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Assessment tool for performance of high capacity combination vehicles including envelopes for A-double vehicles

Master's Thesis in Automotive Engineering

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CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2017

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Abstract

The technological advancements in the automotive industry in past few decades has resulted in a rapid rise in the number of vehicles. In addition to private vehicles, heavy duty vehicles (HDV) have also increased, which play a big part in transporting goods for import, export, and businesses. These rapidly rising numbers, on one hand, contribute to the convenience and development also on the down side contribute to the emissions. In a study conducted in 2017, it was found that 26% of the total CO_2 emissions in Europe came from the HDVs and more than 3/4th of these emissions were from the trucks. In the recent years, a lot of research has been done in the commercial vehicle industry that is focused on making transportation more sustainable and to reduce the emissions.

One of the well-established ways for achieving sustainability in transportation and lower the emissions is by improving the efficiency of vehicles. Using long combination vehicles (LCV) has been proven as one of the ways of tackling this problem and also addressing the issue of congestion on roads. Currently, the allowed maximum length of HDV in Sweden is 25.25 m. In the case of LCVs two or more trailers are used on the same HDV, thereby increasing the effective length of the vehicle. In countries like Australia, Canada, Mexico and the United States, LCVs known as "Road trains" are being used for efficient movement of freight in the rural areas. Similar to this, it is proposed by the government to bring a legislation in Sweden to permit LCVs. However, designing such vehicles requires consideration of both vehicle and the road traffic. To address these issues of safety, performance and congestion, performance based standards (PBS) have evolved.

This thesis work focuses on developing a framework to assess LCVs and provide vehicle manufacturers with allowed ranges for vehicle parameters. The vehicle that complies with these allowed ranges will be permitted on the road. The work done in this thesis project proposes a generic framework considering legal, performance and practical constraints. Thereafter, it can be applied to any LCV to obtain the allowable ranges. The final outcome of the thesis was that the generic framework was applied on an A-double combination vehicle to obtain envelopes. A special study of performance measures for friction demands for low speed maneuvering on low road friction is also included.

Keywords: Performance based standard, Heavy combination vehicles, Envelopes, A-double, Vehicle dynamics, low road friction.

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Contents

List of Abbreviations

This document requires readers to be familiar with terms related to vehicle dynamics. They are summarized with their description before presenting them in next sections.

AC	Acceleration Capability
BST	Braking Stability in a Turn
COG	Center of Gravity
FS	Frontal Swing
FDST	Friction Demand on Steering Tires
FDDT	Friction Demand on Drive Tires
GHG	Greenhouse Gases
GA	Gradeability
HDV	Heavy Duty Vehicles
HSTO	High Speed Transient Off Tracking
HSSO	High Speed Steady state Off Tracking
LCV	Long Combination Vehicle
LSSP	Low Speed Swept Path
LTR	Load Transfer Ratio
PBS	Performance Based Standards
RWA	Rearward Amplification
SA	Startability
SRT	Steady state Rollover Threshold
SRT	Static Rollover Threshold
TASP	Tracking Ability on Straight Path
TS	Tail Swing
YD	Yaw Damping

1

Introduction

This chapter provides a brief overview of the problem that is being addressed, along with the aim, objectives, and limitations.

In the era of technology, the advancements in the field of vehicular engineering are immense. The major developments have been targeted towards safety, transport efficiency and emissions of the vehicles. According to the inventory of U.S greenhouse gas emissions and sinks 1990-2015, transportation sector solely contributed to 27% of overall GHG emissions. According to [3], the contribution by Europe towards global carbon dioxide emissions by burning fossil fuels was 9% of the total emissions. International energy agency [4], reports that the oil demand by truck industry in China, US and Europe together is equal to one-fifth of global demand, a massive 17 millions of oil per day.

The truck industry has been developing various technologies to reduce emissions. The implementations are diverse, they vary from using bio-fuel to electrification. Other approaches adopted include advanced after treatment systems and improvement in transport efficiency. One of the strategies to reduce emissions, adopted by truck industries in Canada and Australia is to implement long combinations vehicles (LCV).

This thesis is part of the project[1] which is focused towards introduction and implementation of longer and heavier combination vehicles for Sweden based on performance based standards. For more details on the work done on motivation, PBS measures and models, refer to [1] and [9]

1.1 Aim

The main goal of this thesis is to develop a framework for the assessment of long combination vehicles which can be permitted in Sweden. A problem-based approach needs to be used to reach this goal. The framework should be generic while considering legal, physical and as many, if not all, practical constraints. The framework should be applied in a test case to demonstrate the working and outcomes of the same.

[1] "Performance Based Standards for High Capacity Transports in Sweden"FFI project, Vinnova reference number 2013-03881

1.2 Objectives

The Objectives of this thesis are

- To qualitatively define envelopes and formulate the mathematical problem. A conventional heavy vehicle, truck-semitrailer combination has many parameters which can be varied. For an LCV the number of parameters is significantly larger. Hence there is a need to define and formulate a solvable mathematical problem.

- To Develop a generic framework or procedure for extracting combination vehicles permissible for Sweden. The framework needs to incorporate how the parameters defined above will be varied. The framework should consider legal, geometrical and practical constraints.

- To extract quantitative envelopes for an A-double combination vehicle for both high and low road friction.

1.3 Limitations

- The current thesis provides an opportunity to investigate different long combination vehicles due to the generic nature vehicle dynamics models and the framework being developed. In other words, different combination vehicles can be studied. This thesis studies only one single vehicle, an A-double combination vehicle in detail.

- The other features like the vehicle type being A-double, the configuration of the vehicle in terms of which and how many axles are driven and steered are locked. The configuration of the modular units is also fixed, see section 2.1.

- The models for vehicle performance measures were developed by Peter Sundström, in the project “Performance Based Standards for High Capacity Transports in Sweden” [9]. Present thesis work uses the models for further studies. The models are used as they are available currently with minimum updates.

1.4 Report Outline

The report briefly introduces the problem, along with aim, objectives, and limitations. The second chapter is allocated to in depth background study into the problem and definitions. The third chapter discusses the details of the generic framework being developed. In chapter four, results and discussion of a use case, the application of the framework to an A-double combination vehicle is provided. Finally, in chapter five, the report is concluded with the discussion on the findings of the study and suggestions for future work.

2

Background

The first legislation in Sweden on limiting vehicle length to 24 m was decided only in 1968, before this there was no limitation on vehicle length. According to [5], this was required, to satisfy the demand for a vehicle, to carry three 20 foot equivalent units, TUE. However, the current legislation is different in different parts of Europe. According to the 1983 directive, a conventional heavy vehicle of length 18.75 m with a load capacity of 40 tons is permitted all over Europe. Only in Sweden and Finland longer combination vehicles are permitted. Under, SFS 1998:1276; a long combination vehicle with vehicle length up to 25.25 m with a load capacity of 64 tons is permitted in Sweden. According to [13], heavy vehicle combinations are an important part of the road freight, which contribute to 45% of total transport within Europe. One of the proposed future legislation for Sweden is to permit longer combination vehicles. A combination vehicle is a vehicle with a prime mover and a modular unit, a truck that hauls modular units. Whereas a long combination vehicle(LCV) is a combination vehicle which is longer than 18.75 m, refer to section 2.2. A detailed explanation of modular units can be found in section 2.1.

2.1 Modular Units

A European directive, 85/3/EEC was passed to harmonize vehicle lengths and weights in 1983. As mentioned in the earlier chapter, it fixed the length of a conventional heavy vehicle to 18.75 m. However, the legislation allows the use of longer combination vehicles, as long as they are based on the modular system. The directive defines the modular system as “the Member State which permits transport operations to be carried out in its territory by vehicles or vehicle combinations with dimensions deviating from those laid down in Annex I, also permits motor vehicles, trailers, and semi-trailers which comply with the dimensions laid down in Annex I to be used in such combinations as to achieve at least the loading length authorized by the Member State, so that every operator may benefit from equal condition of competition (modular concept)”. A combination vehicle primarily consists of modular vehicle units which are combined to make a long combination vehicle. The following subsections provide a description of the modular units. These units are considered under the Performance based standards project for Sweden[1].

2.1.1 Tractor

Tractor, a unit which is common to all classes of vehicles, whether it is a conventional heavy vehicle, for instance, tractor-semitrailer or long combinations vehicles such as an A-double vehicle. The primary purpose of this unit is to haul other units. Generally, tractors are available in different configurations, such as

- Tractors with configuration of 4X2
- Tractors with configuration of 6X2
- Tractors with configuration of 6X4
- Tractors with configuration of 8X4

The front axle of tractor is the steered axle. A tractor with the configuration of 4x2 will have two axles with only the rear axle being driven. The tractor with configuration 6x2 will have three axles, one front, and two rear. This arrangement of a tractor containing two rear axles is known as a tandem axle. A configuration of 6x2 should be understood as only one of the rear axles is being driven. A configuration 6x4 would imply both rear axles are being driven. The figure 2.1 depicts single rear axle driven 4x2 configuration. Whereas figure 2.2 shows the configurations 6x2 or 6x4. The last configuration 8x4 would imply four axles and two of them are driven.

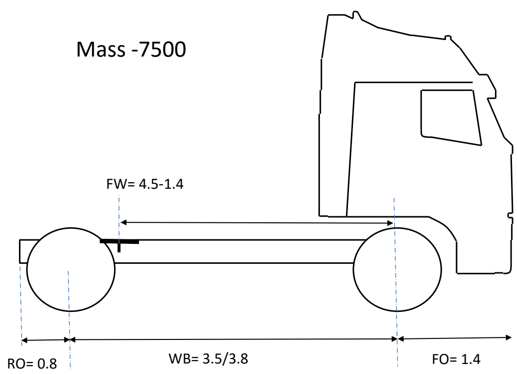


Figure 2.1: Tractor with single axle, configuration 4x2 [9]

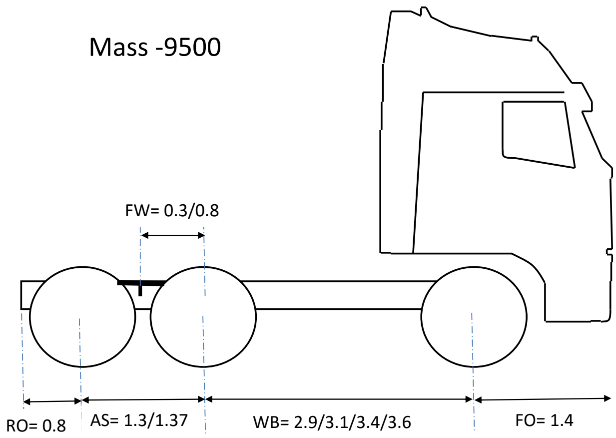


Figure 2.2: Tractor with tandem axles, configuration 6x2 or 6x4[9]

2.1.2 Semitrailer

A semitrailer can be defined as a trailer that does not contain a front axle. In a combination vehicle, it is the semitrailer unit that serves the purpose of carrying the payload. The semitrailers have different configurations, such as semitrailer with a tandem axle or semi-trailer with a tri-dem axle. The configuration used depends on the payload carried by the vehicle. The first part of figure 2.3, depicts a semitrailer with tandem axles with different load lengths. Whereas, the second part of figure 2.3 depicts a semi-trailer with tri-dem axles.

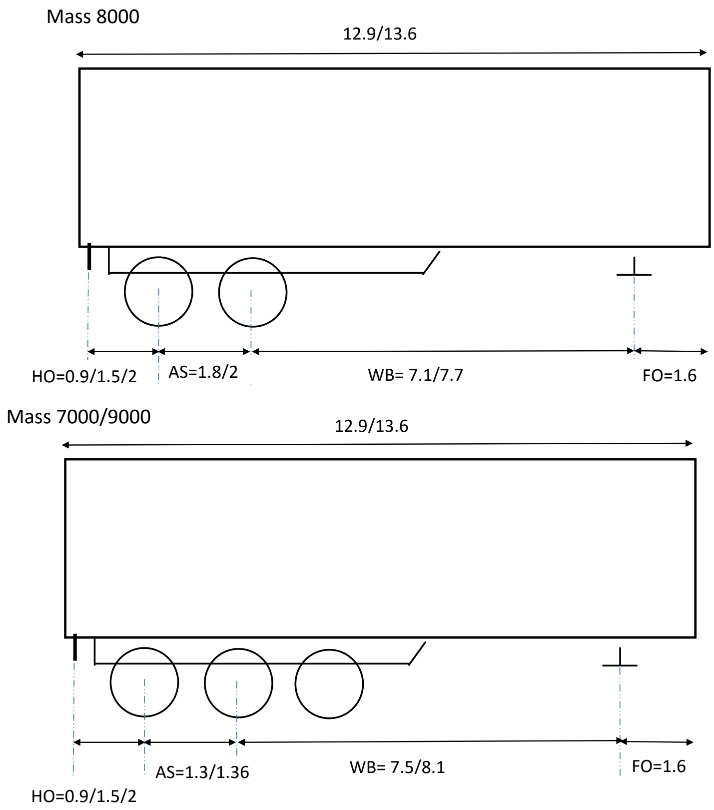


Figure 2.3: Semitrailer in two different configurations[9]

2.1.3 Dolly

According to [10], a dolly is an unpowered modular unit for the purpose of connecting to a tractor unit, truck or prime mover vehicle with strong traction power. Dolly is classified based on the coupling configuration. The two different configurations of dolly are

- A-dolly : has a single drawbar with centered coupling [10].
- C-dolly : has two separate coupling side-by-side [10].

The figure 2.4 depicts the side view of an A dolly.

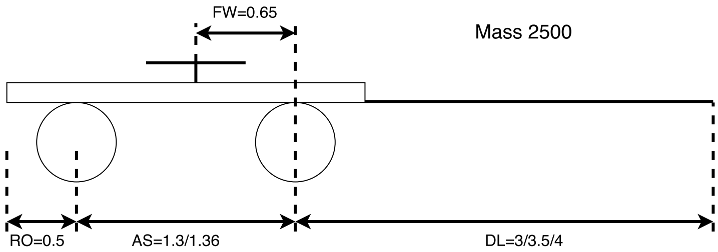
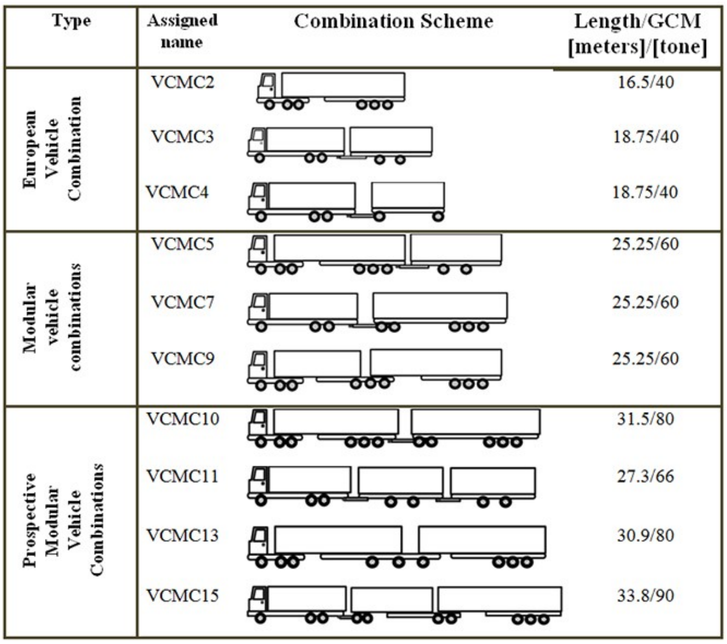


Figure 2.4: Dolly A configuration[9]

2.2 Long Combination Vehicles

A combination vehicle can be realized in many different configurations. The figure 2.5 provides a brief overview of the present configurations that are used in the road freight transport industry.



Type	Assigned name	Combination Scheme	Length/GCM [meters]/[tone]
European Vehicle Combination	VCMC2		16.5/40
	VCMC3		18.75/40
	VCMC4		18.75/40
Modular vehicle combinations	VCMC5		25.25/60
	VCMC7		25.25/60
	VCMC9		25.25/60
Prospective Modular Vehicle Combinations	VCMC10		31.5/80
	VCMC11		27.3/66
	VCMC13		30.9/80
	VCMC15		33.8/90

Figure 2.5: Different configurations of combination vehicle[13]

Since each long combination vehicle has a large number of parameters to study. This thesis work is limited to studying only one combinations vehicle; an A-double combination vehicle. The combination vehicle studied in this thesis consists of a tractor unit of 6x4 configuration with two semitrailers of load length 13.6 m and an A type dolly, see VCMC10 in figure 2.6. This combination vehicle is called an A-double.

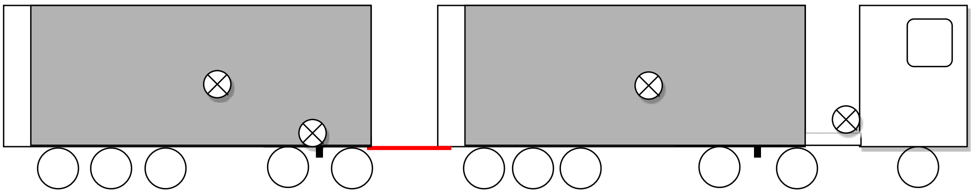


Figure 2.6: A description of the vehicle: A-double

2.3 Performance based standards

To allow longer combination vehicles on the road, an in depth study on the stability and safety of such vehicles is imperative. The project “Performance based standards for HCT in Sweden” is working towards such a study.

According to [9] a performance based standards has three aspects

- A performance measure,
- An acceptable performance level and,
- A test manoeuvre during which the performance of the vehicle should be measured.

One of the major issue that needs to be addressed is that the LCVs need to be stable on both dry and icy roads. It is important that the LCVs allowed on roads are able to fulfill requirements broadly in all aspects of vehicle dynamics, environmental and traffic safety. The work performed in [9] culminated in identifying the most important vehicle performance measures to be considered under PBS for LCVs. The study in [9] also provides a detailed explanation of which maneuver to be used to measure the performance levels. The test maneuvers should be applicable to both real vehicle tests and simulations.

The other matter that should be addressed is how many PBSes are required to cover all aspects of safety, performance, and congestion. The total set of PBSes identified should cover the critical problems that can be foresees with an LCV, but in a non redundant way, so that no two PBSes measure the same potential problem. Present thesis work uses the PBS measures already decided in [1]. But, suggestion will be provided as to which PBS could be added or removed under conclusion based on the outcomes of the thesis.

Performance based standards identified in [9] can be mainly categorized into three section, they are

- Standards pertaining to longitudinal dynamics of a LCV.
- Standards pertaining to lateral dynamics of a LCV.
- Standards pertaining to road friction.

The following subsections 2.3.1 - 2.3.4 provide a brief description of the performance measure chosen in each category. Studies like [9] and [11] provide in depth information and knowledge on all the performance based standards that were chosen. This thesis assumes a high road friction level of 0.8 while using the models to assesses the PBS measures.

2.3.1 PBS for Longitudinal performance

Longitudinal dynamics of the vehicle deals with how well the vehicle performs in acceleration and deceleration. The prime motivation behind choosing these standards is to make sure the traffic does not experience congestion or delay.

The performance measure chosen under longitudinal dynamics are

- Startability (SA).
- Gradeability (GA).
- Acceleration Capability (AC).

2.3.1.1 Startability

According to [11], there are two ways of measuring the traction capability of a vehicle. These two performance measures are called tractive capability and startability. In the PBS study, only startability is chosen as a standard, but tractive capability could also be used in substitution for startability. Since the two metrics are highly correlated [11].

Tractive capability can be understood as the maximum force the vehicle is able to produce. Whereas, startability is defined by [11] as "*the maximum grade that a fully laden combination vehicle is capable to start in and maintain the forward motion at a certain friction level*".

2.3.1.2 Gradeability

Gradeability is another metric to measure the traction capability of a vehicle. Gradeability is defined by [11] as "*the maximum grade that a fully laden combination vehicle is capable to maintain the forward motion on an uphill road at a certain constant speed at a certain friction level*".

For instance, if an LCV fails to start on a road which has more slope than the gradeability of the vehicle, the vehicle would be stuck and create congestion and traffic delays. These standards are important for the vehicle to be safe on road and avoid traffic related issues. More details about this can be found in [11].

