

Automotive Engineering Project

Development of environments to test driver assist functions for
reversing an A-double combination vehicle

Project report

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CHALMERS
UNIVERSITY OF TECHNOLOGY

Report 2021:05

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Göteborg, Sweden
January 18, 2021

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Abstract

High-capacity transport vehicles are finding increased use in transportation to reduce costs and improve transportation efficiency. These vehicles have multiple trailers pulled by a single tractor and the A-double is an example of such a vehicle. Although A-doubles improve transportation efficiency, they are extremely difficult to manoeuvre in the reverse direction. The work done in the project aims to develop a rapid prototype environment that reduces development time and cost of controllers used to assist drivers in reversing the A-double. The assist functions developed using these environments help improve loading and unloading time while also reducing the stress levels of the driver(s). The testing and validation of the controller is done in two tiers. The first tier is a virtual environment to test the basic functionality and the second tier is a scaled environment to test the robustness and performance of the controller. Two control strategies have been developed to validate the test environments and their performance has been discussed. The performance of the test environments and possible improvements have been discussed.

1 Introduction

The Automotive Engineering Project(AEP) is part of the Masters Program in Automotive Engineering with the course code TME180 where the students work on a project in close collaboration with stakeholders in the automotive industry. This particular project deals with long heavy combination vehicles which are very transport efficient but need special solutions to certain practical problems. The project aims to aid develop a feasible solution to one such problem where the said configuration vehicle is facing difficulties in reversing into Göteborgs container harbour.

The prime reason for difficulty in reversing a longer and heavier vehicle combinations is due to multiple articulation points. Investigation of driver's behaviour and directional stability of the vehicle while reversing are considered as a baseline for developing support system framework for a driver. Previously, work has been done to develop similar support systems, like Matsushita et al[1] and J Morales et al[2], where 2 trailer vehicles have been considered for developing systems to assist the driver in reverse manoeuvres and avoiding jack knifing but all these previous works consider a simpler vehicle model or employ a complex controller. This report summarizes the work conducted at Chalmers university, Sweden on developing environments to test reverse assist functions. The environments developed during this project aid in testing semi-autonomous functions being developed to assist drivers during reversing an A-double combination heavy vehicle. These environments create a rapid prototyping platform which reduces development time and costs.

2 Background

An A-double combination consists of a tractor pulling a semi-trailer with a dolly and a draw-bar trailer behind it. It is used to increase freight capacity and improve transport efficiency. The A-double has a total of three pivot points, shown in Figure 1.



Figure 1: The A-double scaled prototype used in the experiments

The A-double is employed in Sweden as a part of the Autofreight project[3]. The A-double transports freight arriving at the Gothenburg harbour to the intended destinations. The A-double is hard to manoeuvre in the reverse direction and the driver has a difficult time backing up the combination into the designated slot specially during heavy traffic at the harbour. This can be overcome by detaching the combination

outside the harbour and driving the semi-trailers one at a time for loading. This increases loading time and decreases efficiency.

In order to improve loading and unloading efficiency and decrease work-related stress induced on drivers, a semi-autonomous driver assist function needs to be developed. The objective of this work is to reduce function development time and costs by creating test environments that aid in rapid prototyping.

The basic requirement of the assist function is to aid the driver in reversing the A-double to the desired loading bay while avoiding Jackknifing. Jackknifing refers to the folding of an articulated vehicle so that it resembles the acute angle of a folding pocket knife[14]. A schematic of the basic requirement is shown in Figure 2.

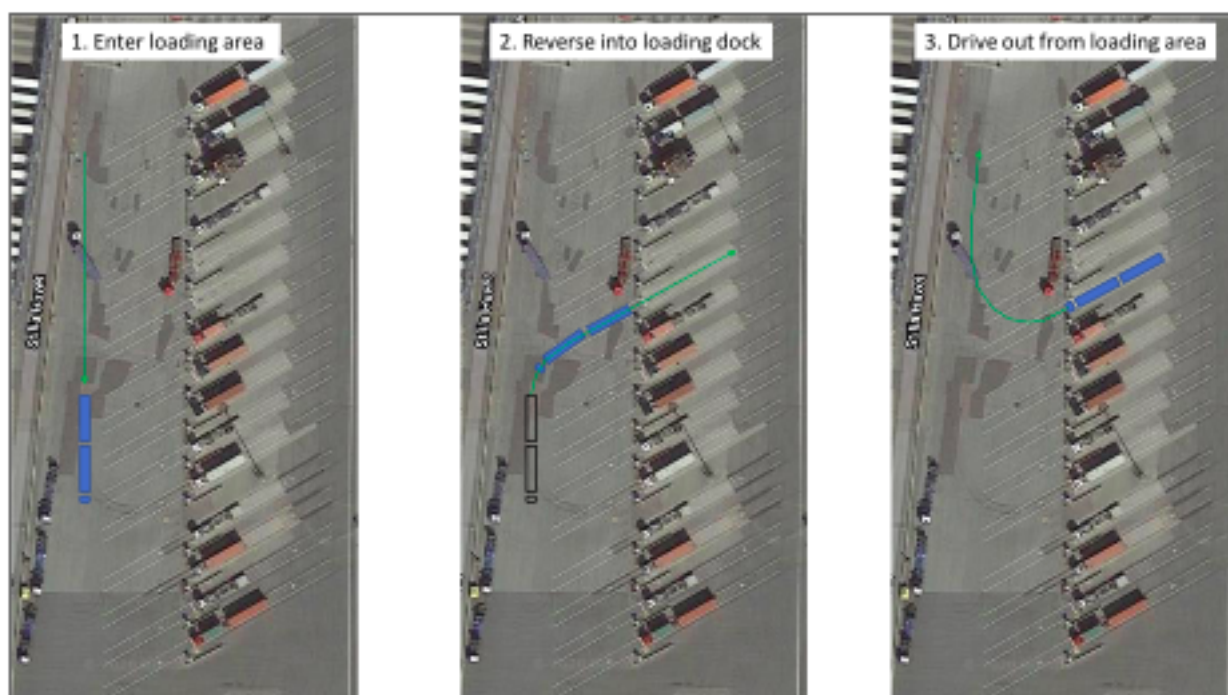


Figure 2: Schematic of the basic requirement of the assist function

3 Limitations

While developing a solution for the above stated problem, some limitations were considered. As the current project is in collaboration with the Auto-freight project, the limitations described here are specific to this project and are not limited to the ones listed here. The harbour is a high-security area and any employment of a plan view camera that shows the live layout of the harbour is not allowed. The driver must stay inside the vehicle when reversing. The use of multiple sensors to perceive the environment to develop a high level autonomous solution is limited as the trailers and dolly are modular. The array of sensors available are tabulated below.

Sl. no	Sensors	Location
1	Articulation angle sensor	Pivot 1 between tractor and trailer 1, pivot 2 between trailer 1 and dolly, pivot 3 between dolly and trailer 2
2	Global Positioning System (GPS)	Tractor
3	Rear view camera	Rear of trailer 2
4	Inertial Measurement Unit (IMU)	Tractor
5	Steering wheel angle sensor	Tractor
6	Vehicle speed sensor	Tractor

4 Method

As autonomous/semi-autonomous functions become common and necessary in automotive applications, it is essential to decrease the amount of time and cost associated with the development of these functions specially with heavy and long vehicle combinations such as the A-double which require a higher degree of preparation and planning if the functions were to be tested on the real vehicle.

