ANALYSIS OF DRIVER BEHAVIOUR DURING REVERSE DRIVING OF DOUBLE ARTICULATED VEHICLES

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Abstract

This paper describes a series of tests done with a double articulated vehicle to investigate the driver behavior and directional stability of the vehicle during reverse driving. The tests have been done with several test configurations and a number of drivers. Besides the conventional instrumentation measuring the vehicle states also eye tracking glasses are employed. These glasses enable to detect the driver's gaze direction, which helps to understand the driver behavior as well as problems being faced by the driver during such a maneuvers. The results from these tests will be used to define a framework for a driver support system during reversing of multi-articulated vehicles.

Keywords: Rearward Driving, High Productivity Vehicles, Driver behavior, Eye tracking

1. Introduction

Longer and heavier vehicle (LHV) combinations, also known as high productivity vehicles, are being used worldwide for their increased capacity and economical benefits compared to conventional commercial vehicle combinations. As mentioned in several studies, for example [1, 2], this leads to a more effective and efficient transport process, which is also more environmental and road friendly. The fact that these combinations are usually composed of more than two vehicle modules implies also an increased number of articulation points linking the vehicles together.

Generally speaking, an increasing number of articulation points is favorable for forward low speed maneuverability. The swept path is minimized and the vehicle is easy to control by the driver as the space required to perform the maneuver and expected vehicle behavior is easy to anticipate. This is however not the case for the rearward driving. Then the towed vehicle that is being originally pulled by the prime mover will be pushed backwards, which may result in unstable behavior because the articulation angle tends to increase without actuating the steering wheel of the prime mover.

As concluded by the query published in [3], reverse maneuvering with multi-articulated vehicles is recognized as one of the most critical tasks by the majority of professional drivers and fleet owners in Netherlands. This scenario is also very specific, as it has resulted in number incidents with minor damage to the vehicles or property [3]. They are solely caused by driver errors [3]. It is very unusual, as in the majority of all documented accidents involving LHV's [3], the driver is not the originator of the accident. It can be explained by the high level of experience of drivers for 'normal forward' operation on the highway. However not everyone has sufficient skills for reverse driving with an arbitrary vehicle combinations. Moreover the kinematic behavior of every combination depicted in Fig. 1. is different, meaning the driver needs to apply a different control strategy to maneuver with the vehicle combination in reverse direction.

Figure 1. Most popular LHV's combination in Netherlands

A major complication is controlling the angle of the articulation points. If one wants to control the direction of the rear most vehicle while reversing, it needs to be done through steering of all preceding vehicles. This is however difficult as the vehicle combination is in most cases unstable. When the vehicle gets beyond controllability limits, it will develop a directional instability known as low speed jack-knifing. The driver has to drive forward and straighten the vehicle to bring the articulation angles into a controllable region again.

When the situation is too difficult for the driver, reversing could be solved by fully autonomous driving of the vehicle, which takes over the vehicle control entirely. Such an approach would however require installation of active control elements (e.g. active steering of axles [10], or electric power steering) and additional sensors on the vehicle combination. This represents additional investment for the fleet owner, which most likely will not be spent as soon as there is a driver who can handle reversing the vehicle combination.

Drivers are able to learn certain control patterns how to maintain the vehicle in the controllable condition as shown in practice. These patterns may be different for each driver and for some driver even very difficult to master or understand. In this paper we will concentrate on understanding the driver control decisions and behavior, as well as possible causes leading to mistakes, which result in losing controllability while reversing. Based on experiments we will try to identify a framework for possible support, which if provided, might lead to the reduction of the driver's errors and thus improve the driver performance during reverse driving. When using most of already present sensors, such a support system would not require large investments, and would represent an intermediate step between fully autonomous driving and nowadays driving controlled solely by the driver's intuition.