2.3.1.3 Acceleration Capability

The study performed on PBS measures in [11] provides the objective behind choosing acceleration capability as a PBS for an LCV. Generally, the LCV takes a longer time to accelerate from the stand still position. Considering real-life situations such as clearing intersections and railway crossings the LCV needs to have good acceleration capability. Acceleration capability is defined by [11] as "*the time taken for a vehicle combination to accelerate from rest and travel a certain distance while being fully laden at a certain friction level*".

An LCV carries higher load and is longer when compared to the conventional heavy vehicle. But, the power in LCV is only slightly higher than the conventional heavy vehicle. Due to this lower power to mass, the LCV has inadequate acceleration capability than the conventional heavy vehicle. This, in turn, leads to traffic congestion and delays due to longer times required for accelerating [12].

2.3.2 PBS based on Lateral performance at Low Speed

The PBS measures under lateral performance can be broadly divided into three aspects based on speed, namely low speed, high speed and steady state. In this section, performance based standards of the vehicle are discussed relating to a vehicle moving at low speeds. The performance measures chosen are provided below along with a brief description of each of the standards. The PBS measures under low speed lateral dynamics are

- Low Speed Swept Path (LSSP)
- Frontal Swing (FS)
- Tail Swing (TS)

2.3.2.1 Low Speed Swept Path

This lateral dynamics performance metric is chosen as a PBS to manage a tight turn at an intersection, safely. Low speed swept path is defined by [11] as "*the maximum width of the swept path between outer most and inner most points of the vehicle combination in a low speed turn with a certain outer radius at a certain friction level and a certain angle between entry and exit*".

An LCV should be allowed only if the LSSP value is below the threshold level. This threshold will be determined based on the available space on the road. If the LSSP value is above this value the LCV will collide with vehicles of other lane while taking a turn.

2.3.2.2 Frontal Swing

The main purpose of this PBS measure is to ensure road safety, the vehicle should be able to take a tight turn at low speed without a high undesirable swing. In a low-speed turn, the front outside corner will track an outward trajectory/path. Frontal Swing is defined by [12] as "*when operating at the maximum laden mass and unladen, the maximum width of the frontal swing swept path of a vehicle taking a tight turn at a specified constant speed*".

Frontal swing is influenced largely by the frontal overhang of the tractor and frontal overhang of the semi-trailer. When the front overhang is fixed, longer the wheelbases result in higher frontal swing. Description of test method, conditions, and how key parameters affect the performance measure is provided in [12].

2.3.2.3 Tail Swing

Tail swing is one of the standards similar to the frontal swing, see 2.3.2.2. Tail swing is the swinging of the rear outside corner of an LCV at the beginning of a turn. In a conventional heavy vehicle, the tail swing is prominent only while entering a turn. Whereas for an LCV tail swing is significant both while entering and exiting a turn. Tail swing is defined by [12] as "*when operating at the maximum laden mass and unladen, the maximum outward lateral displacement of the outer rearmost point on a vehicle unit of a vehicle taking a tight low-speed turn performed at the specified speed*".

The key parameters that influence this measure are rear overhangs on different units like trucks, buses, tractor, and semi-trailers. Large coupling rear overhangs (e.g-coupling point being behind the driven axle) can cause very large tail swing. This is a concern, since the LCV may laterally move into next lane and cause dangerous accidents.

2.3.3 PBS based on Lateral performance at High Speed

In this section, the high speed and high-speed steady state PBS measures are explained. The performance measures chosen are provided below along with a brief description for each of the standards. The high speed PBS measures of a LCV are

- Load Transfer Ratio (LTR)
- Steady State Rollover Threshold (SRT)
- Rearward Amplification (RWA)
- Yaw Damping (YD)
- High Speed Transient Off-Tracking (HSTO)

- High Speed Steady State Off-Tracking (HSSO)
- Tracking ability on straight Path (TASP)

2.3.3.1 Load Transfer Ratio

According to [13], rollovers are the major cause of accidents in case of trucks. This PBS measure is vital to reduce the risk of an LCV rolling over in a transient lateral maneuver. It is extremely hard to obtain an experimental value for this PBS measure. Hence, an approximate value of LTR is obtained by using the formula.

$$LTR = max(abs\frac{(F_{z,l} - F_{z,r})}{(F_{z,l} + F_{z,r})})$$

The above formula for LTR is applicable only for roll coupled units. Roll-coupled units are units which are connected with a fifth wheel. For instance, an A-double has 2 roll-coupled units: Tractor with the lead semi-trailer and dolly with the second semi-trailer. In the OpenPBS toolbox, LTR will be implemented for a single lane change at a certain level of lateral acceleration on the front axle. Load transfer Ratio is defined as " *is the difference in wheel loads from one side of the vehicle to the other divided by the total load of the vehicle" [17].*

2.3.3.2 Steady State Rollover Threshold

The primary purpose of this PBS is to minimize the risk of rollover of an LCV. Steady state rollover is also called as static rollover threshold (SRT) in some studies. The lateral acceleration at which the vehicle will roll-over while taking a steady state turn is termed as static or steady state rollover. Steady state rollover is defined by [11] as "*the steady state level of lateral acceleration of COG that a vehicle can sustain without rolling over during a steady state turn*".

The main objective of this PBS is to ensure safety of an LCV and surrounding traffic and structures. According to [13], 20% of heavy vehicle accidents in New Zealand were due to rollover and lateral instability and in Australia, this rate was 16%, of which, in both cases around 50% were related to vehicle speeding through curves. Rollover stability is extremely sensitive to the ratio of the track width to the height of the center of gravity of the vehicle. Rollover stability increases if we either increase the track width or decrease the height of the center of gravity. The rollover properties for LCV with multiple units is much more complex, for more details read [12] and [14].

2.3.3.3 Rearward Amplification

The lateral acceleration and yaw rate experienced by different units in the combination vehicle is different while performing a single or double lane change maneuver. The rearmost unit experiences the largest lateral acceleration and yaw rate due to delayed and amplified response. The lower the values of RWA, the higher the stability of the vehicle. Studies like [11] and [12] provide information on aim, objectives, maneuver to be used and accepted performance levels.

Rearward amplification is defined by [11] as "*the ratio of the maximum value of the motion variable of interest (e.g-yaw rate or lateral acceleration of center of gravity) of the worst excited following vehicle unit to that of the first vehicle unit during a specified manoeuvre at a certain friction level and constant speed*".

Rearward amplification decreases with lesser articulation joints, shorter distance between C.G of units to their hitch point, longer draw bar length on dollies, longer semi-trailer wheelbase and higher tire cornering coefficient[12].

2.3.3.4 Yaw Damping

From the section 2.3.3.3 on RWA, it was understood that different units oscillate with different amplitude. Yaw damping coefficient measures how quickly these oscillations settle down. If the time taken to dampen the oscillations is large, the vehicle is unstable. This demands extra efforts from the driver to keep the vehicle stable.

Yaw Damping coefficient is defined by [11] as "*as the damping ratio of the least damped articulation joint's angle of the vehicle combination during free oscillations excited by actuating the steering wheel with a certain pulse or a certain sine-wave steer input at a certain friction level*".

The objective of this PBS is to improve the road safety by making sure any sway oscillations will be dampened within a short time. Another important consideration is that yaw damping is speed dependent, as the speed increases the yaw damping reduces leading to higher chances of rollover scenarios at higher speeds. For more details on the formula, maneuver and detailed explanation on yaw damping, see [12].

2.3.3.5 High Speed Transient Off-Tracking

While performing an avoidance maneuver at high speed the rear end of the rearmost unit moves laterally, the amount of lateral displacement is called high speed off tracking. Crash studies propose that the tendency for a crash increases with high transient off tracking. The parameters which affect rearward amplification also affect high speed transient off tracking, refer to 2.3.3.3 .

According to [11], the HSTO is defined as " *an overshoot in the lateral distance between* *the paths of the center of the front axle and the center of the most severely off tracking axle of any unit in a specified maneuver at a certain friction level and a certain constant longitudinal speed*". The objective of this PBS is to manage safety risks by reducing the lateral sway of the rearmost unit. This is crucial because on a dense road network lower values of HSTO is desirable to increase safety.[12] provides details on acceptable values, testing procedure etc.

2.3.3.6 High Speed Steady state Off Tracking

Like HSTO, an LCV exhibits a similar lateral overshoot while performing avoidance maneuvers at constant speed, also known as high speed steady state off tracking. Higher overshoot implies the LCV colloids with road objects and other vehicles and causes damage to property and life. The objective behind introducing this PBS is to increase safety when LCV's are allowed on the road network.

HSsTO is defined by [11] as " *the lateral offset between the paths of the center of the front axle and the center of the most severely off tracking axle of any unit in a steady turn at a certain friction level and a certain constant longitudinal speed*". Since the modular units of an LCV, could move laterally into next lane and collide with other vehicles, it is desirable that the off tracking values are low.

2.3.3.7 Tracking Ability on Straight Path

Tracking ability is also called as straight line off tracking in some studies. It is the ability of an LCV to be able to track the leading unit on a straight road. There could be many reasons like road unevenness, road banking, cross winds and driver steering inputs (small disturbances) due to which the trailers do not follow the lead unit exactly. This could lead to a different amount of lateral offset on different units[12].

TASP is defined by [11] as "*the maximum off tracking between the paths of the center of the front axle and the center of the most severely off tracking axle of any unit while traveling straight on a banked road with a certain lateral slope at a certain friction level*". According to [12] TASP depends on road profiles, the number of trailers, the location of the coupling points, axle spread, wheelbase, payload, tire cornering stiffness, vehicle width and length and front and rear overhang dimensions. A detailed study of the affect of each of the parameters along with sensitivity study is provided in[12].

2.3.4 PBS based on road friction

It is important to consider road friction levels while developing performance based standards for an LCV. Due to very high load carrying capacity of an LCV, the lateral and longitudinal tire forces generated depend significantly on friction levels. The Australian PBS has only friction demand on steering tyres as a measure, whereas the friction demand on driven tyres is equally important to propel the vehicle. Due to coupled longitudinal and lateral dynamics the PBS *braking in curve* is quite complex.

The PBS measures are

- Friction demand on steering tyres (FDST)
- Friction demand on drive tyres (FDDT)
- Braking Stability in a Turn (BST)

2.3.4.1 Friction demand on steering tyres

According to [12], the main objective behind choosing this PBS measure is to reduce the risk of congestion and safety while performing a tight turn at low speed. The vehicle could lose its steering control if the friction required to complete the maneuver is higher than the available friction limit. This PBS can be defined as "*when operating at the maximum allowed gross mass and unladen, the maximum friction level demanded of the steer tyres of the hauling unit in a prescribed 90º low-speed turn performed at the specified speed*"[12].

If the friction limit is reached, the vehicle instead of taking a turn will travel straight. This is undesirable since it could move into another lane and collide with vehicles or property. This behaviour is commonly observed in the vehicle with hauling units having tri-axle drive systems. The friction demand on steering tires is worse when the prime mover has large axle spread and low wheelbase. Other factors that affect friction demand are the vertical load on the steered tires and load on drive axles. More details about the calculations and test procedure can be found in [12]. Since the models developed for assessing this PBS measures were not fully addressing the issue, more rigorous problem formulation and a solution were required. The description of additional work done for this PBS measure can be found in Appendix.

2.3.4.2 Friction demand on drive tyres

This PBS measure is mainly chosen to make sure the driven wheels or axles have sufficient friction both for the purpose of safety and driveability. Assuming the vehicle has enough power to propel an LCV, the friction available at the driven wheels solely determines the driveability of the LCV.

It can be defined as "*when operating at the maximum allowed gross mass and unladen, the maximum friction level demanded of the driven tires of the long combination vehicle in a prescribed 90º low-speed turn performed at the specified speed*". In most cases,more than one axle is driven, hence it is fair to mention that all axles must be powered such that road friction is the limiting factor. In other words, the vehicle should have enough power to propel the vehicle and power should not be the limiting factor. Since the models developed for assessing this PBS measures were not fully addressing the issue, more rigorous problem formulation and a solution were required. The description of additional work done for this PBS measure can be found in Appendix.

2.3.4.3 Braking Stability in a Turn

It is crucial for an LCV to be stable while taking a turn, mainly because this maneuver occurs very often and the risk of accidents and damage is huge. Heavy braking in a turn is complicated because both longitudinal and lateral dynamics of the vehicle are involved. This, in turn, places a heavy demand on the driver, a small error can lead to big accidents and cause tremendous loss to both property and life. Braking stability can briefly be defined as "*The ability to maintain directional stability while braking in a turn*". The vehicle must be stable on the intended curve.

The next section provides a background study into the concept of envelopes with respect to PBS.

2.4 Envelopes

Safety of the vehicles and traffic is the key aspect to be considered for long combination vehicles. According to [15], "safety outcome is highly dependent on vehicle productivity and design which are largely dictated by the characteristics of the product to be transported and the vehicle size and weight constraints contained in regulations". Performance based standards is a novel approach towards an improved safe and sustainable transportation. Proponents of PBS argue that this approach allows flexibility for manufacturers over prescribing strict regulations. Manufacturers can take advantage of the extra flexibility and design the vehicle in order to optimize productivity, transport efficiency, and safety performance. To allow for such flexibility, there has to be in-depth studies and clear legislation system for addressing issues of safety, performance, and stability of the vehicles that will be allowed on the road.

Currently, there are two approaches to implementing the PBS strategy in the industry. One method is to all combination vehicles that comply with the performance based standards, the method implemented in Australia. The other method involves providing a permissible range on vehicle's parameters to the manufacturers before dispensation, and only permitting vehicles that comply to these ranges. The first approach does not provide a lot of flexibility whereas the second method implemented in Canada, provides the manufacturer with high level of flexibility. Sweden is investigating both the schemes to decide which one to choose, or a combination of both. This thesis work presents the framework being developed to obtain permissible vehicle ranges known as envelopes, similar to Canadian PBS.

It is important to understand one of the limitations that will be associated with these permissible ranges. The number of parameters that can be studied for a long combination vehicle is large, in the order of 50-100. These are the properties of the vehicle covering the domain of geometry, load distribution and design. The parameters that will be studied in this thesis are a subset of the larger parameter set. Due to the large number, it is impossible to study all of them in short time. Therefore, the flexibility that the envelopes provide is applicable only to a small set of parameters. All other parameters are fixed to a nominal value.

After extensive study of the literature available, it was observed that there were not many studies which specifically addressed the issue of envelopes. Although, studies such as [20] and [19] performed in-depth studies on parameter variation. In this studies the authors evaluated six combination vehicles and their variations. The authors studied each combination vehicle and varied certain physical parameters to understand their sensitivity. It can be observed that the authors varied one parameter at a time and evaluated each variation for different performance metric. This can be taken as the most fundamental step in developing the methodology for envelopes. A theoretical study in [18] was performed to simulate different combination vehicles to evaluate the performance metrics. A recent study [16] is focused towards the evaluation of vehicle A-double for the PBS defined in above sections 2.3.1-2.3.3. An example of the envelope can be found at [21], implemented by Canadian PBS.

3

Framework for extracting envelopes

This chapter is broadly divided into three parts. The first part, sections 3.1 - 3.2 covers the work done on the method used to develop the framework for extracting envelopes for combination vehicles. It provides the procedure used to convert a vague complex problem into a solvable or manageable mathematical problem. As mentioned in previous chapter not many references apart from [19] and [20] were found which directly address this issue. The second part, sections 3.3 - 3.7 provide details about the parameters and constraints used for a particular combination vehicle, an A-double. The third part, section 3.8, is allocated to the implementation of the general framework in Matlab environment.

The introduction of an LCV would invariably provide some degree of flexibility to the manufacturers. As a result, there would be different configurations with different properties of the same combination vehicle. The vehicles would be different with respect to its geometrical and inertial properties. It would be difficult task for the transport administration to study all variants and take decision on dispensation of the vehicles. Therefore to ease up the workload and reduce delays, it would be beneficial to have prior knowledge of geometrical and inertial allowed ranges for selected LCV's. If the Swedish PBS project chooses envelopes as the strategy for dispensation of vehicles.

3.1 Introduction to Envelopes

As mentioned above, envelopes are ranges for the geometrical and inertial properties of a vehicle. Envelopes can be loosely defined as *geometrical and inertial boundaries or limits within which the LCV has an acceptable level of performance with respect to all PBS's*. For example, the lower bound for a tractor wheelbase with tandem axle should be 3.5 m according to Canadian PBS [21]. The first part of extracting envelopes is to define them. Defining envelopes involves two steps,

- Identifying all the parameters that can be varied for an LCV and
- Distinguishing between the parameters that can be fixed to a nominal value and parameter that needs to be varied. This is an open activity, which requires good experience of normal parameter values and what could be interesting directions for change or variation.

The number of parameters that can be varied for an LCV is large, hence it is vital to filter out important parameters. Once these parameters are identified they need to be studied in detail considering legal, performance and geometrical constraints.

3.2 Structure of the framework

To allow high load capacity vehicles on road, in other words LCV's, performance based standard measures are not the only important constraints. The damage to road infrastructure, safety, stability and driver comfort needs to be considered. After a detailed literature study and consulting with industry experts, the constraints were divided into three parts

- Pre-Check
- PBS Check
- Post Check

The Overall Framework is provided below in figure 3.1

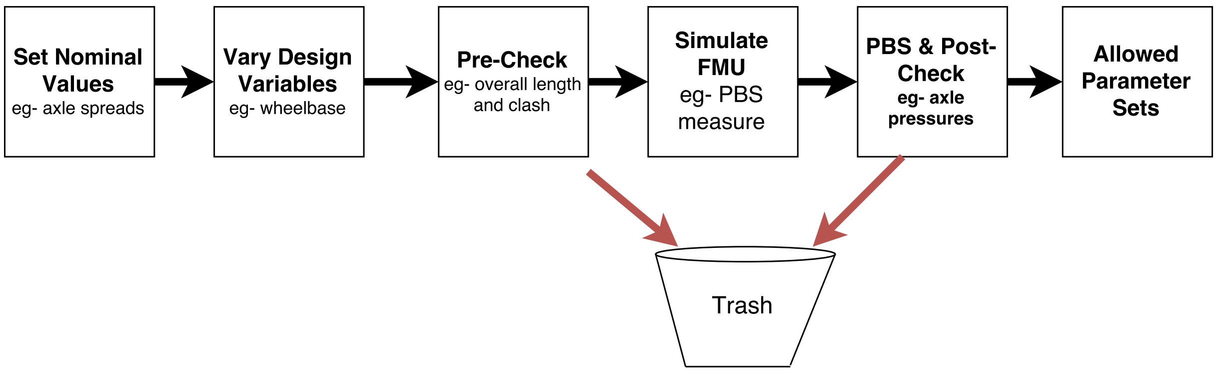


Figure 3.1: A schematic representation of overall framework

The design parameters varied will form different configurations of the vehicle, which will be passed through the above checks. These checks act like a filter to reject undesirable vehicles. From the vehicles that pass the checks, allowed ranges for the design parameters are determined.

3.3 Vehicle Design

To assess PBS measures, vehicle models are required. In simulations the accuracy of the PBS measures directly depend on the level of model complexity. The models developed in OpenPBS toolbox are simple, single track models. The aim of the toolbox is to obtain

PBS measure as accurately as possible with simple models. The following sections deal with the parametrization of the models and loading of the vehicle used in the thesis.

3.3.1 Parametrization

The parametrization developed for OpenPBS toolbox models is generic, it can be used to define any type of combination vehicle. This is crucial to cover all the different configurations of LCV as seen in section 2.2. The two major inputs to the parametrization are the number of modular units and a maximum number of axles on any of the units. The parametrization uses the first axle of each unit as the reference for that unit. For an A-double combination, the first unit tractor has three axles. The distance is defined with respect to the first axle of the tractor. The figure 3.2 below shows how each distance is parametrized for each modular unit and their notations used in the models.

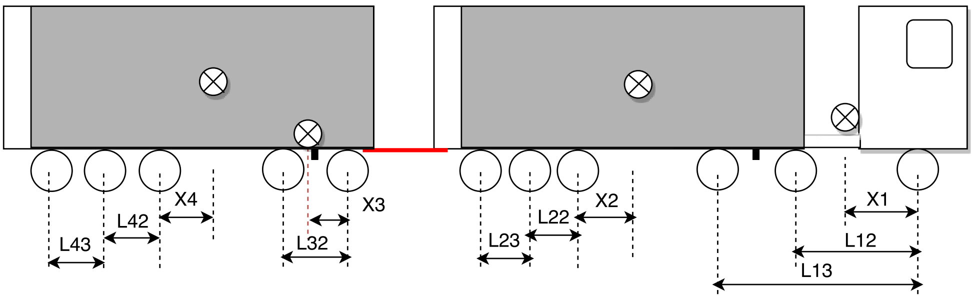


Figure 3.2: A schematic representation of parametrization for distance between axles

The coupling points on modular units are important for force and moment balances. Again the parametrization is such that the distance between the front and rear coupling point is determined with respect to the first axle of each unit. The figure 3.3 below shows the front and rear coupling points for each modular unit and their notations used in the models.