Low velocity manoeuvres during loading and unloading these long combination vehicles contribute to major losses in efficiency. In order to develop functions to assist in these low velocity manoeuvres, test environments need to be created that provide a rapid prototyping platform where multiple control algorithms can be tested and validated at a rapid pace. In order to achieve this, two test environments were chosen to be developed after careful considerations of savings in time, cost and the ease of access.

The test environments developed are described in the following section.

5 Test environments

Considering the limitations and the sensors available for the development of the driver assist function for reversing, two test environments have been developed as part of the rapid prototyping platform. The first is a virtual environment that is used for preliminary tests in an ideal environment to verify function behaviour. The second is a scaled environment that uses a scaled prototype remote control (RC) vehicle to test control algorithms in an environment with a higher degree of fidelity.

5.1 Virtual test environment

The virtual test platform is a Simulink/MATLAB environment that uses a single-track kinematic vehicle plant model. The plant model is based on geometric relations and does not rely on force equations. The model provides the articulation angles as the output and requires velocity and steering wheel angle as the inputs. The virtual environment is ideal and does not consider disturbances and noise that are always present in a system and behave in an unpredictable fashion. The vehicle model does not take into account wheel scrub, tyre slip, axle loads, sensor noise, road unevenness and is simplified in many such aspects. A snapshot of a controller being tested in the virtual environment is shown in Figure 3.

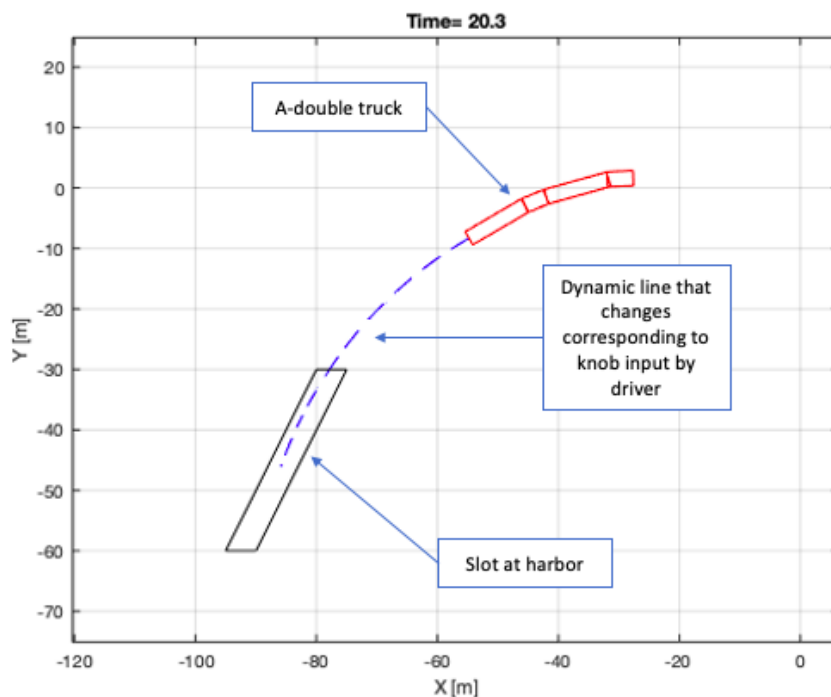


Figure 3: A snapshot of a test simulation in the virtual environment

The kinematic plant model is derived from the geometric relations shown in Figure 4. The vehicle combination consists of the four units, a tractor with length L_1 , first semi-trailer with length L_2 , dolly with length L_3 and the second semi-trailer L_4 . Here, length is the equivalent wheel base of each unit where multiple axles are collapsed into one centre axle.

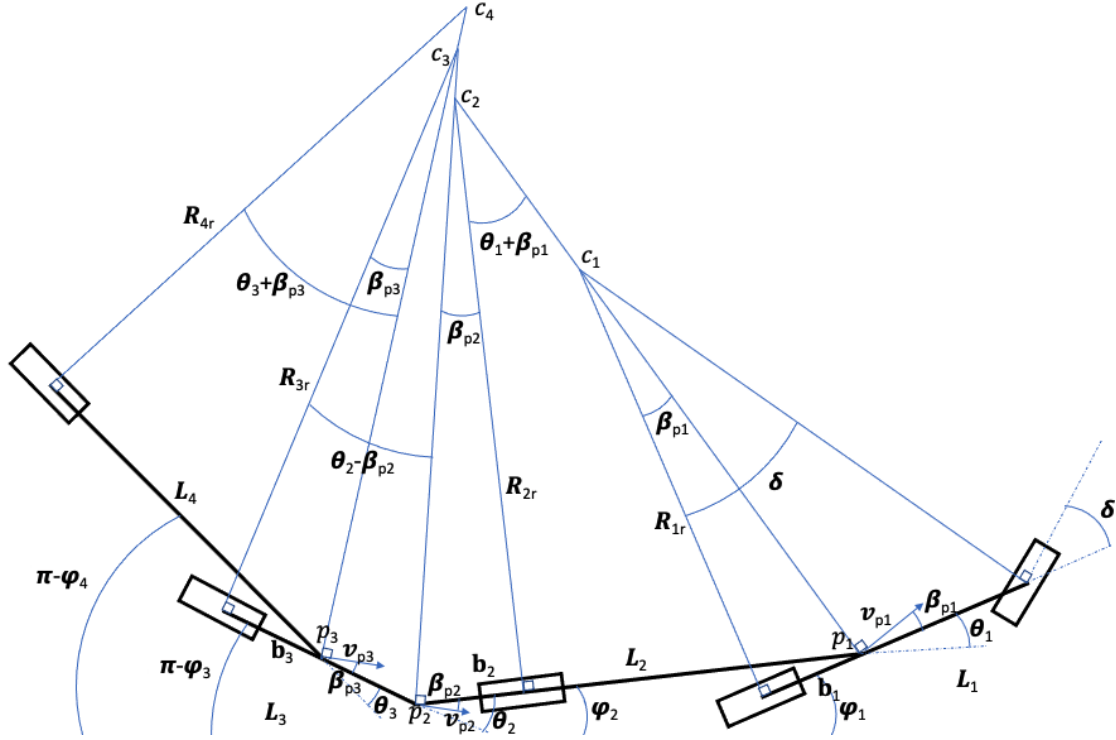


Figure 4: A-double kinematic diagram

- θ_1 = Articulation angle of trailer 1
- θ_2 = Articulation angle of dolly
- θ_3 = Articulation angle of trailer 2
- β_{p1} = Body slip of tractor
- β_{p2} = Body slip of trailer 1
- β_{p3} = Body slip of dolly
- ϕ_1 = Yaw angle of tractor
- ϕ_2 = Yaw angle of trailer 1
- ϕ_3 = Yaw angle of dolly
- ϕ_4 = Yaw angle of trailer 2