This paper is structured as follows. First, in section 2 the research method is described. Section 3 deals with the instrumentation of the test vehicle and sensors that were used to understand the driver behavior. Subsequently in section 4 the test program is explained. The measurement results are discussed in section 5 followed by section 6 where the model is used to define controllability region. The paper is concluded by section 7, which treats the results and draws final conclusions.

2. Research Method

The problem of controlling the directional stability during reversing of a multi-articulated vehicle is not a new challenge. One can find adequate information on this topic in the field of robotics, where the stability of the robot vehicles combination has already been solved by means of various control techniques. The variables to control are the articulation angles between the vehicles and/or the error between the position of the rearmost vehicle and required trajectory. To list some of the approaches, we refer to stabilization using a virtual truck [5], optimal control of the articulation angle [6], or learning based approaches realized through artificial neural networks [4]. These approaches seem to be functional for particular cases, however always have some limitations [7]. For example, an excessive steering velocity of the actuator may be requested, which cannot be met by the driver's physical capabilities. Another example is a requirement for a very high accuracy of the measured states in order to keep the feedback control loop stable. All these aspects compromise the robustness of the method and limit its general applicability.

This paper will not discuss the development of a new control strategy for steering the vehicle combinations while reversing. The goal is to better understand the driver as a non robust controller, trying to regulate the vehicle path based on the inputs, which are observable for him. Furthermore the inputs to the driver are corrupted by a measurement noise, which quantifies how well the driver is able to translate visual signals to a control action. This is of particular importance when processing the output from the rear mirrors.

The set of driver inputs is given by:

- Position of the prime mover as seen by the driver behind the windshield
- Position of the towed vehicles as seen by the driver from the rear view mirror
    - Articulation angle prime mover – 1st towed vehicle - γ_1
    - Articulation angle 1st towed vehicle – 2nd towed vehicle - γ_2
- A sound signal indicating the distance of the rearmost point of the vehicle combination to an obstacle

To control the vehicle path the driver is using:

- Vehicle velocity (both positive for forward driving and negative for rearward driving)

- The steering wheel angle

The driver is mostly seen as a controller, incorporating both a feed forward and feedback loop as depicted in Figure 2. [9].

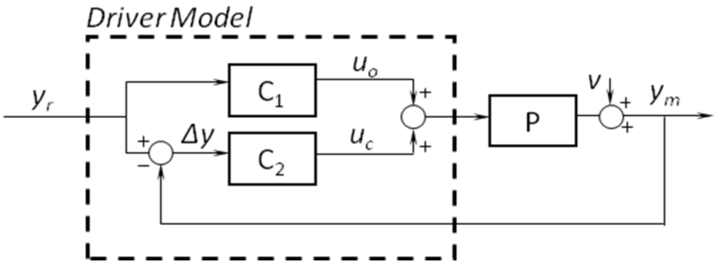


Figure 2. Driver model structure

The feed forward part usually represents the drivers understanding of the vehicle, its limits and general dynamic/kinematic response to the input, which may be different depending on the vehicle lay out. The closed loop part normally regulates plant (vehicle) inputs based on the trajectory deviation from the reference path, which is given by the driver's will.

In order to obtain a more in-depth understanding a series of the tests are carried out, with a double articulated vehicle. The vehicle has been operated by seven drivers with different levels of experience, while wearing eye tracking glasses. The measurement results combined with the model based approach will be used as a framework of the driver support system.

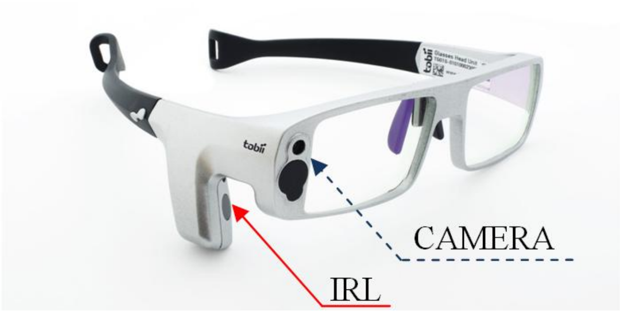
3. Instrumentation

A double articulated vehicle combination has been used for conducting the experiments. The vehicle combination consists of a 6x2 tractor, a 2-axle semitrailer and a 2-axle central axle trailer, as depicted in Figure 3. None of the towed vehicles is actively or passively steered. Both were equipped with deployable outriggers and a frame enabling vertical variation of the centre of gravity by means of concrete blocks, this feature was not used during the reversing tests.