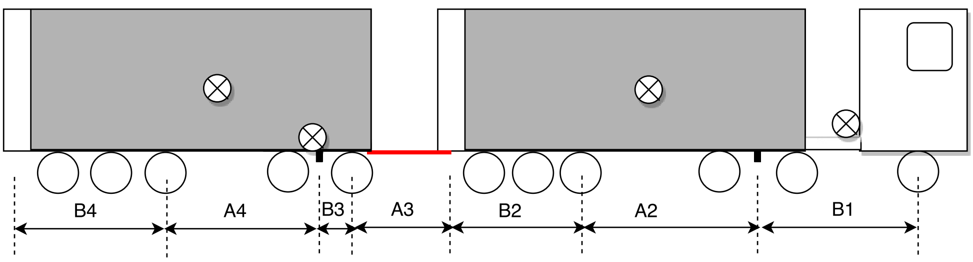


Figure 3.3: A schematic representation of parametrization for coupling points for modular units

The parametrization of a long combination vehicle with different modular units like semi-trailer and dolly has been performed. The equation of motions for a single-track model is developed for the parametrized model. The geometrical constraints at the coupling points are defined completely in [22].

3.3.2 Loading Condition

The important factors affecting the performance of a combination vehicle are geometrical dimensions and the manner in which the payload is distributed. In this study, it was observed that it was crucial to consider different types of loading.

The CoG position and moment of inertia for tractor and dolly are provided by Volvo group. Whereas, the CoG position and moment of inertia of semitrailer is calculated. The semitrailer(kerb weight) without payload is assumed to be of cuboid shape with 6600 kgs and each of the axles are assumed to be a point mass of 800kgs. The payload is also assumed to be in the shape of cuboid. The gross CoG position of the semitrailer is determined from these above assumptions and applying basics of solid mechanics. Please refer to Appendix for the code used to determine the gross CoG and moment of inertia of semitrailer. The overall weight of the LCV can be calculated by adding vertical forces of each axle since vertical forces are reactions which balance the overall mass of the vehicle.

The container length of the semitrailer is fixed to 13.6 m. In this study, three different cases of load distribution are studied. The different type of concentration of payload was an outcome of previous study [6]. In the report [6], the author observes that the combined vertical forces on driven axles of an A-double is lesser than 25% of total weight when both the semitrailers are loaded uniformly throughout. To provide good traction, a requirement on vertical forces of driven axle was set, as mentioned in [6], the threshold value was 25%. If this threshold value is not satisfied, the vehicle is not permitted on road. This value of 25% has further gone down to 20% of overall load nowadays. This thesis considers the current value of 20% as the the limit. The report [6], suggests a solution to this problem, that is to load the semitrailers more in the front.

In the first case, the semitrailer is loaded such that all the payload is assumed to be placed uniformly in the front 80% of the container as depicted in figure 3.4. In the second case, the payload placed such that is covers 90% front loaded, depicted in figure 3.5. Lastly, the container is loaded uniformly all through out, 100% front loading shown in 3.6. The envelopes are obtained for all three loading cases. The 80% front loading is considered as default loading case. The overall masses for each modular unit for an A-double is provided below.

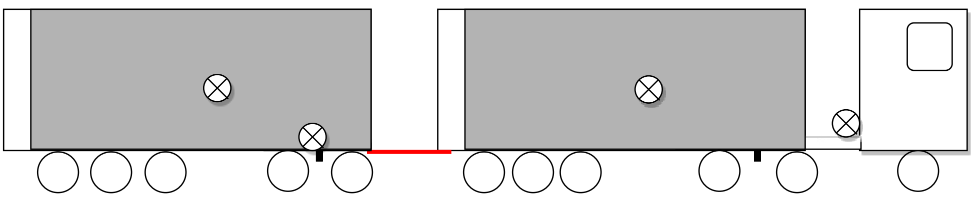


Figure 3.4: Loading - 80% front load

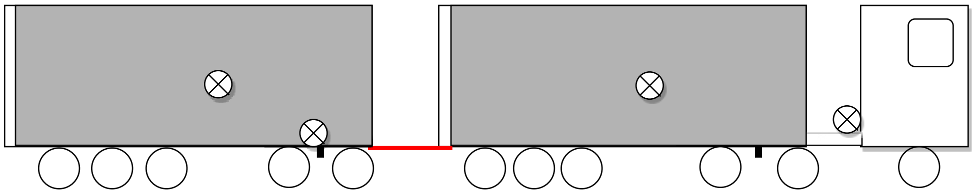


Figure 3.5: Loading - 90% front load

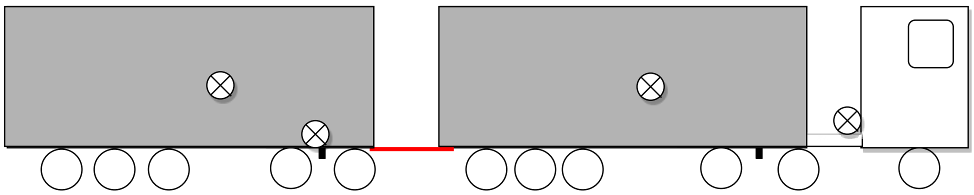


Figure 3.6: Loading - 100% front load

Table 3.1: Table describing Unit masses including payload

Modular Unit	Load (kg)
Tractor	9500
Lead Semitrailer	31000
Dolly	2500
Second Semitrailer	31000

3.4 Pre-Check

There are a large number of parameters that can be varied for a combination vehicle. The outcome of the study majorly depend on both, the parameters that are being investigated and also the ones that are fixed. To solve and visualize the problem of envelopes it is vital to fix certain parameters. The parameters in table 3.2 were fixed to a nominal value after discussing with industry experts.

Table 3.2: The nominal values of geometrical parameters fixed for this study

Module	Parameters	Nominal Value
Overall Vehicle	Max Length	34 m
Overall Vehicle	Max Width	2.6 m
Tractor	Tandem axle spread	1.37 m
Tractor	Fifth wheel position	0.25 m
Tractor	Front overhang	1.4 m
Tractor	Rear overhang w.r.t 1st axle	5.17 m
Tractor	Pos of Gross COG w.r.t 1st driven axle	1.4315 m
Tractor	Number of axles	3
Semitrailer	Load length	13.6 m
Semitrailer	Tri-dem axle spread	2.6 m
Semitrailer	Front Overhang	1.6 m
Semitrailer	Pos of COG w.r.t 1st driven axle	1.2335 m
Semitrailer	Rear overhang	4.3 m
Semitrailer	Number of axles	3
Dolly	Wheelbase	1.3 m
Dolly	Fifth wheel hinge point	0.65 m
Dolly	Front overhang	0.5 m
Dolly	Rear overhang w.r.t 1st axle of dolly	1.8 m
Dolly	Position of COG w.r.t 1st axle of dolly	0.7447 m
Dolly	Number of axles	2
Tire	Cornering Coefficient	6 (1/Rad)

In the table 3.2, the nomenclature under category refers to vehicle parameters being fixed to a certain value for this study. The term "nominal(fixed)" specifies that the parameter is set to a nominal value and fixed to that particular value throughout this study. The models in OpenPBS toolbox are developed such that the parameter itself can be varied. The other constraints that are fixed are that only tractor's first axle is steered and the other two axles are driven. Detailed explanation of the loading of the vehicle is provided in section 4.3.2.3. Cornering coefficient is used to determine cornering stiffness which in turn is used to obtain tire lateral forces. A cornering coefficient of 6 1/rad is used here, probably representing a rather soft tire set with respect to cornering performance.

$$Cy[N/rad] = CC[1/rad] * Fz[N]$$

There are mainly 6 different checks which are implemented under pre-check filter in this study.

- Check on Overall length of the combination vehicle.
- Check on the track width of the combination vehicle.
- Semitrailer consistency check.
- Clash check between modular units.
- Number of units in the combination vehicle.
- Maximum number of axles on any modular unit of the combination vehicle.

The first two conditional checks are performed on the overall length and width of the vehicle, for the vehicle to pass the checks the combination vehicles should not be longer than 34 m and wider than 2.6 m respectively. The semi-trailer load length is the sum of semi-trailer front overhang, distance from kingpin to centre axle, and rear overhang, the distance from centre axle to end of the semitrailer body. In the simulations if the sum of these three parameters is higher than 13.6 m, it would imply the semitrailer is longer than 13.6 m. This is not possible because the semitrailer load length is fixed to 13.6 m. Therefore any combination vehicle with higher load length than 13.6 m will be rejected and this is known as semitrailer consistency check. To avoid a clash between vehicles, a simple geometrical analysis provides a minimum distance of 4 m between any modular units, for instance between lead semi-trailer and dolly. Although the vehicle configuration is fixed, checks on a number of units and number of axles on each unit are performed to confirm that the correct A-double vehicle configuration is being used in the FMU.

After fixing nominal values for geometrical parameters, the parameters that are sensitive to PBS were chosen as design parameters which will be varied to obtain envelopes. A detailed explanation for choosing specific design parameters to study is provided in next chapter.

3.5 PBS

The table below provides a list of PBS and their threshold values. The values for all PBS measures except the friction demands on steered and driven tires, were provided by Transportstyrelsen, the Swedish transport agency. Since this is part of an ongoing study, the threshold values provided in table 3.3 are preliminary values. Some of the thresholds are missing currently.

Table 3.3: PBS Threshold Values

PBS	Threshold Value
Startability (SA)	12%
Gradeability (GA)	1% maintaining 70 km/h speed
Acceleration Capability (AC)	-
Low Speed Swepth Path (LSSP)	Max 10 m in a 90°turn
Frontal Swing (FS)	Max 0.7 m in a 90°turn
Tail Swing (TS)	Max 0.35 m in a 90°turn
Load Transfer Ratio (LTR)	-
Steady State Rollover (SRT)	Min 3.5 m/s^2 -lateral acceleration
Rearward Amplification (RWA)	Max 2.4
Yaw Damping (YD)	Min 0.15 @ 80kmph constant velocity
High Speed Transient Off-Tracking (HSTO)	Max 1.0 m relative to first axle
High Speed Steady state Off-Tracking (HSSO)	-
Tracking Ability on Straight Path (TASP	Max 0.4 m
Friction Demand on Steered Tyres (FDST)	Max 0.25
Friction Demand on Driven Tyres (FDDT)	Max 0.25
Braking Stability in a Turn (BST)	-

3.6 Post-Check

In post check, all vehicle combinations need to satisfy certain conditions on vertical loads on axles. These conditions are mainly on vertical loads on axles of different modular units. By knowing the vertical loads and the friction available, one can largely determine if the vehicle is stable or not. The vertical loads need to be below a certain value for mechanical integrity of the modular unit. If the load experienced is above a certain limit the structural member will be subjected to a higher load than it was designed for and can cause mechanical failure. The load capacity of each axle is also prescribed in order to keep the road damage minimal.

Table 3.4: Post Check Conditions

Module	Parameters	Value
Overall Vehicle	Max combination weight	74 tons
Overall Vehicle	Min Load on driven axles	20% of overall weight
Overall Vehicle	Max load on Single axle	10 tons
Overall Vehicle	Number of Axles	11
Tractor	Max Sum of load on all axles	24 tons if whlbase is 3m 25 tons if whlbase is 3.2m 26 tons if whlbase is 3.4m 27 tons if whlbase is 3.4-3.8m
Semitrailer	Max tri-dem axle load	24 tons
Dolly	Max dolly load	18 tons

3.7 PBS maneuvers

A brief description of vehicle maneuvers and the model implemented to obtain certain PBS measure. More details can be found in [1]

Table 3.5: Table describing the maneuvers

PBS Measure	Vehicle Maneuver
Yaw damping	Singe sine steer 0.4 Hz,0.05 rad amplitude @ 80 kph
Rearward amplification	Singe lane change 0.3 Hz, 3m lane width @ 80 kph
High speed transient off tracking	Singe lane change 0.3 Hz, 3m lane width @ 80 kph
Tracking ability on straight path	High speed straight path
Low speed swept path	Low speed curve 90 degree, 12.5m radius @ 1 m/s
Frontal swing	Low speed curve 90 degree, 12.5m radius @ 1 m/s
Tail swing	Low speed curve 90 degree, 12.5m radius @ 1 m/s
Friction demand on driven tires	Low speed curve 90 degree, 12.5m radius @ 1 m/s
Friction demand on steered tires	Low speed curve 90 degree, 12.5m radius @ 1 m/s

The analysis performed in this study does not consider all the PBS measures for various reasons. The longitudinal PBS measures startability, gradeability and acceleration capability were not investigated because changes in geometrical parameters do not effect these PBSes. These performance measures primarily depend on engine performance characteristics and road friction available. The PBS measures friction demand on steered and driven tires are not completely modeled. It is questionable as to how accurate these models in the OpenPBS toolbox represent these two PBSes. The PBS measure high-speed steady state off-tracking was not considered since there is no threshold value to validate the model. The model and FMU for the same is available on the OpenPBS toolbox. The other PBSes which were not investigated in this study were load transfer ratio, static rollover threshold and braking stability in a turn. The models for this were not available in the OpenPBS toolbox.

3.8 Implementation

Functional mock-up interface (FMI) is used for simulation of Modelica models in MATLAB. The interface aids users to perform both model-exchange and co-simulation. FMI is defined by [23] as *a tool independent standard to support both model exchange and co-simulation of dynamic models using a combination of XML-files and compiled C-code.* The models for evaluation of different PBS are developed in format Modelica on the tool, Dymola [24]. All the studies performed in this thesis were done in Matlab [25].

The models developed in Dymola are divided into different categories of high speed, low speed, and others. A functional mock-up unit (FMU) is generated for each of the maneuvers defined in section 3.7. The FMU generated is only for a model exchange since MATLAB solvers are used for simulating the model. The implementation of the generic framework is be described by the following steps.

The first step is to load the FMU's into the MATLAB work space. The nominal parameters are set to a fixed value in a subscript called pre-check. Subsequently the design variables are varied in a nested for-loop. The important properties which are considered under the pre-check filter, such as overall length, track-width, clash are determined and the combination vehicles are passed through the pre-check filter. After neglecting the combination vehicles which fail pre-check, the FMU's are simulated. The performance measures and axle loads are collected in a separate subscript called post-check. At this stage, the combination vehicles are passed through PBS and post-check filters. The combination vehicles passing all three filters are collected. The parameters of the passing vehicles are stored for identifying the envelopes e.g. multidimensional cuboid. The commands for performing different operations on an FMU can be found in the FMIT toolbox user guide [26].

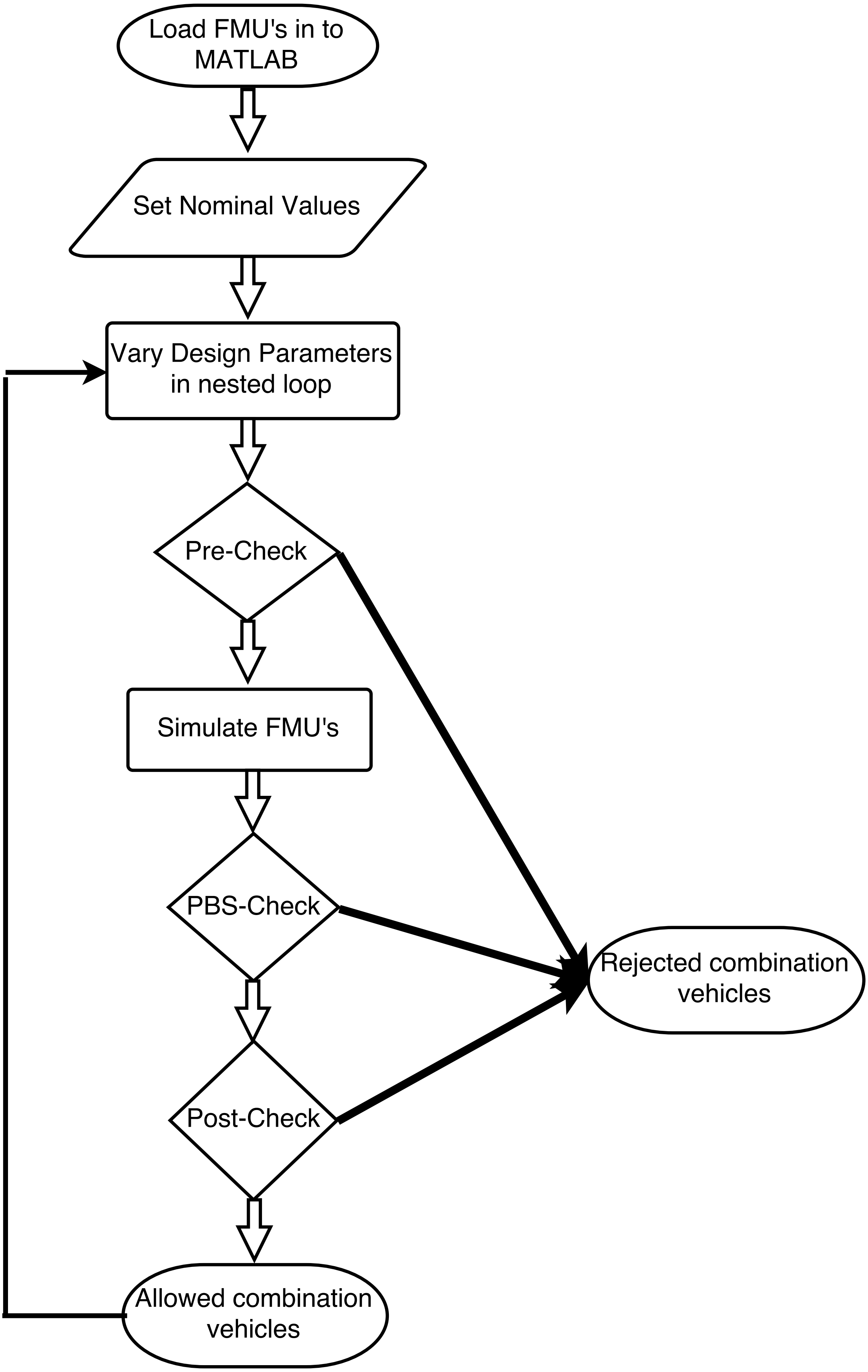


Figure 3.7: A flowchart representing implementation of framework

4

Results

This chapter is divided into three parts. The first part, section 4.1 explains sensitivity analysis, which was performed to choose important parameters to be studied. Next part, section 4.2 deals with single parameter variation study and the corresponding results. The final part, section 4.3 lays emphasizes on the need for multiple parameter variation studies and the following sections 4.3.1-4.3.2.3 provide outcomes and discussions of this study.

4.1 Sensitivity Analysis

Due to large number of parameters, it is vital to study the parameters which have the maximum influence on the PBS measures. Since envelopes are vehicle's geometrical allowable ranges, it is crucial to understand the influence of parameters on PBS measures. Reports such as [12] provide information about the vehicle model parameters affecting the performance measures but, it does not cover all the PBS measures. The values of parameters for default vehicle are given in table 3.2.

A MATLAB script was written to vary each parameter and observe the PBS measures values. The table 4.1 provides the parameters studied and their ranges. The motivation for performing such a study is not only to choose design parameters but also to understand the effects of parameters on PBS measures. In order to vary parameters, a set point or nominal vehicle needs to be defined. The following table 4.1 provides the values for the nominal vehicle.