Tractor

The expression for the rear axle turning radius of tractor is expressed as

$$R_{1r} = \frac{L_1}{\tan(\delta)} \quad (5.1)$$

$$\tan(\beta_{p1}) = \frac{b_1}{R_{1r}} \quad (5.2)$$

Inserting R_{1r} from 5.1

$$\beta_{p1} = \tan^{-1} \left(\frac{b_1 \cdot \tan(\delta)}{L_1} \right) \quad (5.3)$$

The lateral velocity at point P_1

$$v_{yp1} = v_{1x} \tan(\beta_{p1}) \quad (5.4)$$

$$R_{1f} = \frac{L_1}{\sin(\delta)} \quad (5.5)$$

$$R_{p1} = \sqrt{b_1^2 + R_{1r}^2} \quad (5.6)$$

$$R_{p1} = \sqrt{b_1^2 + \left(\frac{L_1}{\tan(\delta)}\right)^2} \quad (5.7)$$

The yaw rate and the lateral acceleration of the tractor can be expressed as below respectively

$$\dot{\phi}_1 = \frac{V_{1x} \tan(\delta)}{L_1} \quad (5.8)$$

$$a_{yp1} = \frac{V_{1x}^2 \cdot \tan(\delta)}{L_1} + \frac{b_1}{L_1} (\tan(\delta) \cdot \dot{V}_{1x} + (1 + \tan(\delta)^2) \cdot \dot{\delta} \cdot V_{1x}) \quad (5.9)$$

Trailer 1

The trailer 1 is connected to tractor via articulation point p. The turning radius of the rear axle of trailer is expressed below

$$R_{2r} = \frac{L_2}{\tan(\theta_1 + \beta_{p1})} \quad (5.10)$$

$$R_{p2} = \frac{L_2}{\sin(\theta_1 + \beta_{p1})} \quad (5.11)$$

$$V_{2x} = V_p \cos(\theta_1 + \beta_{p1}) \quad (5.12)$$

$$V_{2x} = \frac{V_{1x}}{\cos(\beta_{p1})} \cos(\theta_1 + \beta_{p1}) \quad (5.13)$$

The lateral velocity at point P_2

$$V_{2yp1} = v_{yp1} \cdot \cos(\theta_1) + V_{1x} \cdot \sin(\theta_1) \quad (5.14)$$

The yaw rate of the trailer 1 is expressed as

$$\dot{\phi}_2 = \frac{V_{1x}}{L_2} \left(\sin(\theta_1) + \cos(\theta_1) \frac{b_1 \cdot \tan(\delta)}{L_1} \right) \quad (5.15)$$

The yaw rate of the trailer with respect to tractor is given by the difference between yaw rate of the tractor and trailer. And by integrating the yaw rate we determine the articulation angle θ_1 at point P_1 .

$$\dot{\theta}_1 = \dot{\phi}_1 - \dot{\phi}_2 \quad (5.16)$$

Dolly

$$\dot{\phi}_3 = \frac{V_{2x}}{L_3} (\sin \theta_2 - \cos \theta_2 \frac{b_2}{L_2} \tan(\theta_1 + \beta_{p1})) \quad (5.17)$$

$$V_{2yp2} = v_{2x} \cdot \frac{b_2}{L_2} \cdot \tan(\theta_1 + \beta_{p1}) \quad (5.18)$$

$$V_{3x} = V_{2x} \cdot \cos(\theta_2) + V_{2yp2} \cdot \sin(\theta_2) \quad (5.19)$$

$$V_{3yp2} = V_{2x} \cdot \sin(\theta_2) - V_{2yp2} \cdot \cos(\theta_2) \quad (5.20)$$

$$\beta_{p2} = \tan^{-1} \left(\frac{b_2 \cdot \tan(\theta_1 + \beta_{p1})}{L_2} \right) \quad (5.21)$$

$$\dot{\theta}_2 = \dot{\phi}_2 - \dot{\phi}_3 \quad (5.22)$$

Trailer 2

$$\dot{\phi}_4 = \frac{V_{3x}}{L_4} \cdot \left(\sin(\theta_3) + \cos(\theta_3) \cdot \frac{b_3}{L_3} \cdot \tan(\theta_2 - \beta_{p2}) \right) \quad (5.23)$$

$$V_{3yp3} = v_{3x} \cdot \frac{b_3}{L_3} \cdot \tan(\theta_2 - \beta_{p2}) \quad (5.24)$$

$$V_{4x} = V_{3x} \cdot \cos(\theta_3) - v_{3yp3} \cdot \sin(\theta_3) \quad (5.25)$$

$$V_{4yp3} = V_{3yp3} \cdot \cos(\theta_3) + V_{3x} \cdot \sin(\theta_3) \quad (5.26)$$

$$\beta_{p3} = \tan^{-1} \left(\frac{b_3 \cdot \tan(\theta_2 - \beta_{p2})}{L_3} \right) \quad (5.27)$$

$$\dot{\theta}_3 = \dot{\phi}_3 - \dot{\phi}_4 \quad (5.28)$$

The animation of the truck in simulation utilizes the motion of the pivot points in the X-Y global coordinates and the yaw angles of the various links calculated. The equations of motion for the three pivot points is given below. Here, the coordinates X1, X2 and Y1, Y2 are for the pivot point 1 between tractor and trailer 1 but are derived in terms of tractor and trailer 1 parameters.

$$\dot{X}_1 = V_{1x} \cos(\phi_1) - V_{yp1} \sin(\phi_1) \quad (5.29)$$

$$\dot{Y}_1 = V_{1x} \sin(\phi_1) + V_{yp1} \cos(\phi_1) \quad (5.30)$$

$$\dot{X}_2 = V_{2x} \cos(\phi_2) - V_{yp1} \sin(\phi_2) \quad (5.31)$$

$$\dot{Y}_2 = V_{2x} \sin(\phi_2) + V_{yp1} \cos(\phi_2) \quad (5.32)$$

$$\dot{X}_3 = V_{x2} \cdot \cos(\phi_3) + V_{yp2} \cdot \sin(\phi_3) \quad (5.33)$$

$$\dot{Y}_3 = V_{x2} \cdot \sin(\phi_3) - V_{yp2} \cdot \cos(\phi_3) \quad (5.34)$$

$$\dot{X}_4 = V_{3x} \cdot \cos(\phi_4) - V_{yp3} \cdot \sin(\phi_4) \quad (5.35)$$

$$\dot{Y}_4 = V_{3x} \cdot \sin(\phi_4) + V_{yp3} \cdot \cos(\phi_4) \quad (5.36)$$

5.2 Scaled prototype test Environment

The scaled test environment is a 1:14 RC model that has been equipped with multiple small computers, articulation angle sensors at each pivot point, multiple cameras, inertial measurement unit (IMU), vehicle speed sensors and WiFi connectivity. The scaled test platform runs on OpenDLV[8], which is the software platform used at Chalmers University and REVERE to develop autonomous vehicle functions.

Control algorithms that behave as expected in the virtual environment can be further tested and verified on the scaled platform that introduces factors such as noise, surface unevenness, axle loads and other actuator limitations that make the test results closer to reality.