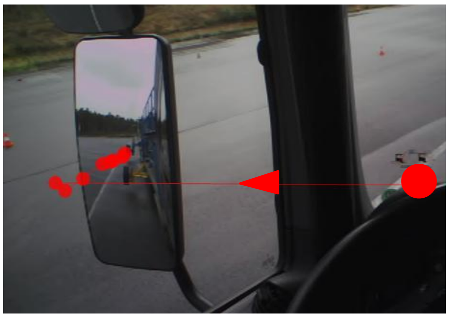
Figure 3. Test vehicle combination

The vehicle is instrumented to record vehicle states such as position, velocities, and accelerations for each vehicle body in translational and rotational direction. Furthermore the articulation angles between the vehicles are measured as well as the steering angle of the tractor. We also employ several cameras attached to the vehicle bodies to record the vehicle motion, these were however not accessible by the driver so he can not use them during the experiment as an aid.

To map the driver view and gaze direction we used eye tracking glasses [8]. The eye tracking is widely used in psychology research, cognitive linguistics and in product design. The glasses can be seen like an ‘eye scanner’. As can be seen in Figure 2.a), the glasses have an infra red light (IRL) emitter/receiver (red solid arrow) that emits the IRL beam to the pupil. The beam subsequently reflects back and based on the directional offset, the gaze vector can be determined.



a) glasses



b) glasses measurement output

Figure 4. Eye tracking glasses

A second part of the eye tracking glasses is the built-in SVGA camera, indicated by blue dashed arrow in Figure 4.a). The video signal of the camera is subsequently overlapped with the measurements of the gaze direction from the IRL sensor by means of a calibration file. This file is obtained for each driver separately by means of a prescribed procedure, when the subject looks to a predefined grid of external IRL emitters. This ensures sufficient measurement accuracy as the glasses might fit to each individual face differently. An example of the resulting video output screenshot can be seen in Figure 4.b). The red circles represent the gaze direction and their size is proportional to the time which is spent on that particular location. The line in between the circles represents the continuity of the gaze.

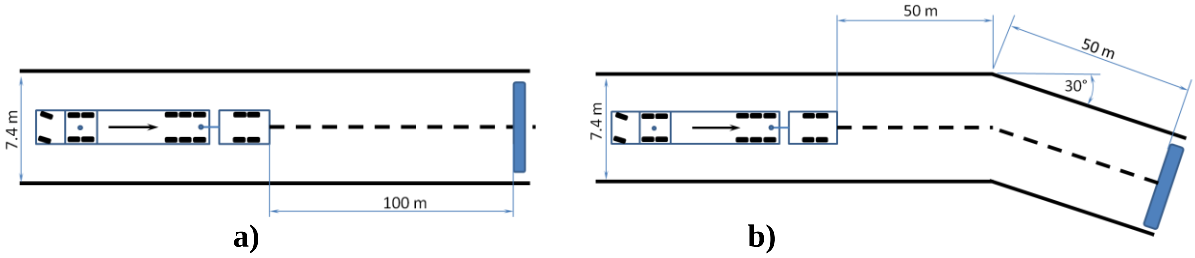
The eye tracking signal together with articulation angles and steer angle will be mainly used in the analysis.

4. Reverse driving

The tests were aimed at low speed reverse maneuvering and were done on the WABCO proving ground near Hannover. The measurements were conducted with seven test drivers of varying age and having a different level of experience. None of the drivers had previous experience with high productivity vehicles, although one has had some experience with a truck - full trailer combination, also having two articulations.