Table 4.1: Nominal/Default values and ranges of parameters

Module	**Parameter**	**Nominal Value** [m]	**Variation** [m]
Overall	Vehicle length	31.7	29 - 34
Overall	Vehicle width	2.5 m	-
Tractor	Wheelbase	3.4	3.0 - 3.9
Tractor	Tandem axle spread	1.37	1.2 - 1.45
Tractor	Front overhang	1.4	1.2 - 1.8
Tractor	Fifth wheel position w.r.t 1st driven axle	0.25	0.1 - 0.4
Tractor	Rear overhang	5.17	-
Semitrailer	Body Length (both I and II)	13.6	-
Semitrailer	Front over hang (both I and II)	1.6	1.2 - 2.0
Semitrailer	Wheelbase(both I and II)	7.7	7.1 - 8.9
Semitrailer	Tri-dem axle spread (both I and II)	2.6	2.0 - 3.2
Semitrailer	Distance to rear hinge pt(both I and II)	3.4	2.7 - 4.0
Semitrailer	Rear over hang(both I and II)	5.6	-
Dolly	Wheelbase	1.3	1.0 - 1.8
Dolly	Draw bar Length	4.2	3.0 - 5.0
Dolly	Front overhang	0.5	-
Dolly	Rear overhang	1.8	-
Tire	Cornering coefficient	6	5.0 - 8.0

Studies such as [12] provides some information on the sensitivity of parameters on performance measures but, are not complete. The idea is to vary each parameter and observe the effect of variation in the value of PBS measures. This was one of the gaps observed in the literature which has been addressed in this thesis. The sensitivity analysis also provides intuitive knowledge. The table below, provides results from the sensitivity analysis performed. The variation range of each parameter is provided in table 4.1. The results for this study is provided below in table 4.2.

Table 4.2: Sensitivity Analysis

Module	Parameters	RWA	1/YD	HSTO	TASP	LSSP	FS	TS	Step (m)
Tractor	Wheelbase	inc	inc	dec	dec	inc	inc	dec	0.2
Tractor	Tandem axl sprd	-	inc*	dec*	-	-	inc	inc	0.1
Tractor	Front overhang	-	-	-	-	-	inc	-	0.1
Tractor	fifth whl positn	inc*	dec*	-	-	dec	-	inc	0.1
Semitrailer	Wheelbase	dec	dec	dec	inc	dec	-	dec	0.2
Semitrailer	Front overhang	-	-	-	-	-	inc	inc	0.1
Semitrailer	Dist to rear hinge pt	inc	inc*	inc	inc	dec	-	-	0.2
Semitrailer	Tri-dem axle sprd	dec	dec	dec	-	inc*	dec*	inc	0.1
Dolly	Wheelbase	dec	dec	dec	-	inc*	inc*	dec*	0.1
Dolly	Draw bar Length	dec	dec*	dec*	inc	dec	dec*	inc*	0.2
Tire	Cornering coefficient	dec	dec	dec	dec	-	inc	inc	1

- inc/dec– change in the value of PBS measure w.r.t nominal value for a step change in the parameter value is >25%
- inc*/dec*– change in the value of PBS measure w.r.t nominal value for a step change in the parameter value is <25%
- — No affect

This study provides both quantitative and qualitative information. The study aids in understanding the effect of vehicle's geometrical parameters on the performance measures. The results of this study provide a motivation to choose the important parameters for an A-double combination vehicle. As it can be observed, the front overhang of tractor and semitrailer does not have any influence on PBS measures, except for frontal and tail swing. The tandem axle spread and fifth wheel position on the tractor have influence on 4 different PBS measures. Whereas the most important parameters that influence all PBS measures are tractor wheelbase, semitrailer wheelbase, distance to rear hinge point from the center axle of the semitrailer, drawbar length of the dolly and tire cornering stiffness. Since tire cornering stiffness is a property of tire, this parameter will not be studied. This study provides the important parameters that are being studied in detail to obtain envelopes.

Table 4.3: The design parameters

Modular Unit	Parameters
Tractor	Wheelbase
Semitrailer	Wheelbase
Semitrailer	Distance between axle and hinge point
Dolly	Draw Bar length

4.2 Single Variable Study

After performing sensitivity analysis, the design variables were chosen. This section provides the results of single variable sweep study. A general framework along with pre, PBS and post checks developed in the earlier chapter was implemented in Matlab. The motivation for the single variable study was to observe the trend and allowed geometrical ranges in depth. The single variable study also provides an initial understanding of the range of each variable.

4.2.1 Design Variable 1 : Tractor Wheelbase

The tractor wheelbase was varied and results for each PBS measure is shown below. The tractor wheelbase was varied certain distance above and below the nominal value of 3.4m as shown in figure 4.1. This parameter sweep can be understood as the variation of only one parameter when all other vehicle parameters are fixed to the nominal value provided in table 4.1

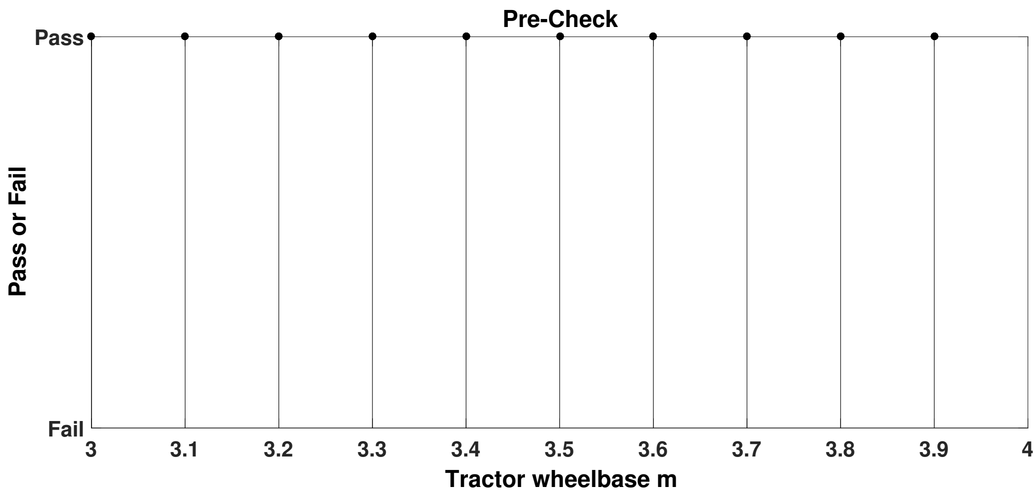


Figure 4.1: Pre-check vs tractor wheelbase (all pass)

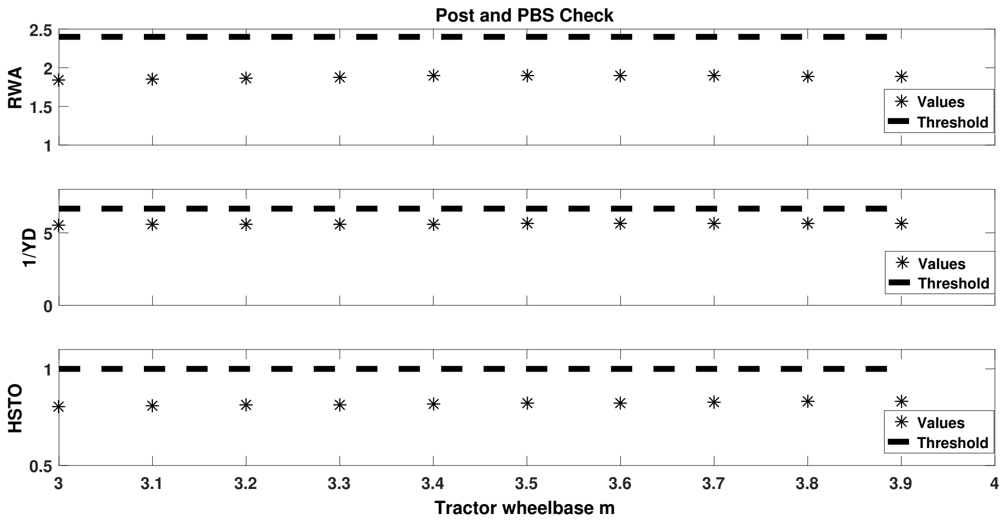


Figure 4.2: RWA, 1/YD and HSTO vs tractor wheelbase

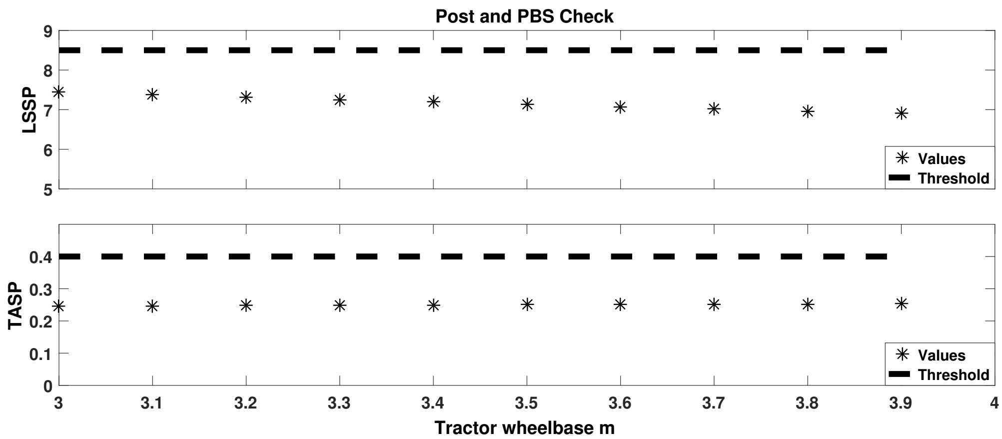


Figure 4.3: LSSP and TASP vs tractor wheelbase

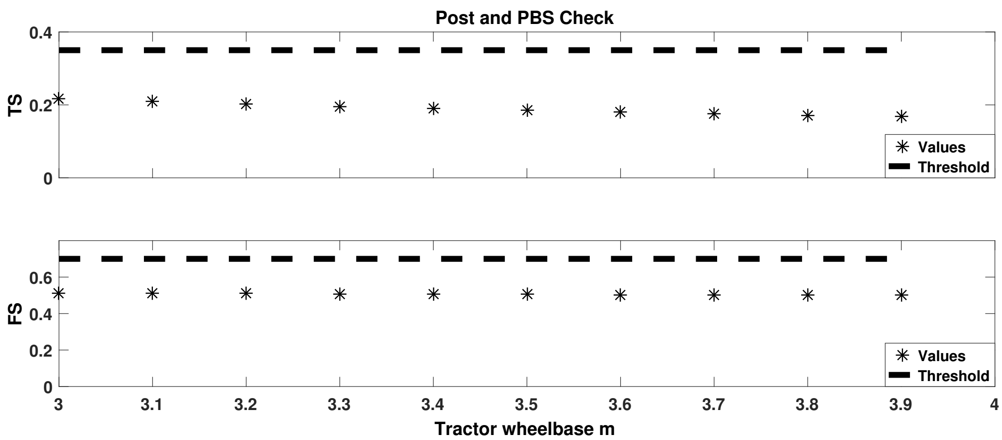


Figure 4.4: TS and FS vs tractor wheelbase

The trend for each performance based standards measures can be observed. The pre-check filter allows all vehicles with tractor wheelbases between 3.0 to 3.9 m. The nominal value was 3.4 m. The post and PBS filter for each measure are shown. From the results, it can be interpreted that for a high road friction surface allowed tractor wheelbase is 3.0 to 3.9 m. It will be important to compare the allowed range when multiple variables are studied. This part was addressed in the following section.

4.2.2 Design Variable 2 : Semitrailer Wheelbase

The semitrailer wheelbase was varied and results for each PBS is shown below. The semitrailer wheelbase was varied certain distance above and below the nominal value of 7.7 m.

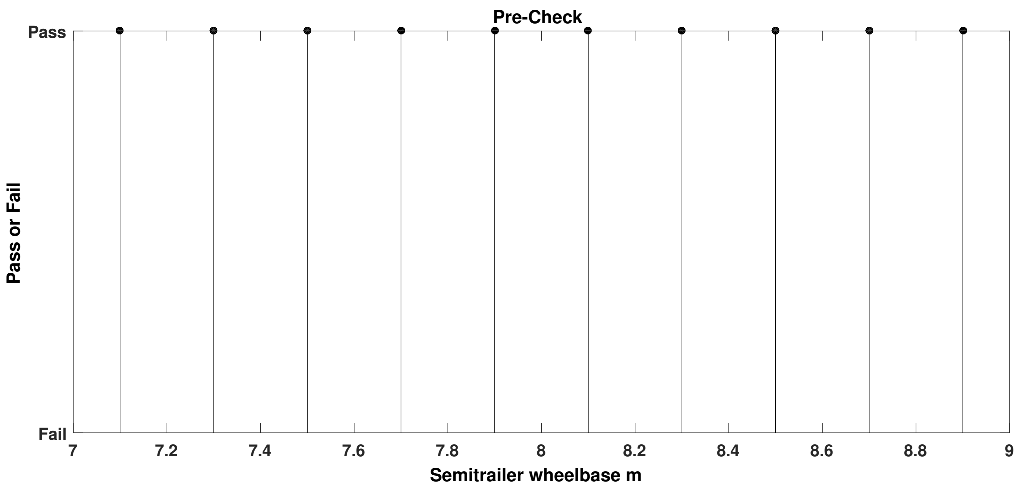


Figure 4.5: Pre-check vs semitrailer wheelbase

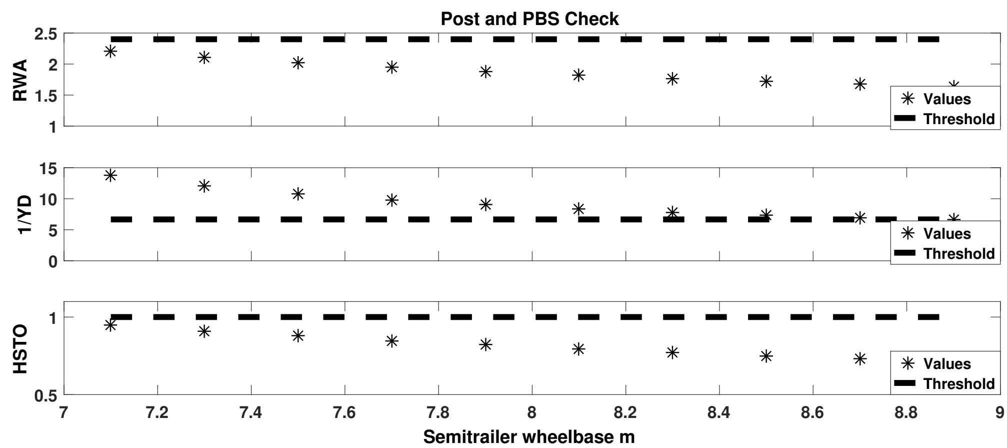


Figure 4.6: RWA, 1/YD and HSTO vs semitrailer wheelbase

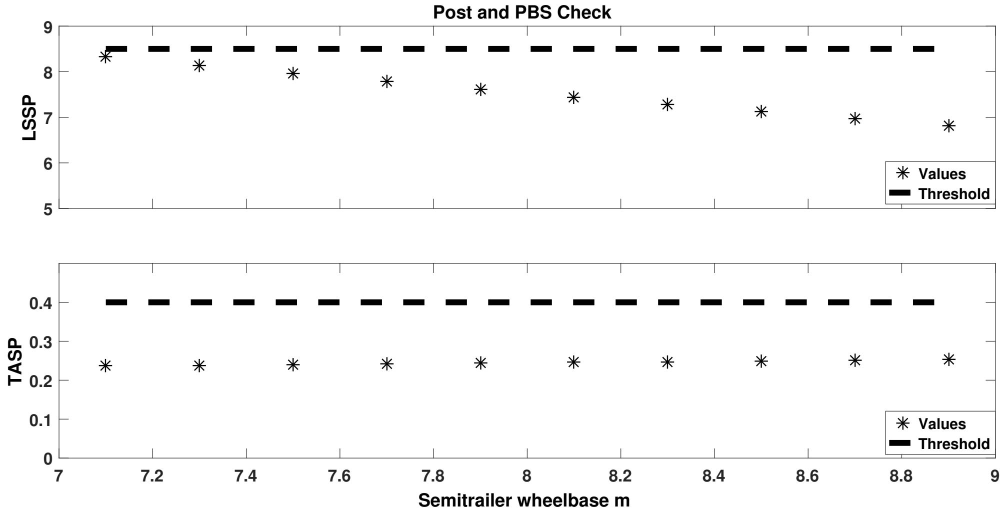


Figure 4.7: LSSP and TASP vs semitrailer wheelbase

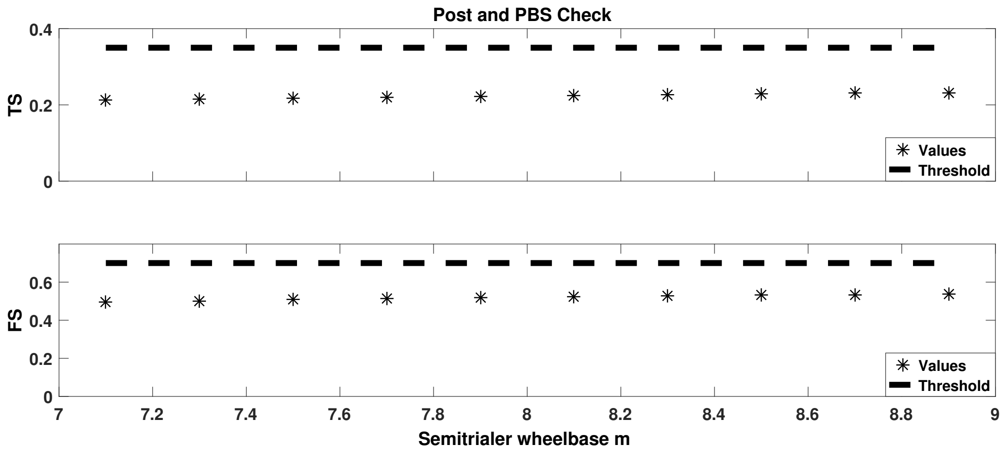


Figure 4.8: TS and FS vs semitrailer wheelbase

It can be observed that the inverse of yaw damping values is below the respective threshold value only for a wheelbase of 8.5 m. The low speed swept path also is very close to the threshold for a wheelbase of 7.2m. The pre-check filter allows vehicle combinations with the wheelbase between 7-8.9 m. The post and PBS filter allow for wheelbase above 8.5 m. It would be interesting to vary the wheelbase higher than 8.9 m and observe the trend of YD values. Longer wheelbases than 8.9 m were not studied because any higher values would make the overall length longer than 34m. It will be important to compare the allowed range when multiple variables are studied.

4.2.3 Design Variable 3 : Draw bar length

The draw bar length was varied and results for each PBS is shown below. The draw bar length was varied certain distance above and below the nominal value.