The plant model is shown in the scaled environment in Figure 5. The Next Unit of Computing (NUC) on the RC vehicle is similar to computers found on the real tractor, it stores and runs the control algorithm. The algorithm is uploaded remotely and any modifications to the code can be done remotely. The algorithm is then tested in a safe and controlled environment. The scaled plant model behaves closer to reality but falls short of the real vehicle in terms of tire grip, accurate axle load induced dynamics, suspension behaviour and other similar factors. The prototype model used in the scaled environment is shown in Figure 5.

This environment looks to provide realistic results while lowering the costs and time that are associated

with testing on a real vehicle. It requires minimal space and personnel to test in contrast to testing on the real vehicle. The environment will provide consistent results regardless of weather conditions, surface conditions and so on. The environment can also be modified or controlled to suit the requirements of the tests being conducted. The test track used in the scaled environment to test and validate control approaches in a safe and controlled manner is shown in Figure 6.

The control algorithms that behave as expected in the test environments can be further tested and validated in the real vehicle combination. This process eliminates control approaches that do not behave as expected in the test environments and improves function development time.

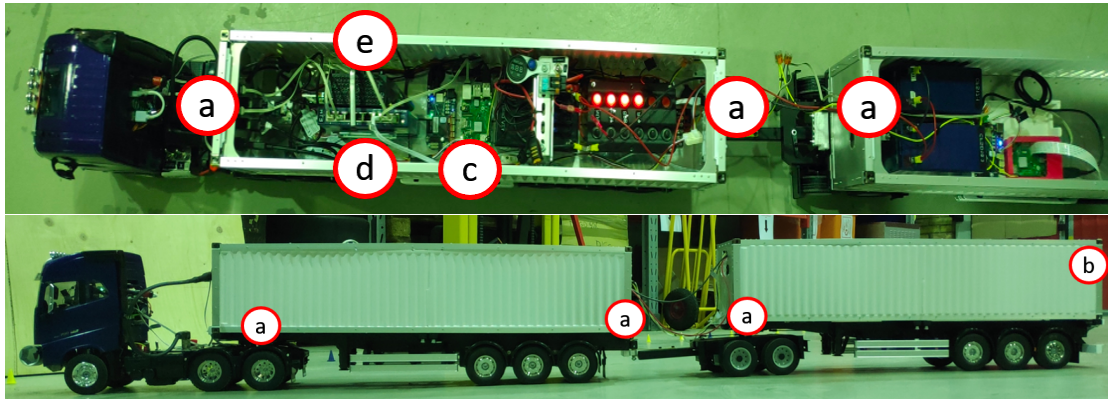


Figure 5: Scaled Prototype

The components used in the scale model are tabulated below:

Sl. no	Sensors	Location
1 (a)	Articulation angle sensor (Grove 12-bit magnetic rotary sensors)	Pivot 1 between Tractor and Trailer 1, Pivot 2 between Trailer 1 and Dolly, Pivot 3 between Dolly and Trailer 2
2	Raspberry pi3	Tractor, Tractor 1 and Trailer 2
3 (b)	pi camera	Rear of Trailer 2 and Tractor cabin
4	Inertial Measurement Unit (IMU)	Tractor, Tractor 1 and Trailer 2
5 (c)	Beaglebone board	Tractor, Tractor 1 and Trailer 2
6 (d)	Next unit of computing (NUC)	Trailer 1
7 (e)	Ethernet and WIFI connectivity	Tractor, Tractor 1 and Trailer 2



Figure 6: Test track used in the scaled environment

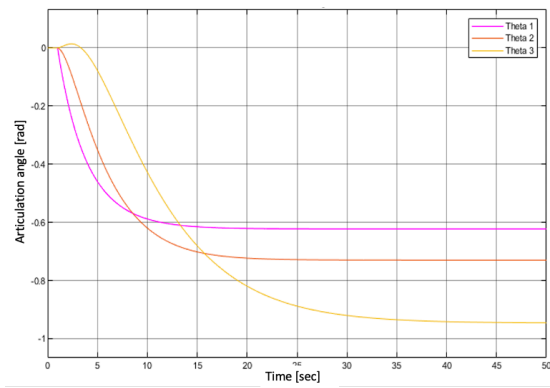
6 Model Validation

The plant models in the virtual environment (kinematic vehicle model) and the scaled environment (RC vehicle) have been compared to Volvo Truck Model (VTM), which is a high fidelity plant model developed and used by Volvo Group.

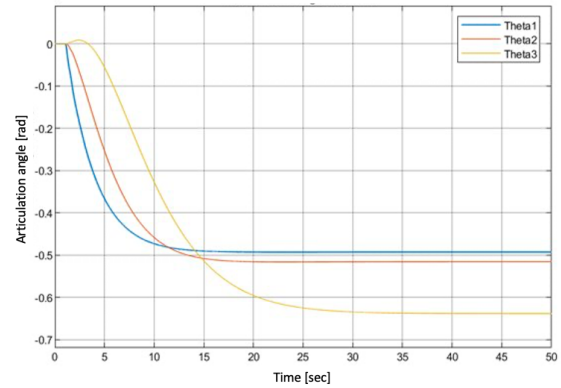
A step steer manoeuvre was conducted on all three vehicle models and the articulation angles at each pivot point was recorded against time. It can be seen from the figure with the plots that the three models behave similarly with some variations which is to be expected. Subplot (a), subplot (b) and subplot (c) in Figure 8 show the simulation data from the virtual environment, simulation data from VTM and sensor data from the scaled environment respectively.

It can be noticed that the amplitudes of subplots (a) and (c) are quite similar but the scaled environment takes longer to reach similar values. This can be attributed to the high slip of the steered wheels on the scaled model as it is unable to develop sufficient lateral force due to lack of grip at the wheels whereas the virtual environment is ideal and only considers the geometric relations.

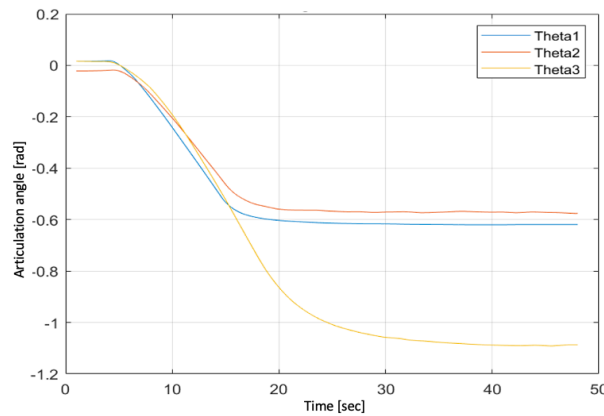
Comparing subplots (a) and (b) show that the two models behave alike and that the kinematic model is a good approximation at low speeds. However, it can be seen that the amplitudes are lower in the VTM plot, this is due to the consideration of wheel scrub, king-pin friction and other effects which reduce the articulation angle amplitudes at pivot points. The results obtained show that the test environments behave as expected at low velocity manoeuvres.



