easy to implement.

6. Future Research

Future research will focus on analysing the feasibility of implementing the VRACS system on the B-Double combination and evaluating the performance of different configurations of the system. For instance, the system could be implemented only on one of the two trailers of the B combination whereas another possibility could be to steer only one or two axles of both semi-trailers of the B-Double. Both methods will lead to a reduction of the number of steerable axle contributing consequently on the economic prospective.

In order to improve the dynamic behaviour of other LHVs, the VRACS steering strategy could be extended to the multi-body model of other combinations. Performance at high and low speeds will be simulated and compared with the results of the un-steered and the command steered versions of the LHV combinations.

7. Acknowledgements

The author wishes to acknowledge all project partners in the international project HTAS-EMS “Greening and safety assurance of future modular road vehicles”. Partners in the project are MAN Truck & Bus, DAF Trucks NV, D-TEC BV, TNO Science & Industry, WABCO Automotive BV, LAG and HAN University of Applied Sciences.

8. References

[1] Eurostat. (2013, June 14). *Modal split of freight transport*. Retrieved September 9, 2013, ec.europa.eu/clima/policies/transport/vehicles/index_en.htm

[2] Schroten, A., Warringa, G., & Bles, M. (2012). *Marginal abatement cost curves for Heavy Duty Vehicles*. Delft: CE Delft. Page 5

[3] White Paper on Transport 2011.

[4] Partners in the international HTAS-EMS project: MAN, LAG, WABCO, DAF, D-TEC, TNO, HAN and TU/e.

[5] ACEA. (2008, September 23). Commercial vehicle manufacturers push fuel efficiency and environmental protection with "vision 20-20". Retrieved August 28, 2013, from ACEA: http://www.acea.be/index.php/news/news_detail/commercial_vehicle_manufacturers_push_fuel_efficiency_and_environmental_pro

[6] v-s-e.com/uploads/files/ets_trailer_eng_2009.pdf.

[7] A. Odhams, R. Roebuck, B. Jujnovich, and D. Cebon, “Active steering of a tractor–semi-trailer,” Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering, vol. 225, no. 7, pp. 847–869, 2011.

[8] Kandathil, J.J., “Improved command steering for a B-double truck combination”, Master thesis, Department Mechanical Engineering, Dynamics and Control Group, Technische Universiteit Eindhoven, 2012.

[9]. Pacejka, H.B.: Tyre and vehicle dynamics, Second edition, Butterworth-Heinemann 2006, Oxford

[10] Kural K., Prati A., Besselink I., Nijmeijer H., Pauwelussen J.; Validation of Longer and Heavier Vehicle Combination Simulation Models, HAN and TUE University, Arnhem, The Netherlands.

[11] R. Jazar, Vehicle Dynamics: Theory and Application. Springer, 2008.

[12].National Transport Commission Australia, 2008, Performance Based Standards Scheme, The Standards and Vehicle assessment Rules, www.ntc.gov.au

[13] M. Luijten, “Lateral dynamic behaviour of articulated commercial vehicles”, Master’s thesis, Department Mechanical Engineering, Dynamics and Control Group, Technische Universiteit Eindhoven, 2010.