Two test scenarios were considered. Firstly all drivers were asked to perform hundred meters of reversing in a straight line within a 7.4 m wide lane as depicted in Figure 5.a). In case of undesired jack knifing drivers were allowed to correct the vehicle articulation angles by driving forward. The drivers could freely choose the velocity and strategy to finish the maneuver; the only requirement was to stay within the width of the lane. The maneuver was done in two configurations, without and with deployed outriggers.

The second reversing maneuver also included cornering. In Figure 5.b) the maneuver is illustrated. It starts similarly as in the previous case, but after fifty meters the direction of the lane is angled by thirty degrees. Here the drivers were allowed to cross the outside lane boundaries during maneuvering, but had to finish between the lines at the end of the curve. As this maneuver is rather complicated this test was undertaken only with four selected test divers, they performed best in the previous scenario.



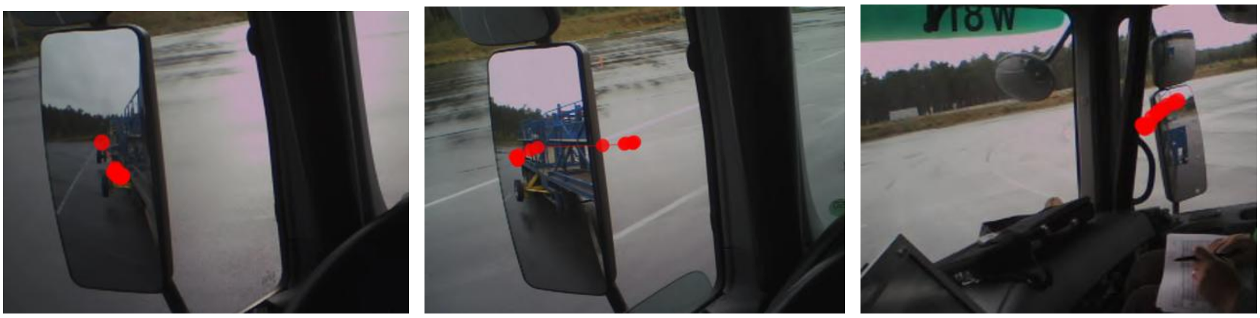
a) **b)**

Figure 5. Reversing maneuvers a) straight lane b) curved lane

Each maneuver was repeated three times for each driver and was concluded with an interview of the driver about his experience and possible problematic issues that were encountered.

5. Measurement Results

Several hours of measurement data were collected and analyzed. The analysis afterwards revealed that knowledge on articulation angles γ_1 and γ_2 between the vehicles is extremely important for the driver to control the vehicle combination. As observed however from the eye tracking data, this information is very difficult to obtain for the driver. He usually try to find reference points on the vehicle bodies, which are used to estimate the articulation angles as depicted on Fig. 6.a), where the outriggers are used for such a purpose.



a) b) c)

Figure 6. Eye tracking data

If those points are absent, or difficult to observe, the performance of the driver becomes substantially worse. This was confirmed by the case without deployed out triggers. The comparison of the performance for one selected driver is shown in Fig. 7. One can observe similar control of the steering angle in terms of amplitude and frequency, but after approx 70 seconds, due to inappropriate control, the articulation angles starts to diverge and vehicle without deployed outriggers became uncontrollable. It results to only a half of the travelled distance compared to the case when the outriggers were deployed.

Further analysis of eye tracking data reveals a critical situation for the driver in case of opposite articulation angles between the vehicles as depicted on Figure 8. During this situation the first semitrailer is obscuring the view on the second trailer. It is then particularly difficult for the driver to control the second articulation, as he does not have sufficient information about the angle. Referring back to Fig. 1, the driver is then forced to operate in the feed forward regime because only the angle for the feedback control is not observable as shown in Fig. 6.b) and c). It is very difficult for the driver and he is mostly not capable of controlling such a maneuver as appeared from the measurements. This situation will always occur when the vehicle needs to reverse a corner.