(a) Kinematic Model



(b) VTM



(a) Scale Model

Figure 8: Articulation Angles

7 Control approaches

The test environments developed have been tested and validated using some basic control approaches. This is to verify that the test environments behave as expected and that the results obtained are acceptable. The following section provides the description regarding the control algorithms used to test the environments developed.

7.1 Pure Pursuit Control

The Pure Pursuit Controller (PPC) is a line following algorithm where a reference path generated on a global plane is followed by the truck. The look ahead distance, the reference longitudinal velocity and path are the inputs to the function block . The outputs of this function block will be the desired longitudinal velocity and the target direction, this target direction is then converted to a required steering angle to trace the required path.

7.1.1 Reference Path

The reference path is the way points on the global plane in x-axis, y-axis and θ (Angular Orientation). This can either be loaded into the controller as GPS way points or it can also be traced on the ground. Pre-loading the way points helps in reducing the complexity of the control system but is not advisable if the vehicle docks at multiple places or if it has to dock in different orientations. A path on the ground can be traced using infrared LIDAR or camera perception using OpenCV algorithms.

7.1.2 Look Ahead Distance

The main tuning parameter for this controller will be 'look ahead distance' and it is the distance between the reference point of the truck to the intersection point of the reference path. If we consider a virtual circle centered around the reference point on the truck, then the radius is the look ahead distance.

7.1.3 Target Direction (α)

Target direction for the vehicle is the difference between the heading angle and the angle created by the intersection point to the reference path. This angle is then converted into a desired steering input for the combination by using relationship between the wheel base, look ahead distance and target direction.

7.1.4 Function Description

The information about the intended line path tracked by IR LIDAR is visualized by the driver through a rear view monitor. The path is shown in red. The driver must monitor the progress of the vehicle for any deviations or obstacles.

The controller is designed by considering the limitations of parameters like vehicle's velocity, articulation angles and look-ahead distance. If the vehicle exceeds the limitations set, the controller must warn or abort the manoeuvre. The driver is the prime decision maker and must abort/stop in case of obstacles or other harmful circumstances.

Functional requirements for this control system can be defined as follows.

Max lateral deviation = 1m

max deviation of articulation angles = 0.2 degrees.

A schematic of the function description is shown in Figure 9.

Input Signals to Controller	Output Signals from controller	Input to driver
Articulation angle sensor [rad]	Steering Wheel Angle [rad]	Reference line from IR LIDAR in HMI
velocity sensor [m/s]	Vehicle Velocity [m/s]	-
Reference Path	-	-

Table 1: Input and output signals for reverse assist function using PPC

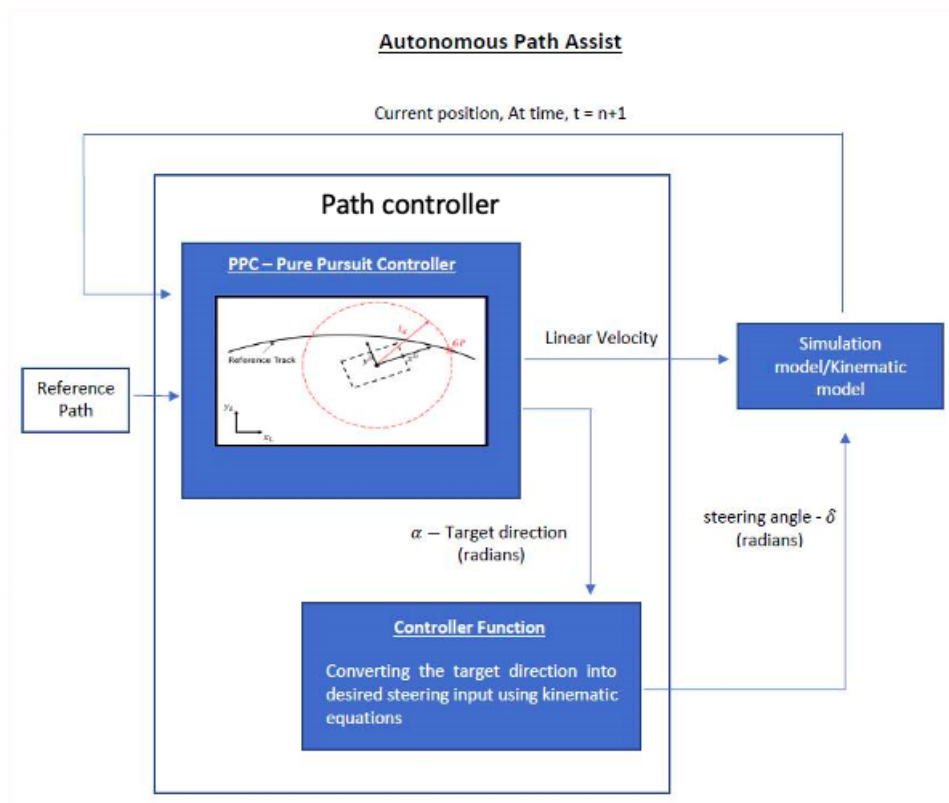


Figure 9: Function Description

The PPC was tested in the virtual environment and the method and results are discussed below.

7.1.5 Reference path generation

The reference path is generated using Driving Scenario Designer which is an inbuilt app under vehicle dynamics toolbox. This enables to design the driving scenarios to test automated driving. This is used to get the way points as a reference path in global plane in terms of x-axis, y-axis & θ (Angular Orientation).

7.1.6 PPC control block

The basic control algorithm is generated using PPC block from the Robotics system toolbox. This standard function block needs an input from reference path (way points), current position (vehicle model), look ahead distance and reference velocity, the outputs being the desired longitudinal velocity and target direction.

7.1.7 Forward direction Tractor + Semi-Trailer

The control strategy was first deployed on Tractor + Semi-Trailer moving in forward direction and tractor being the leading combination in this case and the current positions are from the leading combination (Tractor). The required steering angle is derived from the wheel base of the tractor, look ahead distance and target direction.

$$\delta = \tan^{-1} \left(\frac{2 * L * \alpha}{L_d} \right) \quad (7.1)$$

Where,

L = Wheel Base of the tractor (m)

α = Target Direction (Rad)

L_d = Look Ahead Distance (m)

δ = Steering angle (rad)

7.1.8 Reverse direction Tractor + Semi-Trailer

The control strategy was then deployed on Tractor + Semi-Trailer moving in reverse direction and semi-trailer being the leading combination and the current positions are from the leading combination(Semi-Trailer).

The desired yaw rate of trailer 1 computed by PPC is substituted in Equation (5.15) of the kinematic model developed earlier to obtain the desired steering wheel angle at the tractor

The equation used to calculate the desired steering wheel angle is,

$$\delta = \tan^{-1} \left(\frac{k \cdot \varphi \cdot \frac{L_2}{v_{1x}} - \sin(\theta_1)}{\cos(\theta_1) \cdot \frac{b_1}{L_1}} \right) \quad (7.2)$$

Where,

L_2 = Wheel Base of the trailer (m)

φ = Heading angle from PPC for trailer (rad)

v_{1x} = Desired velocity(m/s)

θ = Articulation angle (rad)

b_1 = Distance from Pivot 1 to Rear axle of tractor (rad)

k = gain

7.1.9 Results

The control approach using PPC works as expected for the Tractor + semi-trailer combination in the virtual environment but fails to work as intended for the A-double and requires further research and development. The results from the tractor + semi-trailer combination are discussed in the following section.