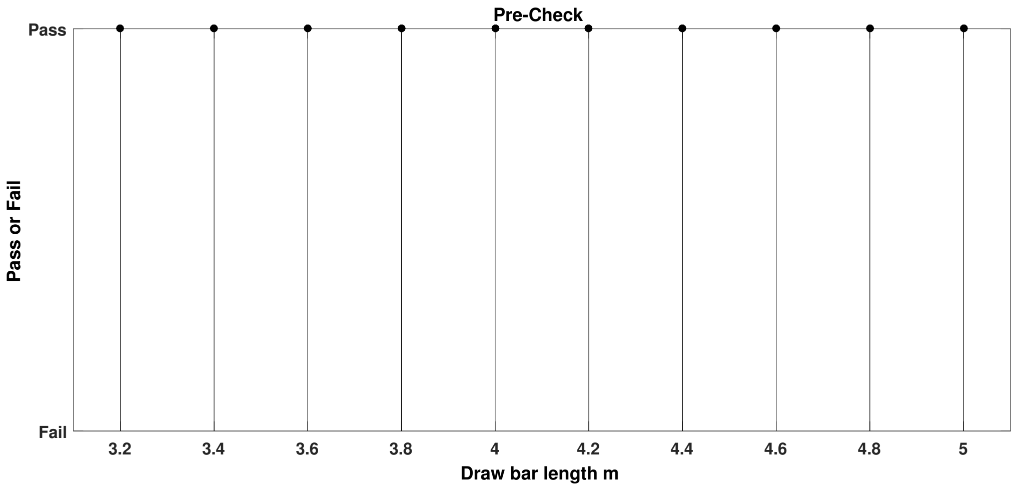


Figure 4.9: Pre-check vs Draw bar length

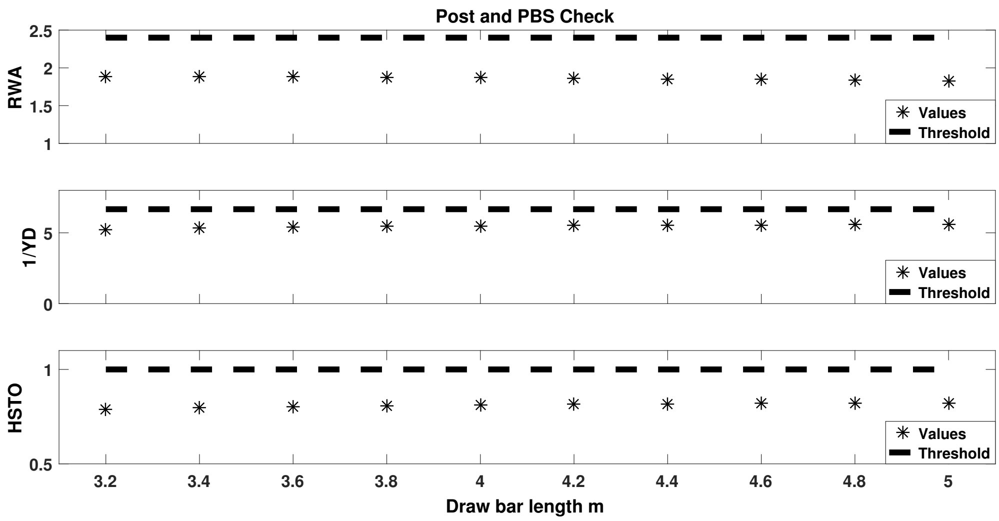


Figure 4.10: RWA, 1/YD and HSTO vs draw bar length

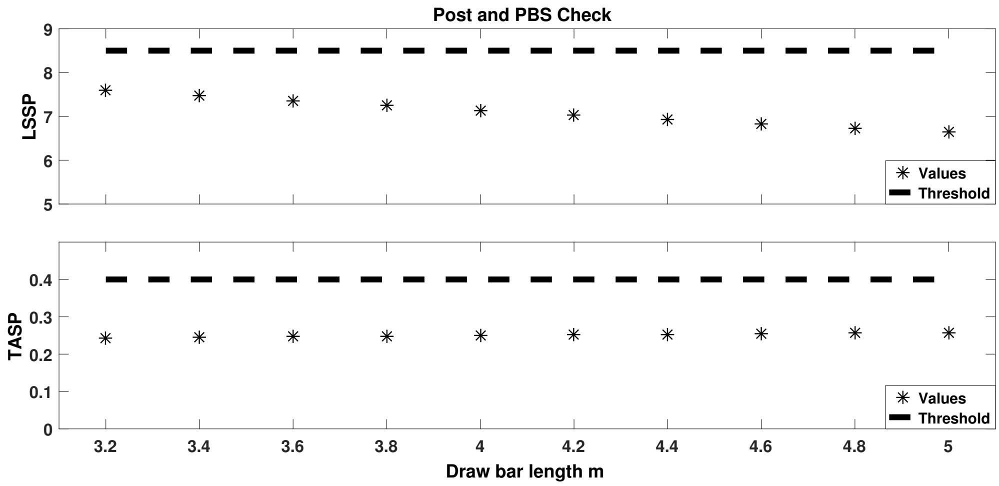


Figure 4.11: LSSP and TASP vs draw bar length

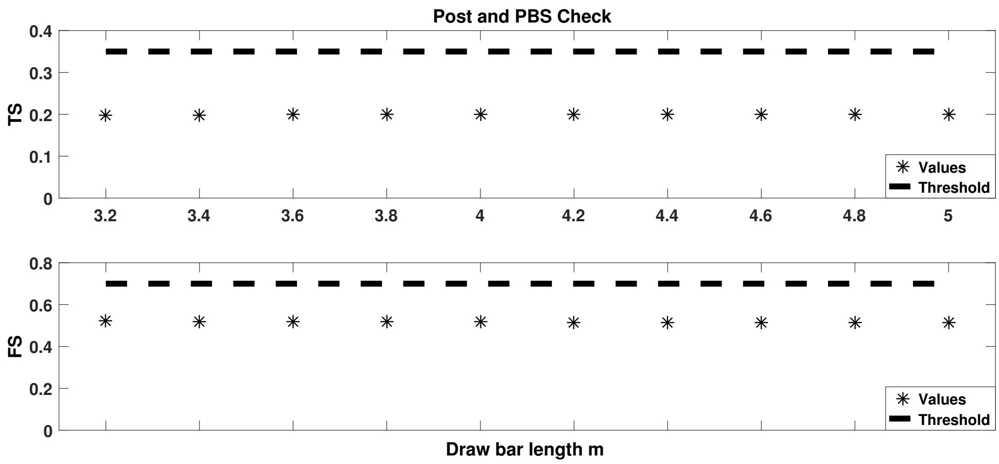


Figure 4.12: TS and FS vs draw bar length

The trend for different PBS measures can be observed in the results. The pre-check filter allows for all combination vehicles. The multiple variable studies will consider the constraints of the clash and a comparison with the single variable study will be crucial to gain a better understanding. The post and PBS filter allow vehicle combinations with draw bar length ranging from 3-5 m.

4.2.4 Design Variable 4 : Distance to rear hinge point

The distance to rear hinge point was varied and results for each PBS is shown below. The distance to rear hinge point was varied certain distance above and below nominal value.

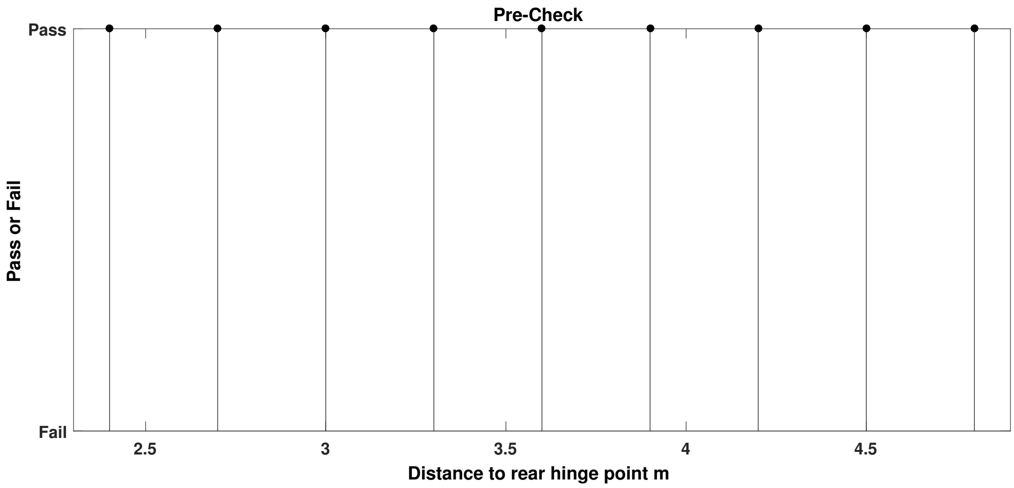


Figure 4.13: Pre-check vs distance to rear hinge point

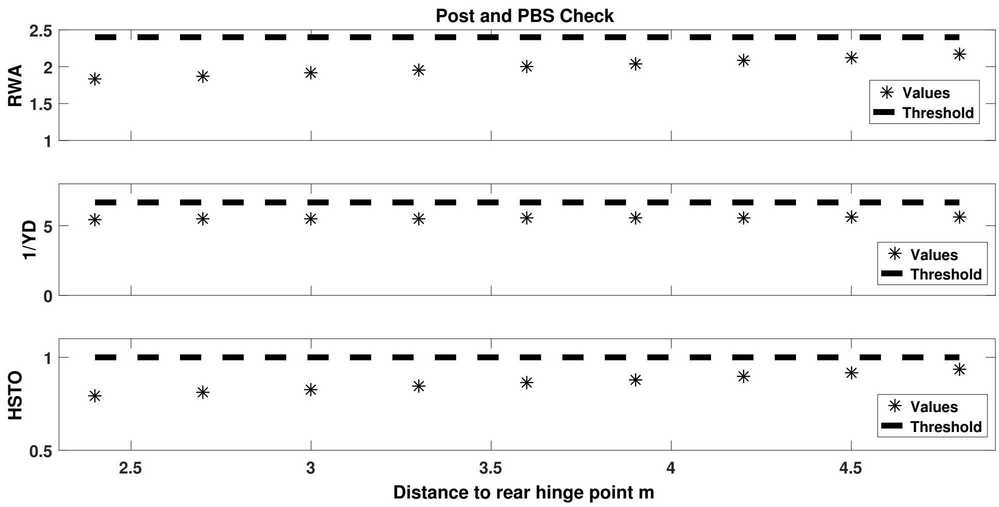


Figure 4.14: RWA, 1/YD and HSTO vs distance to rear hinge point

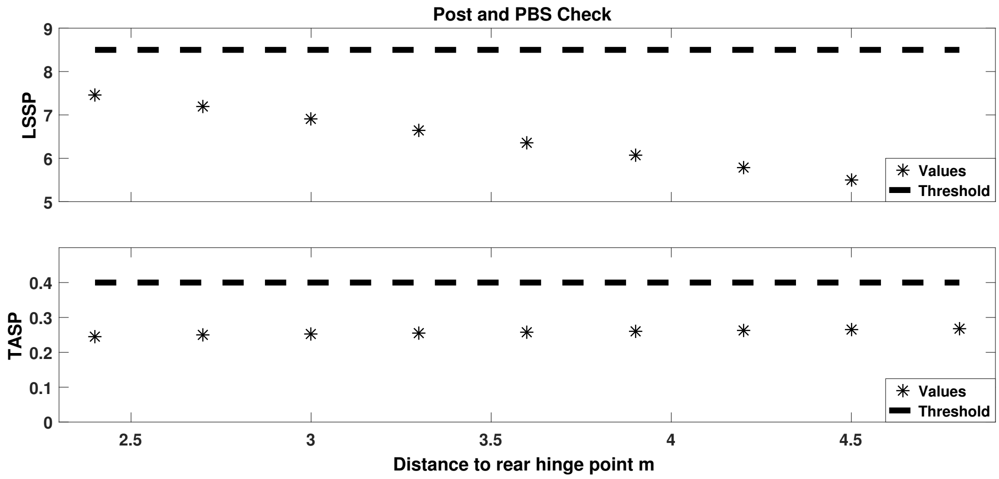


Figure 4.15: LSSP and TASP vs distance to rear hinge point

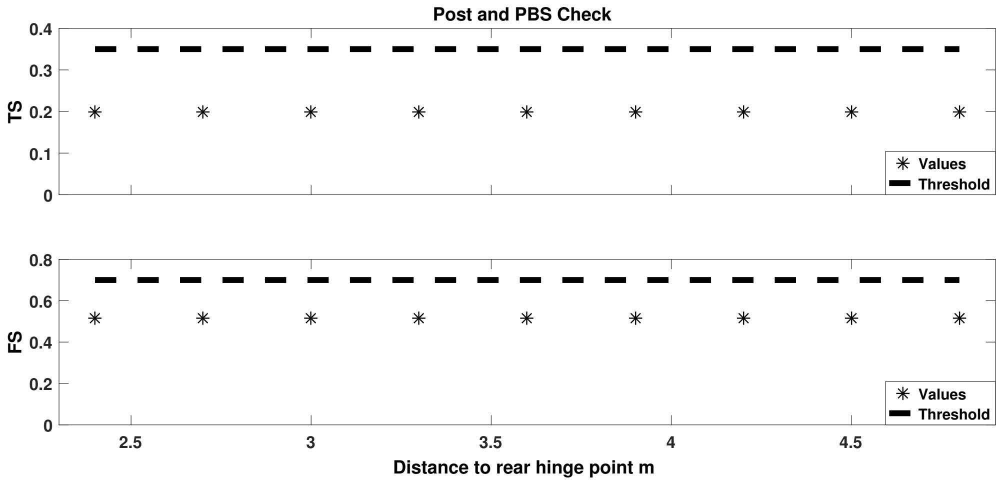


Figure 4.16: TS and FS vs distance to rear hinge point

The pre-check filter allows for all combinations vehicles within the range 2.4-4.8 m. It can be observed that the high-speed transient off tracking is close to the threshold for distance to rear hinge point higher than 4.5 m. There is a trade-off between high speed PBS measures like RA and HSTO with low speed PBS measure LSSP. Other PBS measures are within the threshold. Hence the allowed range is between 2.4-4.5 m.

4.3 Multiple Variable Sweep

The single variable sweep study captures some effects of parameter variation on PBS measures and provides ranges for each variable. However, the problem of envelopes is finding a desirable space in the multi-dimensional variable space. To obtain feasible and realistic outcomes, and to gain a deeper understanding, a combined multiple variable sweep study of higher order is necessary. The following sections 4.3.1-4.3.2.3 provide information about this study and the results obtained.

4.3.1 Combined sweep (3 Dimensional)

This section explains the 3D study performed to extract envelopes and the results obtained. Only three dimensions were chosen because it is easier to represent the results in a 3-dimensional space. The 3D study was crucial to see how the envelopes pan out in 3D space. The inference and the usefulness of 3D study are explained in the results section. The design variables are depicted in the figure 4.17.

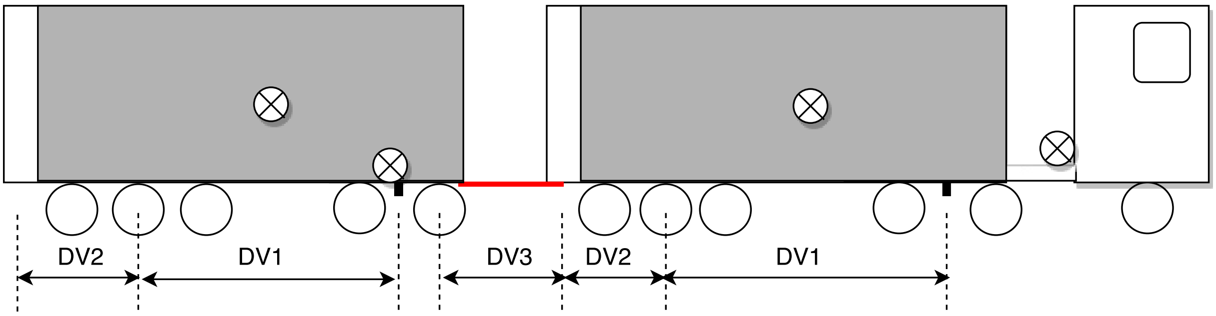


Figure 4.17: Design Variables for 3D study

The variables chosen to study are the ones that have most influence on the PBS. The design variables are

- DV1 - Semitrailer wheelbase
- DV2 - Distance from center axle to rear hinge point on semitrailer
- DV3 - Draw bar length

The following table provides a range of variation of each variable in the study. These ranges were provided by Volvo Group Trucks Technology.

Table 4.4: Table providing information on range of variation

Design Variable	**Range** [m]	**Step** [m]
Semitrailer wheelbase	7.1 - 8.9	0.2
Distance to rear hinge point	2.1 - 4.9	0.2
Draw bar length	3.0 - 5.0	0.2

4.3.1.1 Results for 80% front loading

As mentioned above the main reason behind studying three variables was to be able to visualize the envelopes. Higher dimensional studies require special methods to represent the envelopes. It is crucial for the end user to interpret the results to build allowable combination vehicles.

One of the issues is to choose an allowable range for each variable. The problem could be seen as optimally fitting a cuboid in the 3D space. There could be many different solutions for this because in this study we are only performing variable sweep unlike doing optimization with an objective function. Industrial expertise was used to choose the final envelopes. The figure below provides the chosen allowed ranges for the three variables.

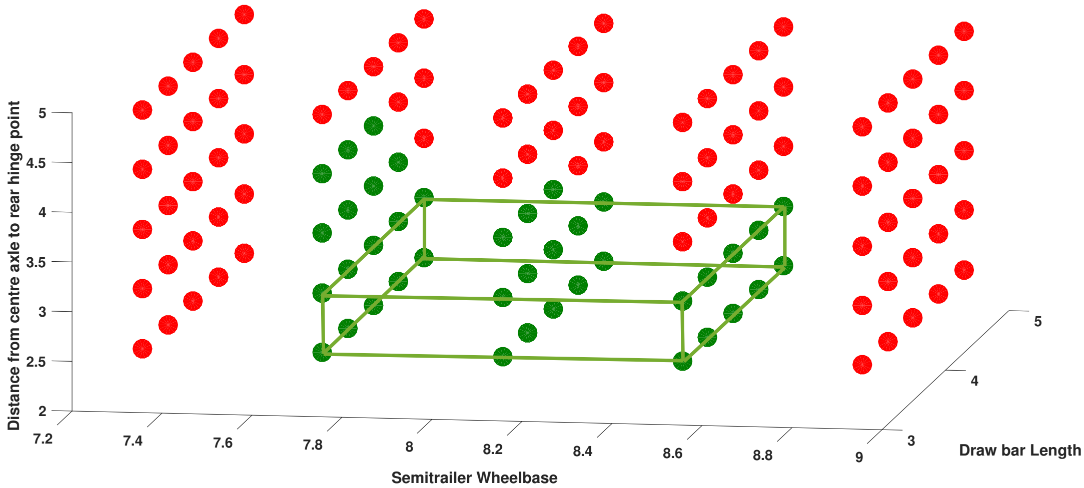


Figure 4.18: Envelopes for 3D combined sweep for 80% front loading

Figure 4.18, depicts the envelope space for this study. One of the problem that was foreseen was that, if the allowed ranges marked by green dots would lie in separate isolated regions in the design space, it would be difficult to choose one specific range. As it can be observed, there are no separate isolated spaces of allowed ranges hence making it easy to inscribe a cuboid and obtain allowed ranges. For the given space the cuboid can be inscribed in many ways. The cuboid covering the maximum area is chosen.

4.3.1.2 Results for 90% front loading

This section deals with results obtained for a 3D combined sweep study with 90% front loading. The loading is such that the semitrailer is loaded uniformly for only 90% of the space, the last 10% of space is kept empty. The results are provided below in figure 4.19.

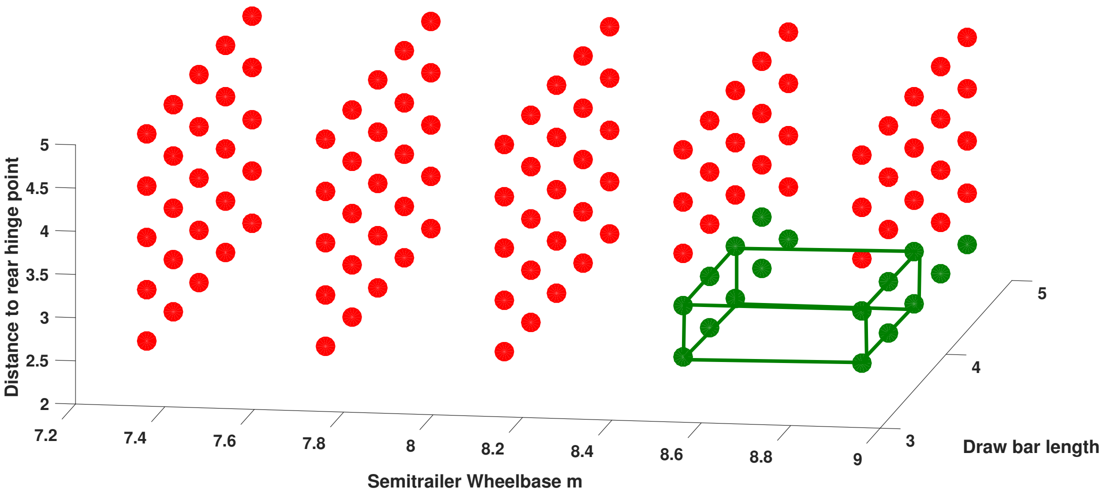


Figure 4.19: Envelopes for 3D combined sweep for 90% front loading

When compared to figure 4.18, the envelope space in figure 4.19 has less number of passed parameter sets, denoted by green dots. The primary reason for this is the way the semitrailers are loaded. The constraint that the driven axles vertical load must have a minimum of 20% of overall weight is not met. This constraints cuts the design space to larger extent and allows lesser combination vehicles than that in subsection 4.3.1.1

4.3.1.3 Results for 100% front loading

This section consists of the results for loading case 100% front loaded, the semitrailer is loaded all through out its load length uniformly 3.6. As discussed in section the A-double does not satisfy the legal constraint of 20% overall weight on driven tires. The results obtained also agree with this observation. No vehicles pass the post check since the vertical load on driven axles is lower than 20% of overall weight. If varying the parameters in the 3D sweep, no A-double can not be allowed with 100% front loading.