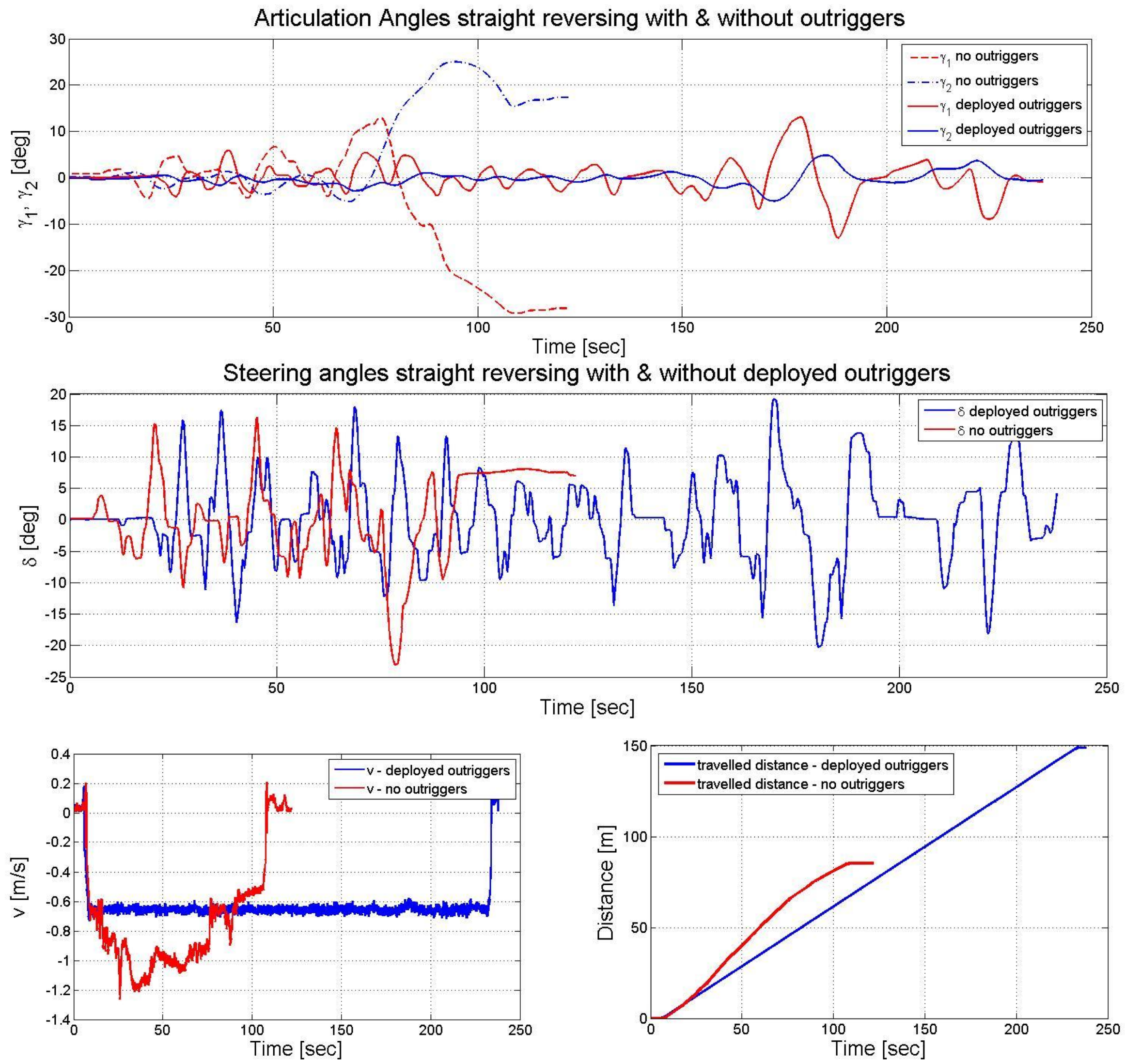


Figure 7. Performance comparison for the driver with and W/O deployed outriggers

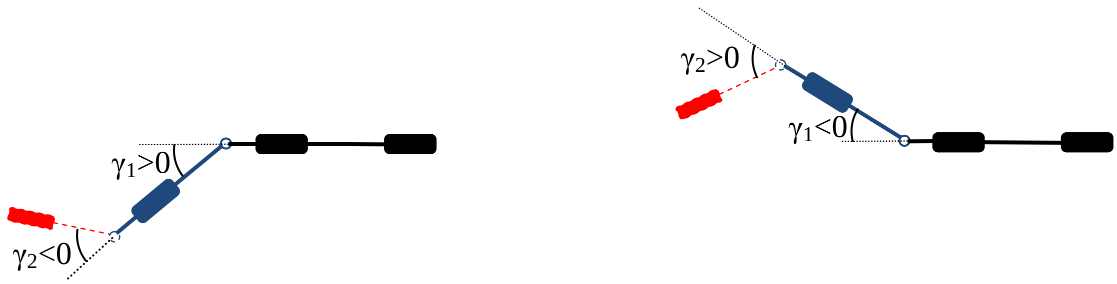


Figure 8. Situations when the second articulation angle is not visible for the driver

Furthermore the effect of the reversing velocity on the driver performance has been investigated. When drivers were asked to perform a straight reversing maneuver (see Fig. 5.a) during a higher reversing velocity, their performance according to the expectations dramatically decreases. This can be also seen in Fig. 8. Although here the driver was not specifically asked to reverse faster, the higher velocity most likely contributed to bad performance. This can be explained by the increased requirements for the steering rate and processing time. It is not analyzed in detail in this paper, but considering the steering angle as a main input to control the vehicle combination one might investigate the correlation between steering rate and reversing velocity. The steer rate is generally limited by physical and processing capabilities of the driver. Based on known capabilities of the driver, a limit reversing velocity can potentially be identified.

Finally it was observed, that the controllability boundary of the vehicle combination while reversing depends on the combination of articulation angles. When exceeding a threshold, there is basically no way to bring back the vehicle to straight position i.e. $\gamma_1 = \gamma_2 = 0$. Hence the driver needs to correct articulation angles by driving forward again. The main problem is that the driver is not able