The main variables that can be tuned to get the desired effect from the simulation are look ahead distance, longitudinal velocity and gain.

When a large look ahead distance is used, the phenomenon of corner cutting is observed where the truck + trailer combination traces a shorter path around the reference path but it is also observed that the path traced during this setup is smoother meaning the controller makes fewer but larger corrections.

When the look ahead distance is smaller, the trajectory is oscillatory meaning the controller makes many minor corrections. The plots showing the comparison between large, small and optimal look ahead distance is shown in Figure 10.

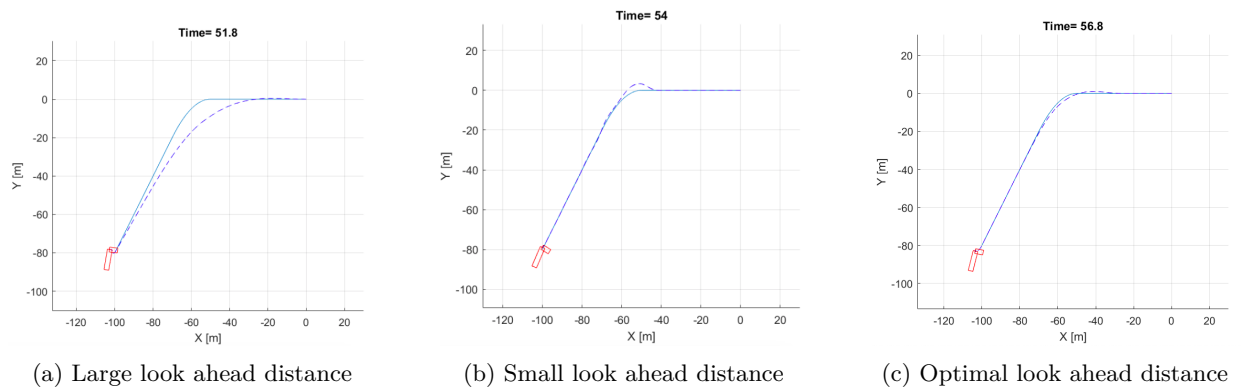


Figure 10: Look ahead distance sensitivity

A high reference velocity increases the deviation from the reference path and the vehicle combination takes a less than optimal trajectory. A lower velocity increases simulation time and decreases efficiency.. An optimal reference velocity is to be chosen to obtain the best possible trajectory while keeping simulation time low and efficiency high. The plots comparing different reference velocities is shown in Figure 11.

The gain factor 'k', used in equation (7.2) is another variable that is used to tune the controller to obtain the desired behaviour.

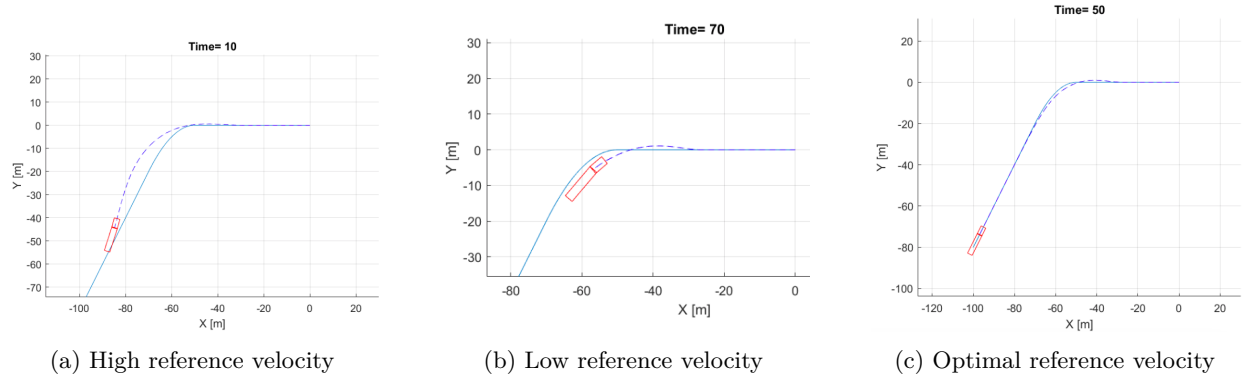


Figure 11: Reference velocity sensitivity

7.1.10 Discussions and future work

The experiments conducted using PPC show that a slightly more complex controller is required to develop an assist function using this approach. Studies show that a controller to follow a given path such as PPC must be assisted by another controller that maintains the articulation angles within set limits to avoid jack-knifing.

The plan for future work is to utilize a knob controller to maintain the articulation points within limits while the PPC will maintain the orientation of the whole combination.

LQR (Linear Quadratic Regression) algorithm to stabilize the articulation angles and to keep it within the safety envelope to avoid jack-knifing is an approach being developed by another similar project in collaboration with this project where the test environments developed in this project are being used to test and validate this algorithm.

7.2 Radius Control

Every axle on a vehicle turns about the centre of a circle with a certain radius such that the axle is always aligned along an imaginary radius line. A point on the centre of the said axle follows the circumference of this circle. The turning radius followed by the last link of the articulated combination (trailer 2) in reverse will be the direction of motion of the whole combination provided that it is a steady state low speed reversing manoeuvre.

7.2.1 Reference path

The path to be followed by the combination is obtained by setting the desired radius of the turn to be taken by trailer 2 in reverse direction. This is an input from the driver based on the current orientation of the vehicle and the desired destination. The controller relies on the availability of a rear view camera at the end of combination. The rear view monitor must project dynamic lines on the ground that correspond to the radius of the turn being chosen. The desired path to be followed, given by the radius of the turn can be adjusted by the driver during the manoeuvre to make necessary corrections to the direction of travel.

7.2.2 Function description

The rear view camera displays the space behind the second trailer and projects a dynamic line on the ground which is depicted by red line from rear centre of the second trailer that corresponds to the desired path which is an input provided by the driver through the radius control knob. The dynamic line and hence the projected path to be followed changes with the position of the knob, this is to help the driver perceive the trajectory the second trailer will follow and hence help set the desired trajectory and make necessary corrections during the manoeuvre. Once the desired trajectory is set, a velocity input is provided using the velocity knob. The rear view monitor and knob are shown in Figure 13.

The controller then computes the necessary steering input required to follow the set trajectory using the articulation angle sensor values, steering angle sensor value and the desired radius of path set by the driver.

Any deviation in the path being followed due to noise and other disturbances can be corrected by the driver by making necessary changes to the radius of the reference path using the knob.

Since the orientation of the rear trailer is of importance, a radius correction factor is introduced which effectively moves the axle from its original position to the rear end of the trailer and the deviation of the rear end of the trailer changes with different correction factors. An optimal correction factor must be introduced to keep the deviation minimal.

A schematic of the function description is shown in Figure 12.