4.3.2 Combined sweep(4 Dimensional)

Since there are many variables that can be varied by a manufacturer, it is important to study more than just three variables. This section explains the study performed by adding another dimension to 3-dimensional study. The major concern for this study is the final representation. In the future, all other variables also can be studied like the ones in above section. This possibility is due to the parametric approach used for modeling. All the variables are available to perform a study.

The design variables variation range was provided by Volvo Group Trucks Technology. The following table provides ranges to vary for the design variables.The procedure and script developed are kept generic, which can be used to study more than four variables.

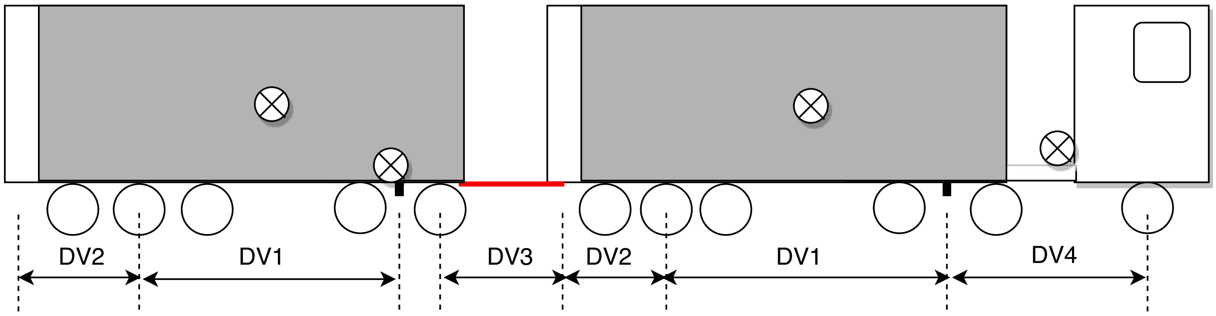


Figure 4.20: Design Variables for 4D study

Table 4.5: Parameter variation for 4D sweep

Design Variable	**Range** [m]	**Step** [m]
Semitrailer wheelbase DV1	7.1 - 8.9 m	0.2
Distance to rear hinge point DV2	2.1 - 4.9 m	0.2
Draw bar length DV3	3.0 - 5.0 m	0.2
Tractor wheelbase DV4	3.0 - 3.8 m	0.2

4.3.2.1 Results for 80% front loading

The visualization of the results obtained from 4D sweep can be done in many ways. Three different methods namely, radar plot, pivot table, and dimensional chart were investigated. First, the below figure 4.20 provides the visual representation of the design variables, namely semitrailer wheelbase, distance from center axle to rear hinge point, draw bar length and tractor wheelbase.

Radar plot is a graphical representation method to represent multivariate data in 2-dimensional space. The radar plot of allowed combinations of A-double is shown below.

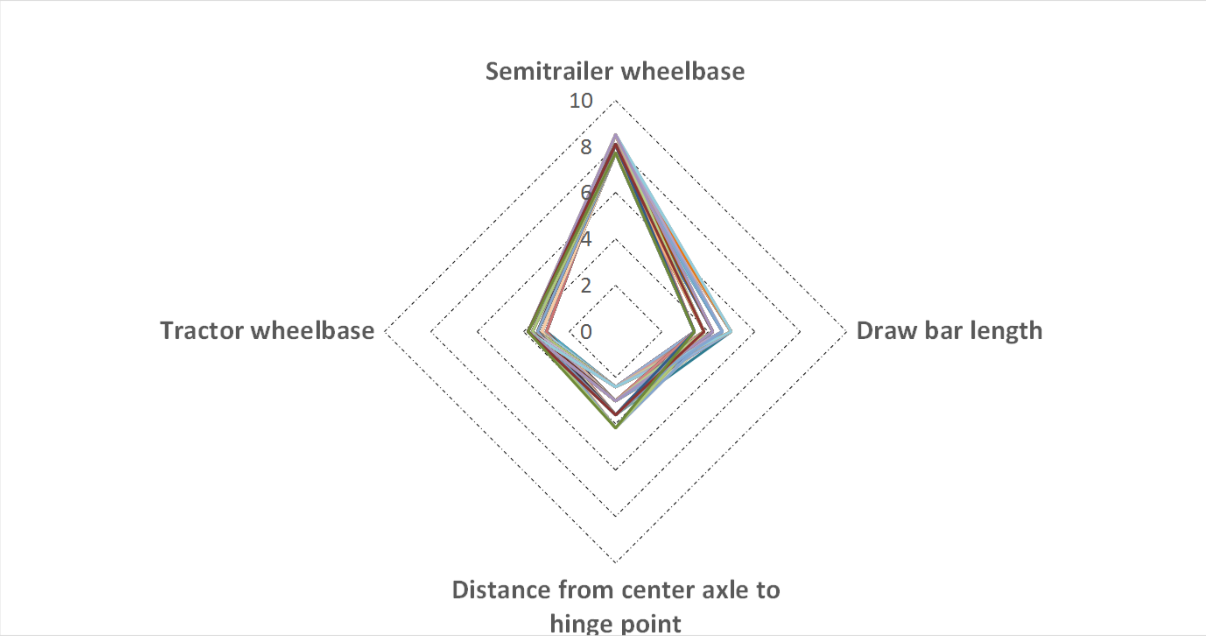


Figure 4.21: Envelopes for 4D combined sweep for 80% front loading

The radar plot 4.21 has 153 quadrilateral lines, each of the quadrilaterals represents an allowed vehicle combination. From the figure 4.21 it is unclear as to what are the combinations that are allowed. The lines intersect each other and valuable information is lost. The radar plot can be used to represent the final allowed ranges as shown in the figure below 4.22.

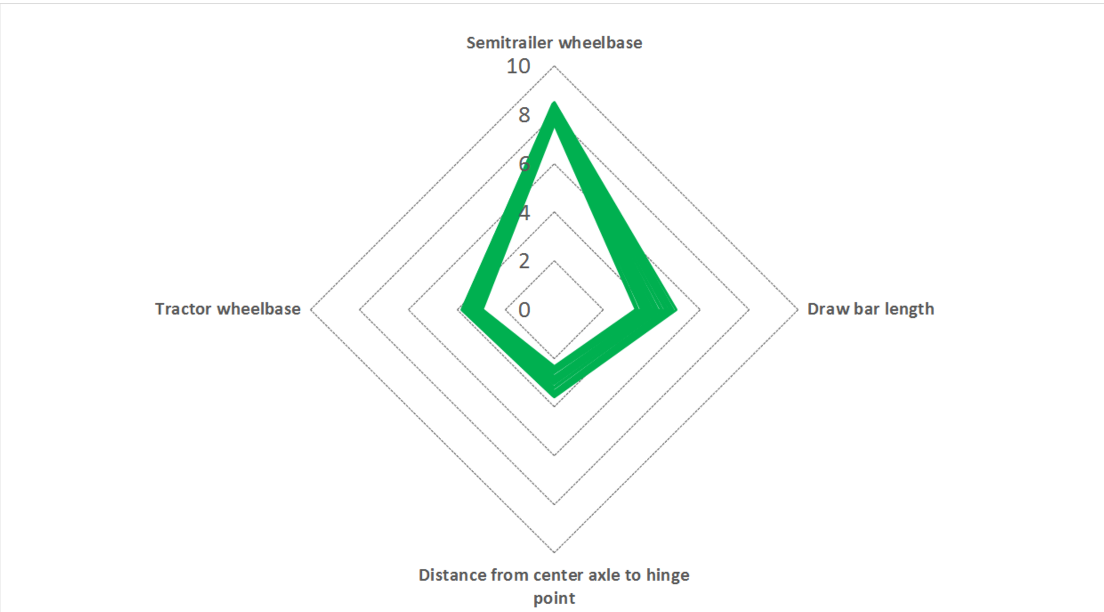


Figure 4.22: Envelopes for 4D combined sweep for 80% front loading

The solid green region is the allowed ranges. The inner point is lower bound and the outer point is upper bound for each design variable. Even this does not address the issue of if conditions. The pivot table is not suitable representation for this study due, to the number of allowed vehicles being very large. A dimensional chart is chosen for final representation of envelopes. The dimensional charts are provided below.

The post check constraints are provided in table 4.6

Table 4.6: Inertial properties of allowed A-double

Modular type	**Parameter**	**Value**
Overall	Max combination weight	74 tons
	Min load on driven axles	20% of gross weight
Tractor	Max sum of load on all axles	24-27 tons
Tractor	Max load on tandem axles	19 tons
Semitrailer	Max load on tri-dem axles	24 tons
Dolly	Max load on axles	18 tons

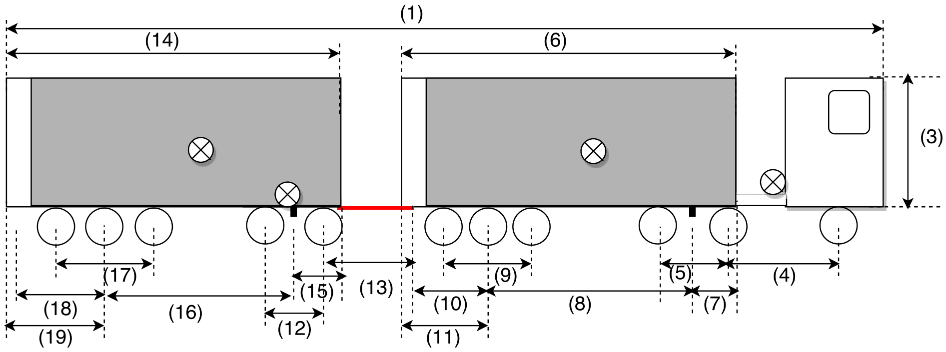


Figure 4.23: A-Double : Description and Dimensions

Table 4.7: Dimensional limit chart for A-double

Vehicle	Ref	Feature	Dimensions(Sweden)	Dimensions(Canada)
Overall	(1)	Length of the combination	Max 34m	Max 40 m
	(2)	Width of Vehicle	Max 2.6m	Max 2.6 m
	(3)	Height of the Vehicle	-	Max 4.15 m
Tractor	(4)	Wheelbase	3.0 - 3.8 m	Min 3.5 m
	(5)	Tandem axle spread	1.37 m	1.2 - 1.85 m
Lead Semi-trailer	(6)	Length	13.6 m	14.5 - 16.2 m
	(7)	Front Over-hang	1.6 m	Max 2 m
	(8)	Wheelbase	7.7 - 8.5 m	10.9 - 12.5 m
	(9)	Tridem axle spread	2.6 m	2.4 - 3.7 m
	(10)	Distance to hinge point	2.4 - 3.6 m	not defined
	(11)	Rear Over-hang	3.5 - 4.3 m	Max 3.4 m
Converter Dolly	(12)	Wheelbase	1.3 m	1.2 - 1.85 m
	(13)	Drawbar length	3.0 - 5.0 m	Max 3m
Second Semi-trailer	(14)	Length	same as Semi I	14.5 - 16.2 m
	(15)	Front Over-hang	same as Semi I	Max 2 m
	(16)	Wheelbase	same as Semi I	10.2 - 12.5 m
	(17)	Tridem axle spread	same as Semi I	2.4 - 3.7 m
	(18)	Distance to hinge point	same as Semi I	-
	(19)	Rear Over-hang	same as Semi I	35% of wheelbase

Table 4.8: Allowed ranges for the design variables for 80% front loading

Trctor whlbase[m]	Trailer whlbase[m]	Dist to rear hinge[m]	Drawbar length[m]
3.0	8.1	2.4 - 3.6	3.0 - 4.6
3.2 - 3.4	7.7 - 8.5	2.4 - 3.0	3.0 - 5.0
	7.7 - 8.1	3.6	3.0 - 4.6
	7.7 - 8.5	2.4	3.0 - 5.0
3.6	7.7 - 8.5	3.0	3.0 - 4.2
	7.7 - 8.1	3.6	3.0 - 3.8
3.8	7.7 - 8.5	2.4	3.0 - 4.2
	7.7 - 8.1	3.0 - 3.6	3.0 - 3.8

The results for 80% front loading is summarized in tables 4.7-4.8. It must be noted that the results provided in table 4.7 are allowed ranges but with certain conditions. There are many cuboids that can be inscribed into permissible design space. Not all combinations of parameter set made out of this table constitutes envelopes. The permitted cuboids which can be formed are provided in table 4.8. The results provided in table 4.8 are combinations of vehicle parameter sets that form multidimensional cuboids. These can be viewed as permissible isolated cuboids in design space. Each row of table 4.8 can form an envelope for an A-double. The interpretation is same for results provided for 90% front loading in section 4.3.2.2

4.3.2.2 Results for 90% front loading

This section deals with results obtain from a 4D sweep study with 90% front loading. The loading is such that the semitrailer is loaded uniformly for only 90% of the space, the last 10% of space is kept empty.

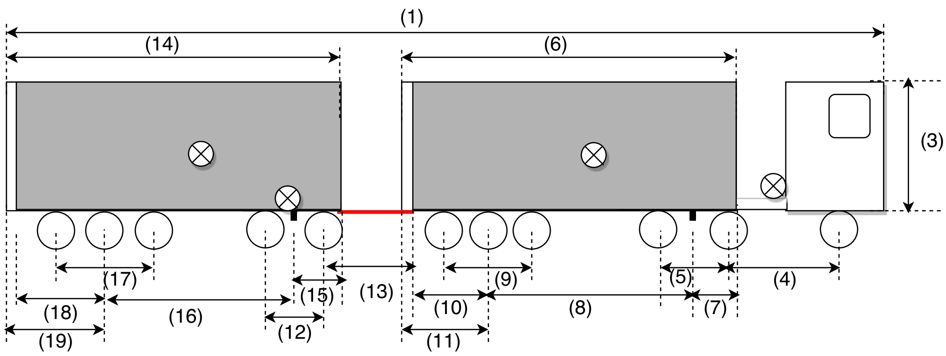


Figure 4.24: A-Double : Description and Dimensions

Table 4.9: Dimensional limit chart for A-double

Vehicle	Ref	Feature	Dimensions(Sweden)	Dimensions(Canada)
Overall	(1)	Length of the combination	Max 34m	Max 40 m
	(2)	Width of Vehicle	Max 2.6m	Max 2.6 m
	(3)	Height of the Vehicle	-	Max 4.15 m
Tractor	(4)	Wheelbase	3.0 - 3.8 m	Min 3.5 m
	(5)	Tandem axle spread	1.37 m	1.2 - 1.85 m
Lead Semi-trailer	(6)	Length	13.6 m	14.5 - 16.2 m
	(7)	Front Over-hang	1.6 m	Max 2 m
	(8)	Wheelbase	8.1 - 8.9 m	10.9 - 12.5 m
	(9)	Tri-dem axle spread	2.6 m	2.4 - 3.7 m
	(10)	Distance to hinge point	2.4 - 3.6 m	-
	(11)	Rear Over-hang	3.5 - 4.3 m	Max 3.4 m
Converter Dolly	(12)	Wheelbase	1.3 m	1.2 - 1.85 m
	(13)	Draw bar length	3.0 - 5.0 m	Max 3m
Second Semi-trailer	(14)	Length	13.6 m	14.5 - 16.2 m
	(15)	Front Over-hang	1.6 m	Max 2 m
	(16)	Wheelbase	8.1 - 8.9 m	10.2 - 12.5 m
	(17)	Tri-dem axle spread	2.6 m	2.4 - 3.7 m
	(18)	Distance to hinge point	2.4 - 3.6 m	-
	(19)	Rear Over-hang	3.5 - 4.3 m	35% of wheelbase

Table 4.10: Allowed ranges for the design variables

Trctor whlbase[m]	Trailer whlbase[m]	Dist to rear hinge[m]	Drawbar length[m]
3.0	8.9	2.4 - 3.0	3.0 - 4.6
3.2 - 3.4	8.5 - 8.9	2.4	3.0 - 5.0
	8.5	3.0	3.0 - 4.6
	8.9	3.0	3.0 - 4.2
3.6	8.1 - 8.9	2.4	3.0 - 5.0
	8.1 - 8.9	3.0	3.0 - 4.6
	8.1	3.6	3.0 - 4.2
3.8	8.1 - 8.9	2.4	3.0 - 4.6
	8.1 - 8.9	3.0	3.0 - 4.2
	8.1	3.6	3.0 - 3.8

4.3.2.3 Results for 100% front loading

This section consists of the results for loading case as shown below in figure 4.25.

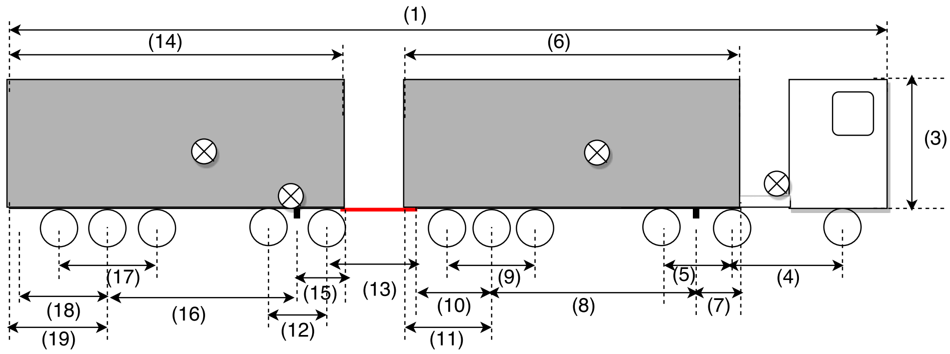


Figure 4.25: A-Double : Description and Dimensions

This section consists of the results for a semitrailer loaded all through out its load length uniformly 3.6. As discussed in section the A-double does not satisfy the legal constraint of 20% overall weight on driven tires. The results obtained also agree with this observation. No vehicles pass the post check since the vertical load on driven axles is lower than 20% of overall weight. If varying the parameters in the 3D sweep, no A-double can not be allowed with 100% front loading.

5

Conclusion

The present thesis work addresses all the issues mentioned under objectives, section 1.2. The initial part of thesis work focused towards qualitatively defining envelopes and gaining an understanding of the methodology. After literature study and initial discussion with industry experts, the definition was clear. Envelopes are boundaries or dimensional limits on geometrical and inertial properties of a combination vehicle.

Most important part of this thesis was to develop a generic framework to extract combination vehicles that a permissible to run on roads in Sweden. The generic framework has been developed in collaboration with Volvo Group Trucks Technology and Swedish national road and transport institute (VTI). The current framework considers performance, safety, legal, geometrical and physical constraints. The performance safety and legal constraints are implemented as post-checks. Whereas the geometrical and physical constraints are implemented as pre-checks. The parameter sweep study is investigated in two different methods. The single parameter sweep study was performed to understand envelopes design space. The limitations observed from this study led to the second method, combined multiple parameter sweeps. During the parameter sweep, the combination vehicles are passed through pre and post filters. The combination vehicles that pass through both filters are then the allowed vehicles from which the envelopes are finally extracted. The pre check contains constraints on length, width, and the clash between units, which trim the design space by being the upper limit. The performance based standards and legal standards clip the envelope space further to provide desired spaces. The methodology is generic and can be applied to any combination vehicle.

The sensitivity study reflects upon the effect of each parameter on PBS measures. This study was performed in the early phases of the thesis, to gain intuitive understanding. This study also brought out the motivation behind choosing the design variables. The single parameter study provides numerical values on simulation of simple models implemented in PBS project. This study was an attempt to understand the envelopes but did not address all issues. An important outcome of this study was the validation of the simple models built in the OpenPBS toolbox. One of the key observation was that the PBS measure yaw damping was the limiting PBS. Further tuning of model parameters was performed based on this study. This proved beneficial for the higher dimensional studies performed later on.

The multiple parameter studies were performed to fully address the issues of envelopes and also bridge the gap observed in single parameter study. Firstly, a three variable combined sweep was performed followed by four dimensional combined sweep. The 3D study was performed to visualize the envelopes. This study was done mainly for two reasons, visualization and spread of envelopes in the design space. Three variations of the loading were studied and the results for each were provided.The results from 4D combined sweep study provide the envelopes for different load cases. The allowed ranges for design variables are provided in table 4.7-4.10. The vehicle combinations realized out of these ranges will be stable for the PBS measures and other constraints considered in this study.

A brief study was performed to understand the PBS measure friction demand on steered FDST and friction demand on driven tires FDDT. These are crucial to evaluate envelopes and vehicle combinations on low road friction. The work done on this is provided in the appendix section.