to identify the exact moment of exceeding the threshold. He tries to control already uncontrollable vehicle while continuing the reverse motion. It actually gets even worse and subsequently takes him many more meters of forward driving to reduce the articulation angles.

To identify in general the threshold limits the kinematic model of the single track double articulated vehicle is used.

6. Modeling

The model consists of three vehicle units, see Fig.9. The tyres in the axle group are substituted by the model of the axle and since kinematic steering is considered the model does not involve any tyre slip, which is simplification compared to the reality.

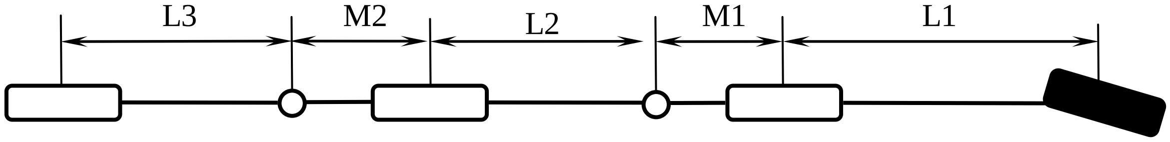


Figure 9. Kinematic vehicle model

We simulated a number of scenarios, with non zero initial articulation angles γ_1 and γ_2 and observed when the vehicle combination is able through the number of control actions, return to the straight line position. The control actions involve only variation of the steering angle δ in measured range of the steering mechanism. In our case the front wheel steering angle δ is operating within the range of -40 to 40 degrees. The initial conditions are established such that all possible combinations of articulation angles γ_1 and γ_2 within range of estimated mechanical limits from -100 to 100 degrees are simulated. Note that control strategy has not been optimized for any specific criteria, and works simply on the principle of logic stepwise minimization of γ_1 and γ_2 by steering angle δ, as depicted on Fig.10 for initial conditions $\gamma_1 = 30°$ and $\gamma_2 = 20°$.