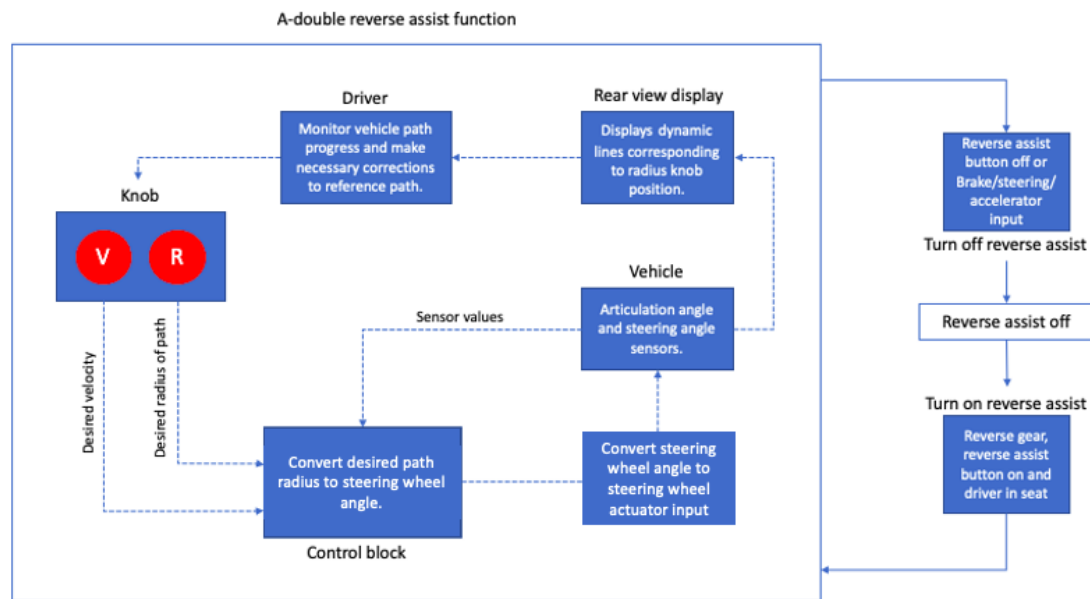


Figure 12: Function description of radius control strategy

The input signals required by the controller, the output signals produced and the inputs to the driver are tabulated below.

Input signals to controller	Output signals from controller	Input to driver
Articulation angle sensor [rad]	Steering wheel angle [rad]	Dynamic lines in rear view display
Steering wheel sensor [rad]	vehicle velocity [m/s]	Vehicle progress from rear view display and mirrors
velocity sensor [m/s]	-	-
Radius knob position	-	-
Velocity knob position	-	-

7.2.3 Human machine interface (HMI)

The HMI consists of the rear view monitor and a control panel of three knobs. One knob is used to set the desired path radius and the other is used to provide a velocity input.

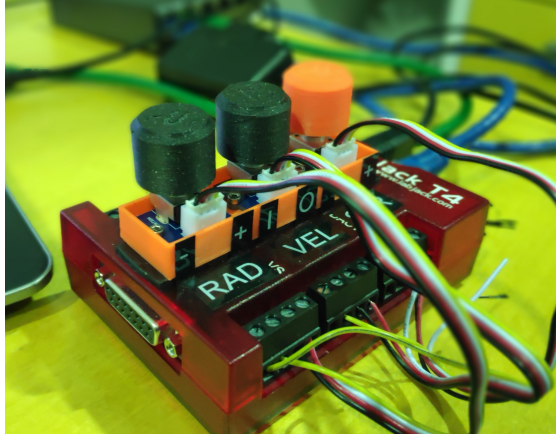
The radius knob has a 0 position which corresponds to a straight reversal path which is a turn radius of infinity and hence the midpoint of the axle on trailer 2 follows the circumference of a circle infinitely large and the dynamic line on the rear view monitor is a straight line.

Turning the knob in either direction will set the radius of the path corresponding to the position of the knob and the dynamic lines on the rear view monitor show the curvature of the path corresponding to the set radius.

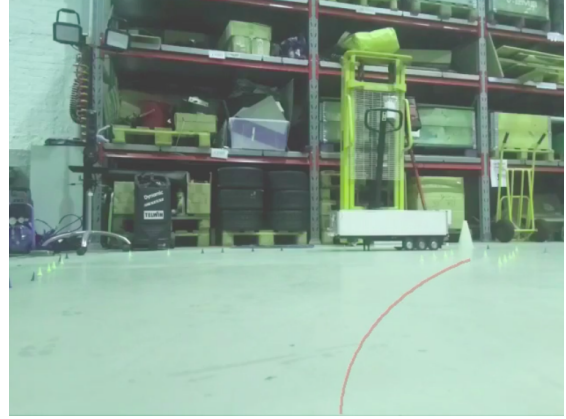
This HMI is intuitive and provides assistance to the driver by converting the whole combination with multiple articulation points into a vehicle with no articulation points where the algorithm controls the

articulation points.

The knob and the rear view monitor which is part of the HMI is pictured below in Figure 13. The left most knob is used to set the desired path and to make corrections in path during manoeuvre. The knob in the centre is to provide velocity input and the rightmost (Part of scaled model prototype only and is used to straighten the steering wheel offset in RC model).



(a) Knob panel



(b) Rear view monitor

Figure 13: Prototype HMI

7.2.4 Control block

When the radius of curvature of the desired path to be followed by trailer 2 is set, the articulation angle, θ_3^* which is required for the trailer 2 to follow this path is calculated by substituting and expanding Equations (5.27), (5.21), (5.3) and (5.1) from kinematic model developed earlier into equation:

$$\tan(\theta_3 + \beta_{p3}) = \frac{L_4}{R} \quad (7.3)$$

The error is then computed from the current articulation angle, θ_3 from sensor and the desired articulation angle. The correction needed for the calculated error is provided by a change in articulation angle at pivot point 2 (between dolly and trailer 1). This correction is then provided by a correction in articulation angle at pivot point 1 (between trailer 1 and tractor) which is then provided by an input to the steered wheels on tractor via steering wheel.

The equations used in the control block are as follows:

$$\theta_3^* = \arctan\left(\frac{L_4}{R}\right) - \arctan\left(\frac{b_3}{L_3} \cdot \tan\left(\theta_2 - \arctan\left(\frac{b_2}{L_2} \cdot \theta_1 + \arctan\left(\frac{b_1}{L_1} \cdot \tan(\delta)\right)\right)\right)\right) \quad (7.4)$$

$$\theta_2^* = -k_3 \cdot (\theta_3^* - \theta_3) \quad (7.5)$$

$$\theta_1^* = -k_2 \cdot (\theta_2^* - \theta_2) \quad (7.6)$$

$$\delta^* = -k_1 \cdot (\theta_1^* - \theta_1) \quad (7.7)$$

Where,

R is the desired radius of turn.

$\theta_1^*, \theta_2^*, \theta_3^*$ are the desired articulation angles at pivot points 1, 2 and 3 respectively.

δ is the current steered wheel angle.

δ^* is the required steered wheel angle.

k_1, k_2, k_3 are positive numbers.