To summarize, the concept of envelopes were qualitatively defined. A generic framework to quantitatively extract envelopes for any vehicle combinations was developed. Envelopes were extracted for A-double vehicle combination.

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A

Appendix

This chapter covers the work done on PBS measures called friction demand on steered tires and friction demand on driven tires. During winters the road are slippery. It becomes crucial to understand the effect of low road friction on vehicle's performance and safety. Adequate road friction level is necessary to propel the vehicle and complete the maneuver safely.

Literature suggests that safety of an LCV is the prime reason for these performance based standards. The friction demand on steered tires is important in scenarios where the vehicle loses steering control. For an LCV to be safe on road, the road friction level should be sufficient to complete the maneuver. Additionally, since the speed is low for FDST and FDDT, they can cause congestion problems. The next section provides a brief introduction to the definitions of PBS friction demand which is used in Canada and Australia. Since the definition is not fully clear, an attempt to understand them and validate numerical values through our simulations will be provided. In the last section, the implementation in current Swedish PBS model will be discussed.

A.1 Friction demand in Canadian PBS

The Canadian PBS considers only friction demand in tight turns. The friction demand is mainly on focused on driven axles. As per [27], the PBS measure called friction demand in a tight turn "pertains to the resistance of multiple, non-steered axles to travel around a tight turn radius such as an intersection". One of the dangerous scenario's is the driven axles not producing enough lateral forces due to low friction levels leading to jackknife type response.

The Canadian PBS prescribes a target performance level. According to [27]"The vehicle should be able to negotiate a 90°turn with an outside radius of 11 m, the peak required coefficient of friction on the highway surface to avoid loss of traction by tractor drive axles should not exceed 0.1". The maneuver is the standard tight 90°turn but the road friction levels are very low compared to general road conditions. So a study of forces on the tandem axle on the tractor for an A-double is crucial to understanding the friction used and the above target level.

The following figure shows the forces on the tandem axle both in longitudinal and lateral direction.

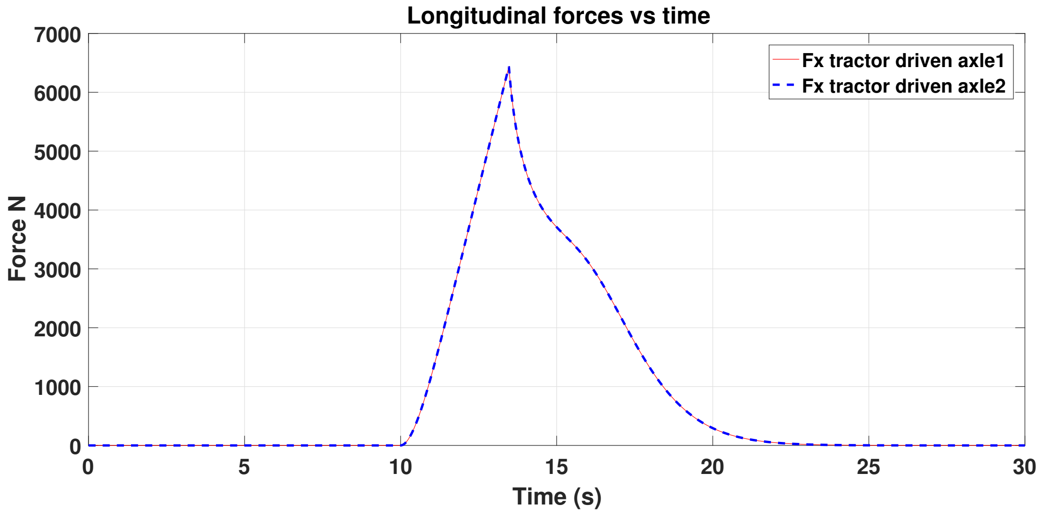

Figure A.1: Longitudinal forces on tandem axle of tractor

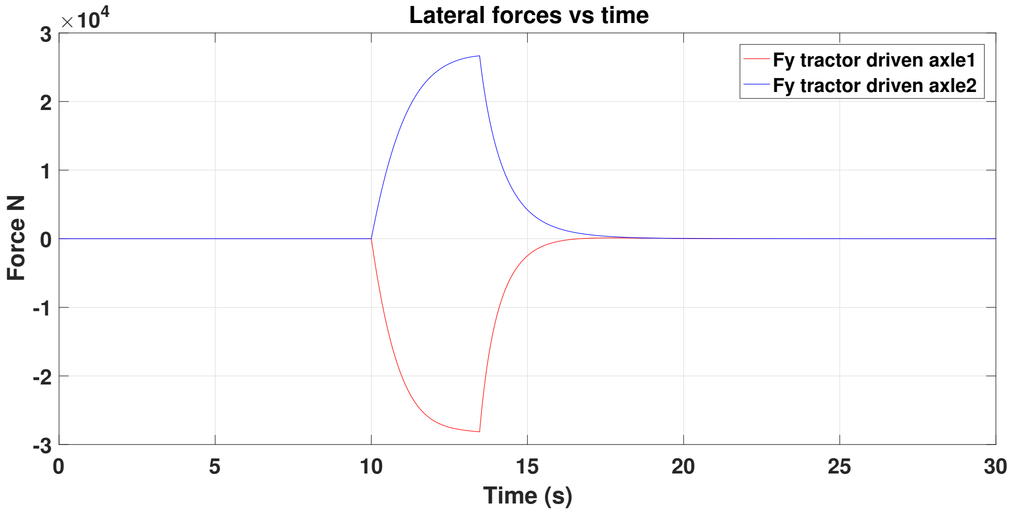

Figure A.2: Lateral forces on tandem axle of tractor

The lateral forces in the above figure are in the opposite direction. If individual axles are considered the friction utilized by each axle computed by dividing the resultant forces by vertical forces are provided figure . The formula used for each axle to compute the friction utilized was

$$\mu_{util} = \frac{\sqrt{Fx^2 + Fy^2}}{Fz}$$

Note that the value calculated like this does not have the normal physical meaning of friction coefficient.

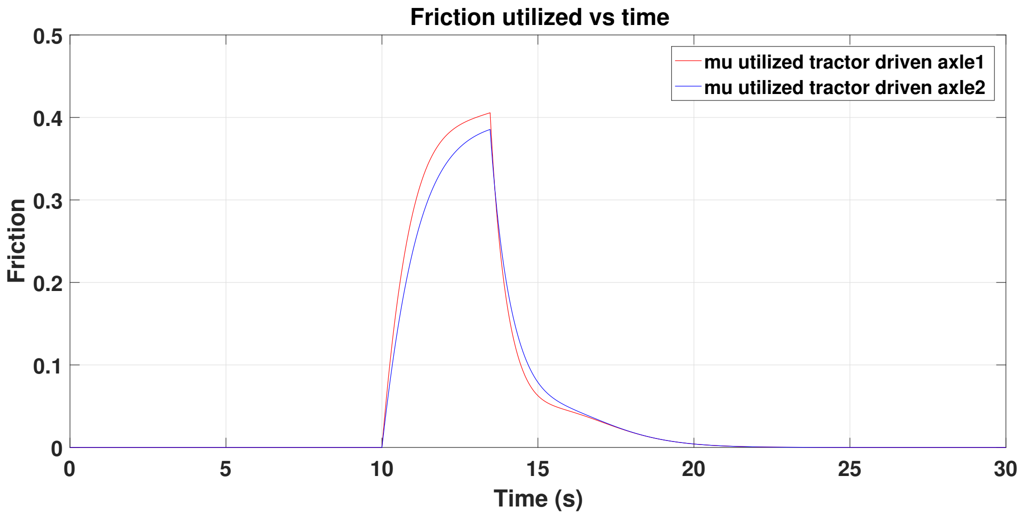

Figure A.3: Friction utilized on tandem axle of tractor

From above figure A.3, it can be observed that the friction used on individual axles is as high as 0.4. This value is very high compared to the threshold level provided by Canadian PBS of 0.1. A deeper reading of the work done in [19] provides the numerical value of 0.1. The forces that are required at driven axles should oppose the reaction force on the fifth wheel on tractor developed due to the non-steered, non-driven axles of semitrailers and dollies. Hence one needs to consider the sum of driven axle forces to be opposing the forces on the fifth wheel. A new approach to this problem was used to gain a better understanding. This approach considers the sum of all the forces of the tandem axle together and then this resultant force is divided by the vertical forces of both axles. The results of this study are provided for a single combination vehicle completing the maneuver of low speed 90°curve. The formula for utilized friction is given below

$$CanadianFDDT = \frac{\sqrt{(Fx_{12} + Fx_{13})^2 + (Fy_{12} + Fy_{13})^2}}{Fz_{12} + Fz_{13}}$$

Note that the value calculated like this does not have the normal physical meaning of friction coefficient.

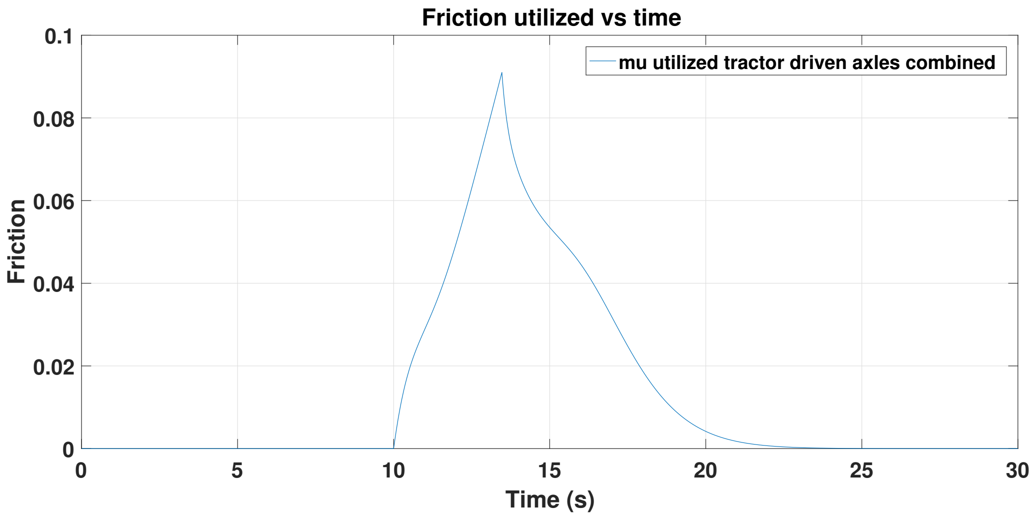

Figure A.4: Friction utilized on tandem axles of tractor combined (FDDT Canada)

The Canadian FDDT value calculated with this approach is below the threshold value of 0.1. An alternative way to calculate the FDDT Canada with the OpenPBS tool could be to model the tandem axle a single axle and then pull out the utilized coefficient of friction from that model. However, this would not be in-line with the very physical approach in the OpenPBS tool, so it is not the recommended way.

A.2 Friction demand in Australian PBS

While performing low-speed small-radius turns the vehicle will lose steering ability if the utilized friction exceeds the available road friction [12]. In such cases, the vehicle will not be able to take the turn and plow straight ahead risking low-speed collisions with other vehicles and objects by the road. The steer-ability is of major concern when the axle spread on drive axles is large and the wheelbase itself is small.

The definition for friction demand on steered tires in [12] is "when operating at the maximum allowed gross and unladen, the maximum friction level demanded of the steer tires of the hauling in a prescribed 90°low-speed turn performed at the specified speed must be no greater than the specified value".

$$\text{friction demand } (\%) = 100 * \frac{\text{friction required}}{\text{friction available}}$$

This definition of friction demand was not investigated. But, it is similar to determining friction utilized on individual axles and then dividing the term by peak friction.

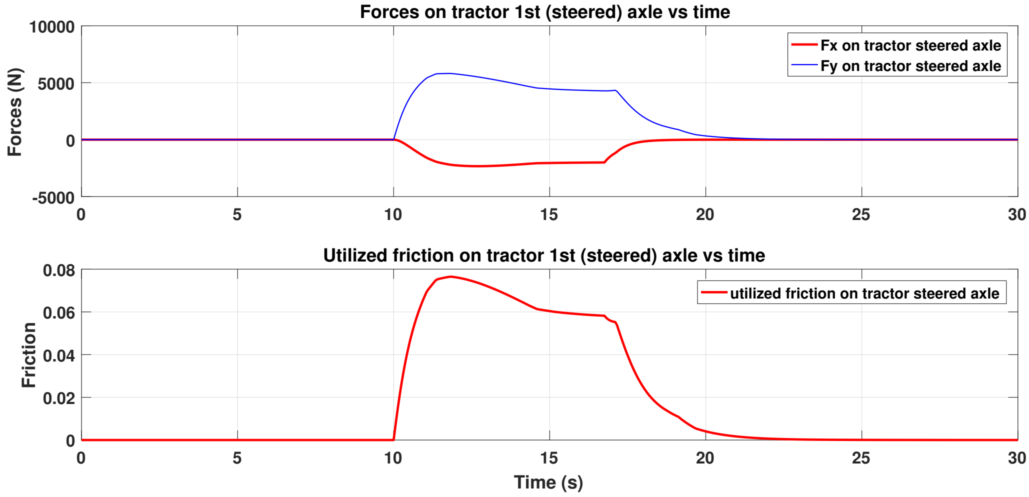

Figure A.5: Friction utilized on steered axle of tractor

The figure A.5, shows the forces and utilized friction on the steered axle of the tractor. It can be observed that the utilized friction for this axle is very low compared to a threshold of 0.25.Also note that the value calculated like this does not have the normal physical meaning of friction coefficient.

A.3 Friction demand in Swedish PBS

After understanding the definitions and inferences of PBS in Canada and Australia, the approach used in Sweden PBS is focused on modeling the reality than coming up with a new definition. The low road friction is considered as a parameter and the tire model is updated. The new tire model contains friction saturation implemented on all axles except the steered axle. Along with road friction, even friction circle concept is implemented. The friction circle is important because some amount of friction is used up to propel the vehicle forward. The non-zero longitudinal force needs to be incorporated into the overall model. The lateral forces are saturated since the maneuver used to compute this PBS measure is low-speed tight turn.

The forces build up due to the lateral forces on the trailer's axles. These lateral forces would have to be able to saturate, so the tire models on the (non-driven and non-steered) trailer axles have to have a saturation, but they can be purely lateral slip models (no longitudinal forces). The first axle is steered and ahead of driven axles, and it could potentially be modelled without saturation, and simply monitored to find out the FDST. But it can also be modelled as the trailer axles, including a saturation. So, non driven and non steered axles are saturated

$$Fyw_{ij} = -\text{sign}(\alpha_{ij}) * \min(C_{ij} * \alpha_{ij}, \mu * Fz_{ij})$$

The driven axles have to develop both longitudinal and lateral forces. The tire models hence have to cope with both combined slip and friction saturation, as shown in the formula below. This formula depicts the saturation with the minimum of available forces due to friction and forces that tire generates. Both the terms are compensated by the effectively available friction after deducting the friction used to generate longitudinal forces.

$$Fyw_{ij} = -\text{sign}(\alpha_{ij}) * \min(C_{ij} * \alpha_{ij}, \mu * Fz_{ij}) * sqrt(1 - \frac{(Fyw_{i,j})^2}{(\mu * Fz_{ij})^2})$$

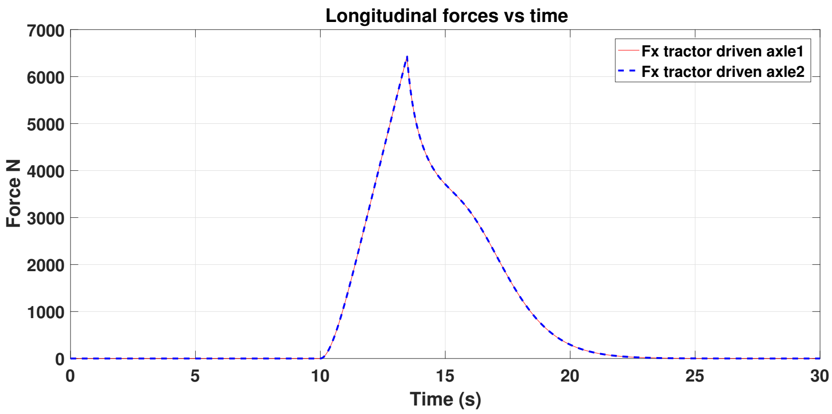

Figure A.6: Longitudinal forces on tandem axle of tractor

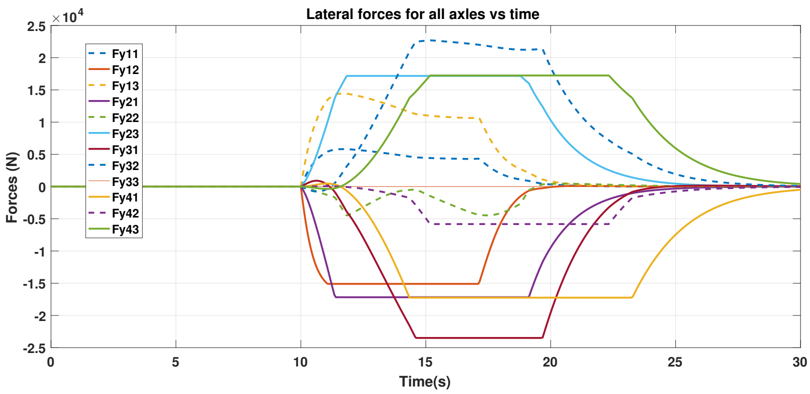

Figure A.7: Lateral forces on all axles of A-double

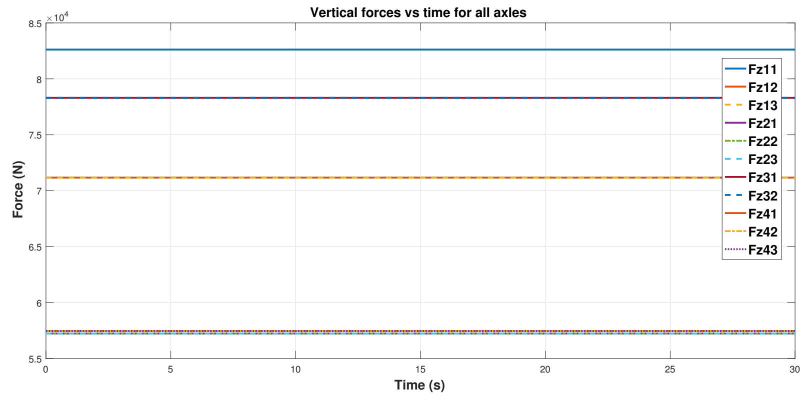

Figure A.8: Vertical forces on all axles of A-double

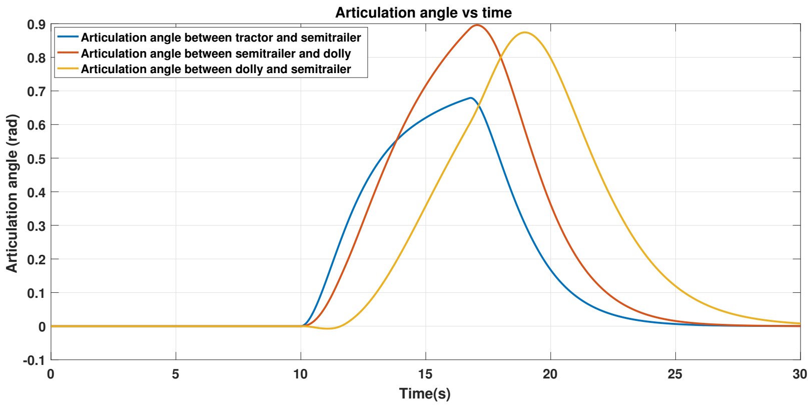

Figure A.9: Articulation angles on modular units

A single configuration of A-double vehicle was simulated and the axle forces were observed. The vehicle maneuver is such that it goes straight for first 10 seconds and then makes a 90 degree turn. It is vital to remember that the axles are saturated as per formulas provided above. The figure A.6, depicts the variation of longitudinal forces on tractor driven axles in time. In figure A.7, the dashes lines represent axles which are not fully saturated and the solid lines represent full saturation. The road friction value used in this simulation was 0.3.