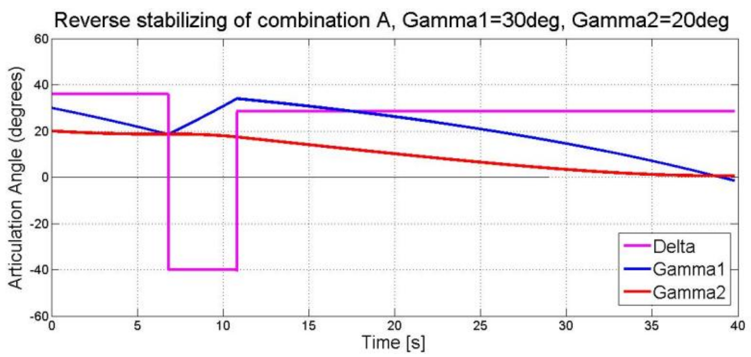


Figure 9. Stabilization of kinematic model

Due to the nonlinear character of the problem the threshold limits are not determined analytically, but in a series of simulations for specific vehicle combination. Firstly, we identified the limit case for the largest controllable γ_1 that is initially equal to γ_2. It results in generating controllability limit line for $\gamma_1 = \gamma_2$ represented by blue color on Fig. 10, which symmetrically splits the 1st and 3rd quadrant. Subsequently we collected all cases crossing the blue line, from its initial conditions by means of application arbitrary steering angle in interval (-40°:40°) before exceeding mechanical limits. Such cases are claimed as controllable. An example can be seen in Fig. 10. for two sets of initial conditions. The red lines originating at point (representing the initial conditions) $\gamma_1 = 10°$, $\gamma_2 = 45°$ and green lines originating at $\gamma_1 = 40°$, $\gamma_2 = 17°$. There are four curves coming from each origin, representing the response of the vehicle combination in terms of γ_1 vs. γ_2, when applying steering angle δ = -40°, -20°, +20°, +40°. In the first case we can see that γ_1 vs. γ_2 diverges from the blue line towards to the mechanical limits showing an uncontrollable case, contrary to the second case, which crosses the blue line and can be claimed as controllable.