The desired articulation angles at pivot points 1, 2 and the steering angle required are calculated using errors and gains. The behaviour of the vehicle changes with the value of gains. These gains must be tuned to obtain the desired behaviour of the tractor. The optimal gain values for the simulation were obtained through iteration.

7.2.5 Results

The radius control strategy works as intended for the whole combination in the virtual environment. The vehicle follows the desired path and the prototype HMI works as intended.

The vehicle follows the desired path successfully without much correction needed to the reference path radius at low vehicle velocity. As the velocity increases, the orientation of the trailer 2 changes rapidly and hence the reference path radius needs to be corrected more often by the driver in order to compensate for the change in orientation of trailer 2. Hence the driver needs to be attentive and make necessary corrections at a higher rate. It is therefore recommended that the manoeuvre be carried out at low velocities below 2[m/s]. The gain values obtained through iteration for the intended behaviour of the A-double are:

$$k1 = -1$$

$$k2 = -5$$

$$k3 = -13$$

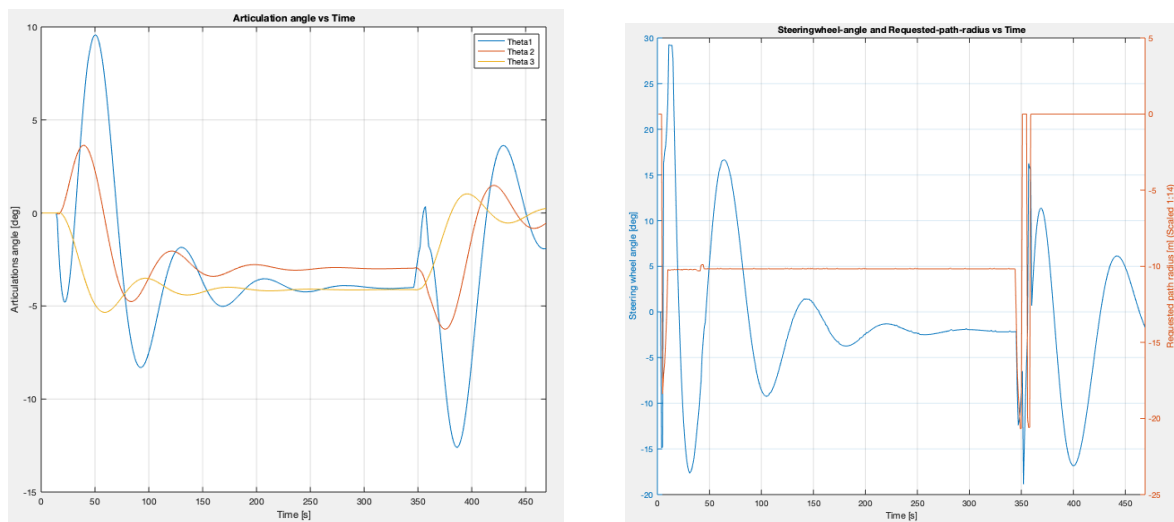
The minimum path radius the A-double can reverse into in the virtual environment is 40m and the scaled environment is 65m.

As the radius control strategy performed as intended in the virtual environment, it has then been tested in the scaled environment. The results from the scaled environment are discussed in the following section.

Tests were carried out on the tractor + semi-trailer combination to ascertain the degree of compliance in moving from virtual to scaled environment. Once the results were deemed satisfactory, tests on the whole combination were conducted.

It was observed that the vehicle followed the desired path and several reverse parking manoeuvres were conducted to evaluate the controller and the test environment. As discussed earlier in the virtual environment section, the reverse velocity must be as low as possible to achieve the desired path radius with minor corrections. The requested path radius, calculated steering angle for the desired path and the articulation angles of the A-double are plotted for a reverse manoeuvre in Figure 14

A snapshot of the video demonstration of the scale model performing a reverse parking manoeuvre is shown in Figure 15. The bottom left corner shows the video feed to the rear view monitor.



(a) Articulation angle vs Time

(b) Requested path radius and calculated steering wheel angle vs Time

Figure 14: Test data from scaled model



Figure 15: Snapshot of radius control on prototype

7.2.6 Discussions and future work

As the radius control performed as expected in both the virtual and the scaled environment. The next step is to test and validate the controller in the real vehicle combination which is yet to be conducted.

As the radius control only partially uses the kinematic vehicle model developed earlier in the project, the performance is affected by gains to a major extent. The performance of the controller can be improved by developing a linear vehicle model or linearizing the model already developed. Although this would increase the complexity of the controller, it is yet to be ascertained if the improvement in performance will justify the complexity.

As the HMI is an important aspect to be considered in development of a driver assist function, the HMI developed in this project needs to be evaluated in terms of usability by conducting reviews and tests by drivers handling A-double vehicles.

The robustness of the controller also needs to be evaluated in different surface conditions, weather and time of day as all these can affect the performance of the controller and the HMI.

8 Results and Discussion

The rapid prototype platform consisting of the two environments developed in the project effectively reduces significant amount of testing and development time of controllers. The two tier prototype platform also provides an opportunity to compare the results from two different environments which improves the validation accuracy. The environments helped understand the areas of improvement of the controllers being tested at a fraction of the cost and time it would have taken to test the controllers in the real vehicle combination.

The test environments have been validated and can aid in development of more complex controllers for low-velocity manoeuvres of an A-double at a rapid pace. The test environments are currently being used by another similar project to test and validate a reverse assist function for an A-double.

It was noted that the tires play an important role even at low velocity manoeuvres. The approximations made in the virtual environment led to a behaviour that is quite different from reality in regards to tire scrub and lateral force generated by the tires, most importantly the steered wheels. The environment also does not consider ground irregularities and noise from sensors. The environment can be improved further by adding these factors.

The effect of tire dynamics and noise become more evident when testing the controller on the scaled environment. Although the behaviour of scaled environment deviates from reality as well, the deviation is much smaller than the virtual environment. The factors deviating the prototype from reality the most are friction between the tires and ground, and its ability to handle surface irregularities. It was found that the steered wheels were unable to generate enough lateral force and were often found slipping. Attempts of increasing vertical loads to match the scale were made but it was noticed that the servo mechanism on the RC model was unable to bear these loads. A last resort to increase friction was made using WD40 on the tyres to soften the tires and increase grip. This showed a small improvement.

The surface irregularities create high disturbances at the dolly. As the dolly is a very sensitive link in the A-double combination, it impacts the performance of the controller being tested.

9 Ethics

Ethics in engineering is becoming important everyday with the advances in technology. In this project, we are working to improve the efficiency of an operation that reduces the amount of energy spent which translates to lower costs and resources consumed which in turn reduces the burden on the environment. The project also looks to reduce the work and stress of the truck drivers involved in this project which in turn reflects their behaviour on the road. A human being operating such heavy machinery must be alert and calm at all times, the developments made in this project reduces the stress of the human operators involved and makes roads in the world safer.

Although the project helps development of assist functions, it must be stressed that the functions developed using these test environments must be used responsibly and that the drivers using these functions must be vigilant at all times and to make sure no harm is caused to life and property.

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