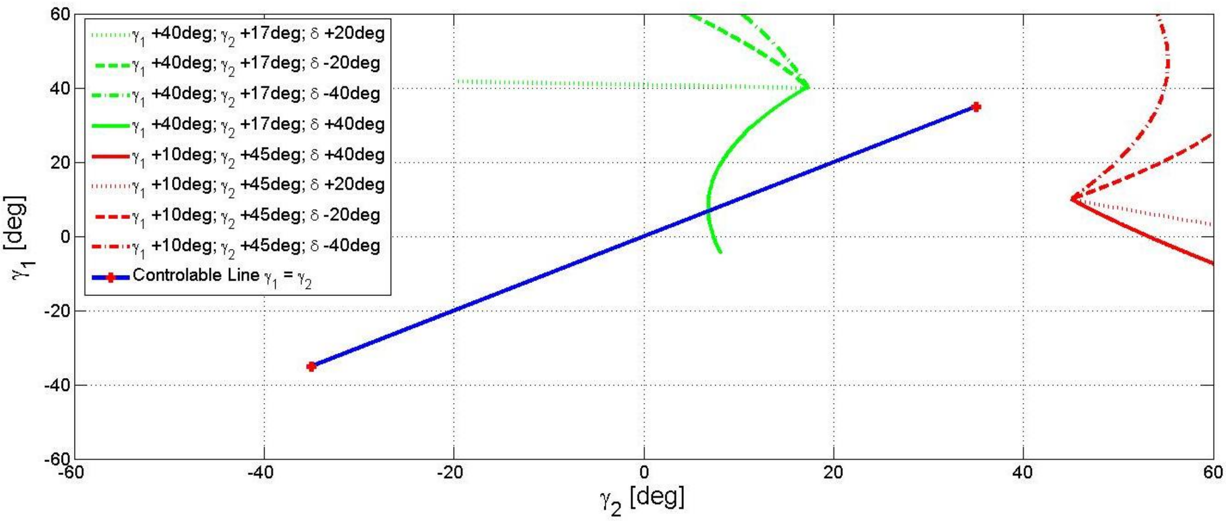


Figure 10. Kinematic model simulation results

As there exist infinity of controllability limit lines and we assumed only one, for the case $\gamma_1 = \gamma_2$, this approach is not as accurate and robust as the analytical one. On the other hand gives a good qualitative understanding of the controllability limits, with a minimal effort. The controllability region for the combination A is depicted on Figure 11. by green color circles, the red crosses label the combinations of γ_1 and γ_2, which can not be controlled by reversing to the state $\gamma_1 = \gamma_2 = 0$.

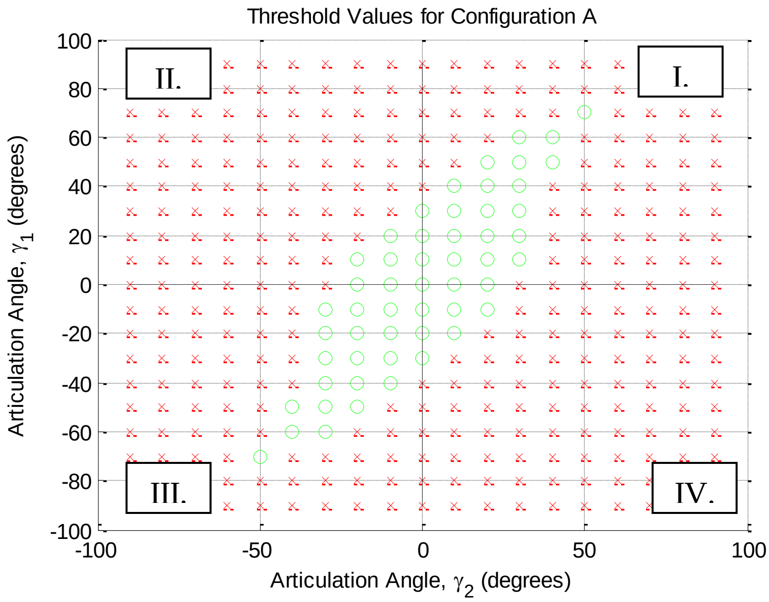


Figure 11. Controllability limits vehicle combination A

From Fig.11 one can see that controllable area for quadrants I. and III. is significantly larger than for quadrants II. and IV. It means that the driver should preferably control articulation angles that they have the same orientation. Further we can observe the symmetry in the graph around the origin. A larger controllability threshold is applicable for the first articulation angle γ_1, which might go up to ±70° compared to γ_2 that reaches its boundary at maximum ±50°.

7. Summary and outlook

A double articulated experimental vehicle operated by seven drivers was measured during two different reversing scenarios. Majority of drivers had problems to control the vehicle during the testing. For understanding the driver behavior an eye tracking glasses were employed. From the measurements can be concluded that drivers are controlling the vehicle through articulation angles, which are being estimated from available visual signal, as seen from rear view mirrors. Since this signal is during some situations not available, or difficult to process, it is expected that performance of the driver would improve if this information would be provided to the driver together with the controllability limits, which were defined in a series of simulations.

For the future research it is planned to evaluate the analytic model to determine the controllability threshold as well as to determine the maximal driving velocity limits corresponding with a driver's physical ability to control the steering angle.

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