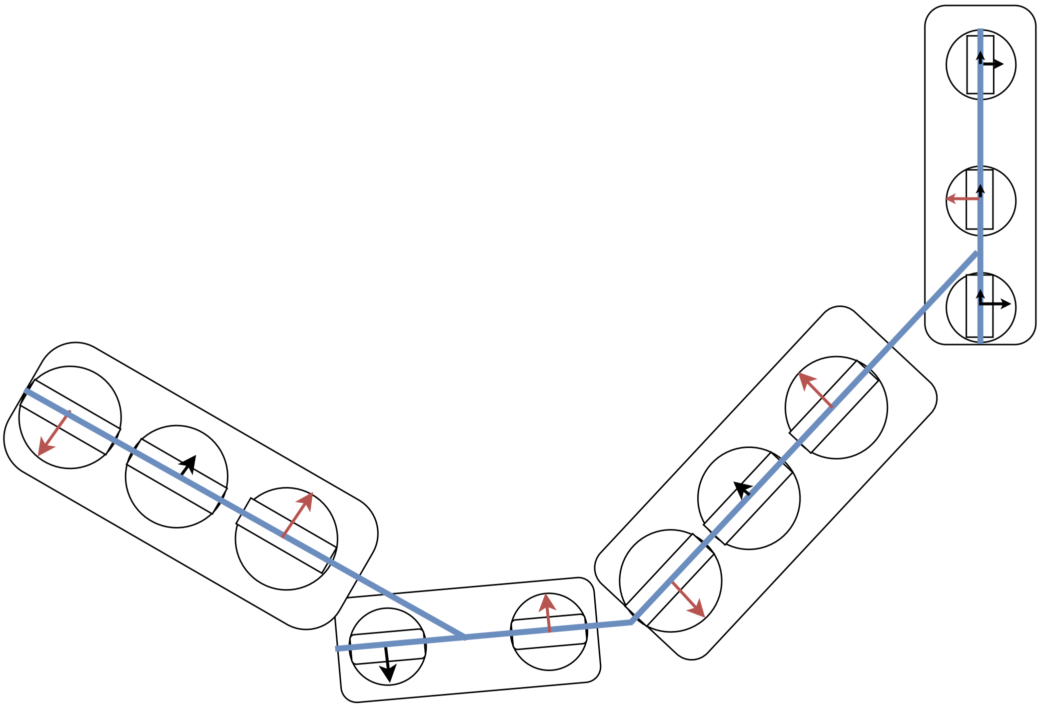

Figure A.10: Friction utilized on all axles of A-double

The figure A.10, depicts the vehicle in the turn with friction circles on each axle. This is important to understand which axles are saturated and the reasoning behind this. The red arrows represent saturation. The primary cause is that the semitrailer axles saturate and place a demand for forces via coupling forces on tractor. This in turn causes the tractor driven axles to be saturated. Even though the third axle of tractor is not fully saturated but it is impending. The important conclusions after adding friction saturation are

- It is crucial to model friction saturation and combined slip to be able to address the real problem.
- The PBS friction demand on driven tires is now just a pass or fail, because the numerical value of the model parameter available friction has to be given for each simulation. The combination vehicle passes, only if it completes the low-speed maneuver. No clear way of always calculating a required coefficient of friction is seen, except trying different model parameter values on the available friction.
- The PBS friction demand on steered tires will have a target threshold value and the friction utilized needs to be lower than this value for the combination vehicle to pass. To observe the friction utilized on steered axle.

A.4 Code for Single Variable Study

...............Main Code..................

This section of code is finding Ranges for DP1 tractor wheelbase for PBS measure RWA

```
  tic
 final_time=20;
 g=9.8;                              % gravity constant

 for i=1:10
fmu_obj1 =  FMUModelME1('OpenPBS_PBS_SingleLaneChange.fmu');
fmu_obj1.fmiInstantiateModel;% Here we instantiate the fmu taken from dymola
fmu_obj1.initialize; % Initialization-setting the parameters to default
%vehicle,check report for values used in the default vehicle
% Here we can set different parameters to perform parameter sweep
fmu_obj1.setValue('paramSet.A[2]',6.9);
% Set value of semitrailer wheelbase
fmu_obj1.setValue('paramSet.A[4]',6.9);
% Set value of semitrailer wheelbase
fmu_obj1.setValue('paramSet.L[1,2]',-2.9-0.1*i);
% Set DP1 for the performing parameter sweep study of tractor wheelbase
fmu_obj1.setValue('freqHz',0.3);
fmu_obj1.setValue('width',3);
precheck1;
if total_length_1(i)<34 && trackwidth < 2.6
disp('Configuration has passed the test')
  allowed_range_pre_RWA_DP1(i)= -2.9-0.1*i;
  allowed_range_pre_RWA_bool_DP1(i)=true;
else
  disp('Configuration failed the test')
  allowed_range_pre_RWA_bool_DP1(i)= false;
end
Outputs_defined_here;
[tout1,yout1,yname1]=fmu_obj1.simulate([0,final_time],'Output',output);
RWA(i)=max(yout1(:,1));
RWA_threshold(i) = 2.4;
range_RWA(i)=-2.9-0.1*i;
postcheck1;
if RWA(i)< 2.4 && load_driven_axle(i)>0.20*Overall_mass(i)*g && ...
 load_front_axle(i)<10000*g && load_dolly(i)<18000*g &&  ...
 load_tridem1(i)< 24000*g  && load_tridem2(i) < 24000*g
  disp('Configuration has passed the test')
  allowed_range_post_RWA_DP1(i)= -2.9-0.1*i;
```

```
else
  disp('Configuration failed the test')
end
 end
 toc
```

..............Pre-check..................

```
% Pre check - This part of the script is used to set values for parameters
trackwidth = fmu_obj1.getValue('paramSet.w[1,1]');
% Get value for the trackwidth (tractor)
tractor_wheelbase1 = fmu_obj1.getValue('paramSet.L[1,2]');
% Obtain the wheelbase of the tractor
semitrailer_wheelbase(i) = fmu_obj1.getValue('paramSet.A[2]');
DrawBar_length(i) = fmu_obj1.getValue('paramSet.A[3]');
%
fmu_obj1.setValue('paramSet.L[1,3]',tractor_wheelbase1-1.37);
% This makes sure the tandem axle spread on tractor is always 1.37m,nominal value;
fmu_obj1.setValue('paramSet.L[2,2]',-1.3);
% This sets the semitrailer i tridem spread to 1.3m, nominal value.
fmu_obj1.setValue('paramSet.L[2,3]',-2.6);
% This sets the semitrailer i tridem spread to 2.6m, nominal value.
fmu_obj1.setValue('paramSet.L[3,2]',-1.3);
% This sets the dolly wheelbase to 1.3m, nominal value.
fmu_obj1.setValue('paramSet.L[4,2]',-1.3);
% This sets the semitrailer ii tridem spread to 1.3m, nominal value.
fmu_obj1.setValue('paramSet.L[4,3]',-2.6);
% This sets the semitrailer ii tridem spread to 2.6m, nominal value.
fmu_obj1.setValue('paramSet.B[3]',-0.65);
% This sets the semitrailer ii hitch point on dolly to be in
%center of wheelbase 0.65m, nominal value.
fmu_obj1.setValue('paramSet.B[1]',tractor_wheelbase1-0.25);
fmu_obj1.setValue('paramSet.X[1]',-1.4335);
fmu_obj1.setValue('paramSet.X[3]',-0.7445);
% fmu_obj1.setValue('paramSet.X[2]',2.4335);
% fmu_obj1.setValue('paramSet.X[4]',2.4335);

%
A1_1(i)=fmu_obj1.getValue('paramSet.A[1]');
% Get value for the front coupling point of unit 2 (tractor)
A2_1(i)=fmu_obj1.getValue('paramSet.A[2]');
% Get value for the front coupling point of unit 2 (semitrailer i)
A3_1(i)=fmu_obj1.getValue('paramSet.A[3]');
% Get value for the front coupling point of unit 3 (Dolly)
A4_1(i)=fmu_obj1.getValue('paramSet.A[4]');
```

```
% Get value for the front coupling point of unit 2 (semitrailer ii)
B1_1(i)=fmu_obj1.getValue('paramSet.B[1]');
% Get value for the Rear coupling point of unit 2 (tractor)
B2_1(i)=fmu_obj1.getValue('paramSet.B[2]');
% Get value for the Rear coupling point of unit 2 (semitrailer i)
B3_1(i)=fmu_obj1.getValue('paramSet.B[3]');
% Get value for the Rear coupling point of unit 3 (dolly)
B4_1(i)=fmu_obj1.getValue('paramSet.B[4]');
% Get value for the Rear coupling point of unit 4 (semitrailer ii)

%
fmu_obj1.setValue('paramSet.FOH[1]',1.4)
fmu_obj1.setValue('paramSet.FOH[2]',semitrailer_wheelbase(i)+1.6)
fmu_obj1.setValue('paramSet.FOH[3]',0.5);
fmu_obj1.setValue('paramSet.FOH[4]',semitrailer_wheelbase(i)+1.6)
fmu_obj1.setValue('paramSet.ROH[1]',tractor_wheelbase1-2.17)
fmu_obj1.setValue('paramSet.ROH[3]',-1.8)
%
% fmu_obj1.setValue('paramSet.ROH[2]',-(13.6-semitrailer_wheelbase(i)-1.6));
% fmu_obj1.setValue('paramSet.ROH[4]',-(13.6-semitrailer_wheelbase(i)-1.6));

ROH2_1(i)=fmu_obj1.getValue('paramSet.ROH[2]');
ROH4_1(i)=fmu_obj1.getValue('paramSet.ROH[4]');
Check_semtrialer_length1_1(i) = 13.6-(1.6+A2_1(i)-ROH2_1(i));
Check_semtrialer_length2_1(i) = 13.6-(1.6+A4_1(i)-ROH4_1(i));
%setting masses
fmu_obj1.setValue('paramSet.m[1]',9500);
fmu_obj1.setValue('paramSet.m[2]',31000);
fmu_obj1.setValue('paramSet.m[3]',2500);
fmu_obj1.setValue('paramSet.m[4]',31000);
%
fmu_obj1.setValue('paramSet.I[1]',4.1341e+04);
fmu_obj1.setValue('paramSet.I[2]',4.6248e+05);
fmu_obj1.setValue('paramSet.I[3]',0.0728e+05);
fmu_obj1.setValue('paramSet.I[4]',4.6248e+05);
%
fmu_obj1.setValue('paramSet.Cc[1,1]',6);
fmu_obj1.setValue('paramSet.Cc[1,2]',6);
fmu_obj1.setValue('paramSet.Cc[1,3]',6);
fmu_obj1.setValue('paramSet.Cc[2,1]',6);
fmu_obj1.setValue('paramSet.Cc[2,2]',6);
fmu_obj1.setValue('paramSet.Cc[2,3]',6);
fmu_obj1.setValue('paramSet.Cc[3,1]',6);
fmu_obj1.setValue('paramSet.Cc[3,2]',6);
fmu_obj1.setValue('paramSet.Cc[4,1]',6);
fmu_obj1.setValue('paramSet.Cc[4,2]',6);
```

```
fmu_obj1.setValue('paramSet.Cc[4,3]',6);
%
m1_1(i)=fmu_obj1.getValue('paramSet.m[1]');
m2_1(i)=fmu_obj1.getValue('paramSet.m[2]');
m3_1(i)=fmu_obj1.getValue('paramSet.m[3]');
m4_1(i)=fmu_obj1.getValue('paramSet.m[4]');
%
FOH1_1(i)=fmu_obj1.getValue('paramSet.FOH[1]');
% Get value for the front coupling point of unit 2 (tractor)
FOH2_1(i)=fmu_obj1.getValue('paramSet.FOH[2]');
% Get value for the front coupling point of unit 2 (semitrailer i)
FOH3_1(i)=fmu_obj1.getValue('paramSet.FOH[3]');
% Get value for the front coupling point of unit 3 (Dolly)
FOH4_1(i)=fmu_obj1.getValue('paramSet.FOH[4]');
% Get value for the front coupling point of unit 2 (semitrailer ii)
ROH1_1(i)=fmu_obj1.getValue('paramSet.ROH[1]');
% Get value for the Rear coupling point of unit 2 (tractor)
ROH2_1(i)=fmu_obj1.getValue('paramSet.ROH[2]');
% Get value for the Rear coupling point of unit 2 (semitrailer i)
ROH3_1(i)=fmu_obj1.getValue('paramSet.ROH[3]');
% Get value for the Rear coupling point of unit 3 (dolly)
ROH4_1(i)=fmu_obj1.getValue('paramSet.ROH[4]');
% Get value for the Rear coupling point of unit 4 (semitrailer ii)
%
Overall_mass(i) = m1_1(i)+m2_1(i)+m3_1(i)+m4_1(i);
total_length_1(i) = FOH1_1(i)-B1_1(i)+A2_1(i)-B2_1(i)
+A3_1(i)-B3_1(i)+A4_1(i)-ROH4_1(i);
%
%it is important remember that all axle positions are found w.r.t first
%axle hence the values are negative,the same can be seen above when we set
%dolly wheelbase,tractor tandem axle spread
```

...............Post-check...............

Postcheck - this is done to satisfy the legal and geometrical constraints

```
Fz11(i) = max(yout1(:,4));  % Axle pressure- unit 1 axle 1
Fz12(i) = max(yout1(:,5));  % Axle pressure- unit 1 axle 2
Fz13(i) = max(yout1(:,6));  % Axle pressure- unit 1 axle 3
Fz21(i) = max(yout1(:,7));  % Axle pressure- unit 2 axle 1
Fz22(i) = max(yout1(:,8));  % Axle pressure- unit 2 axle 2
Fz23(i) = max(yout1(:,9));  % Axle pressure- unit 2 axle 3
Fz31(i) = max(yout1(:,10)); % Axle pressure- unit 3 axle 1
Fz32(i) = max(yout1(:,11)); % Axle pressure- unit 3 axle 2
```

```
Fz33(i) = max(yout1(:,12)); % Axle pressure- unit 3 axle 3
Fz41(i) = max(yout1(:,13)); % Axle pressure- unit 4 axle 1
Fz42(i) = max(yout1(:,14)); % Axle pressure- unit 4 axle 2
Fz43(i) = max(yout1(:,15)); % Axle pressure- unit 4 axle 3
%
Overall_weight(i) = (Fz11(i)+Fz12(i)+Fz13(i)+Fz21(i)
+Fz22(i)+Fz23(i)+Fz31(i)+Fz32(i)+Fz33(i)+Fz41(i)+Fz42(i)+Fz43(i))/g;
% Overall weight of the combination
load_front_axle(i) = Fz11(i) % Load on the first axle of the combination
load_driven_axle(i)= Fz12(i)+Fz13(i) % Load on the driven axles
load_dolly(i) = Fz31(i)+Fz32(i)+Fz33(i); % Load on the dolly axles
load_tridem1(i) = Fz21(i)+Fz22(i)+Fz23(i);% Load on the semitrailer I axles
load_tridem2(i) =Fz41(i)+Fz42(i)+Fz43(i);% Load on the semitrailer II axles
```

A.5 Code for Multiple Variable study

.............Main code.........

```
This is for the maneuver single sine steering for YD PBS
final_time = 20;
g = 9.8;
for i = 1:10 %5
    for j = 1:10 %5
         for k = 1:10 %5
             for l = 1:5 %14

fmu_obj1 =  FMUModelME1('OpenPBS_PBS_SingleSineSteering.fmu');
fmu_obj1.fmiInstantiateModel % Here we instantiate the fmu taken fro dymola
fmu_obj1.initialize% Initialization-setting the parameters to
%default vehicle,check report for values used in the default vehicle
%Here we can set different parameters to perform parameter sweep

fmu_obj1.setValue('paramSet.A[2]',5.6+0.2*i);
% Set DP2 for the performing parameter sweep study of semitrailer wheelbase
fmu_obj1.setValue('paramSet.X[2]',1.2335+0.2*i);
% Set DP2 for the performing parameter sweep study of semitrailer wheelbase
fmu_obj1.setValue('paramSet.A[4]',5.6+0.2*i);
% Set DP2 for the performing parameter sweep study of semitrailer wheelbase
fmu_obj1.setValue('paramSet.X[4]',1.2335+0.2*i);
% Set DP2 for the performing parameter sweep study of semitrailer wheelbase
fmu_obj1.setValue('paramSet.A[3]',3+0.2*j);
% Set DP3 for the performing parameter sweep study of draw bar length
fmu_obj1.setValue('paramSet.B[2]',-3.1-0.3*k);
% Set DP4 for the performaing parameter sweep study of hinge offset or rear
% coupling point on semitrailer
fmu_obj1.setValue('paramSet.B[4]',-3.1-0.3*k);
% Set DP4 for the performaing parameter sweep study of hinge offset or rear
%coupling point on semitrailer
fmu_obj1.setValue('paramSet.L[1,2]',-2.8-0.2*l);
% Set DP1 for the performing parameter sweep study of tractor wheelbase


precheck_single_sine_steer_4D;
if total_length_single_sine_steer(i,j,k,l)<34 & ...
trackwidth_single_sine_steer < 2.6 & ...
Semitrailer_precheck_single_sine_steer(i,j,k,l)<12.1 ...
& Clash_single_sine_steer(i,j,k,l) > 4
disp('Configuration has passed the test')
disp(['total_length_single_sine_steer(i,j,k)'=
```

```
     num2str(total_length_single_sine_steer(i,j,k))]);
allowed_range_pre_single_sine_steer_pass{i,j,k,l} =
 [5.6+0.2*i,3+0.2*j,-3.1-0.3*k,-2.8-0.2*l];
allowed_range_pre_single_sine_steer_fail{i,j,k,l} = [0,0,0,0];
allowed_range_pre_single_sine_steer_bool{i,j,k} = [true,true,true,true];
else
disp('Configuration has failed the test')
allowed_range_pre_single_sine_steer_pass{i,j,k,l} = [0,0,0,0];
allowed_range_pre_single_sine_steer_fail{i,j,k,l} =
[5.6+0.2*i,3+0.2*j,-3.1-0.3*k,-2.8-0.2*l];
disp(['total_length_single_sine_steer(i,j,k)'=
       num2str(total_length_single_sine_steer(i,j,k))]);

allowed_range_pre_single_sine_steer_bool{i,j,k} =[false,false,false,false];
end
outputs_defined_here_4D
[tout1,yout1,yname1]=fmu_obj1.simulate([0,final_time],'Output',output);
YD(i,j,k,l)=max(yout1(:,2));
postcheck_single_sine_steer_4D;

if l==1 & YD(i,j,k,l)> 0.15 ...
& load_front_axle_single_sine_steer(i,j,k,l) < 10000*g...
& load_dolly_single_sine_steer(i,j,k,l) < 18000*g ...
& load_tridem1_single_sine_steer(i,j,k,l) < 24000*g ...
& load_tridem2_single_sine_steer(i,j,k,l) < 24000*g
& load_tractor_single_sine_steer(i,j,k,l) < 24000*g   ...
& load_front_axle_single_sine_steer(i,j,k,l)> ...
0.2*load_tractor_single_sine_steer(i,j,k,l) ...
& load_driven_axle_single_sine_steer(i,j,k,l)> 0.20*Overall_mass(i,j,k,l)*g

disp('Configuration has passed the test')
 allowed_range_post_single_sine_steer_pass{i,j,k,l} =
 [5.6+0.2*i,3+0.2*j,-3.1-0.3*k,-2.8-0.2*l];
 allowed_range_post_single_sine_steer_fail{i,j,k,l} = [0,0,0,0];

 elseif l==2 & YD(i,j,k,l) > 0.15 ...
& load_front_axle_single_sine_steer(i,j,k,l) < 10000*g...
& load_dolly_single_sine_steer(i,j,k,l) < 18000*g ...
& load_tridem1_single_sine_steer(i,j,k,l) < 24000*g ...
& load_tridem2_single_sine_steer(i,j,k,l) < 24000*g
& load_tractor_single_sine_steer(i,j,k,l) < 25000*g   ...
& load_front_axle_single_sine_steer(i,j,k,l)> ...
0.2*load_tractor_single_sine_steer(i,j,k,l) ...
& load_driven_axle_single_sine_steer(i,j,k,l)> 0.20*Overall_mass(i,j,k,l)*g
disp('Configuration has passed the test')
allowed_range_post_single_sine_steer_pass{i,j,k,l} =
```

```
 [5.6+0.2*i,3+0.2*j,-3.1-0.3*k,-2.8-0.2*l];
allowed_range_post_single_sine_steer_fail{i,j,k,l} = [0,0,0,0];

elseif  l>2 & YD(i,j,k,l) > 0.15 ...
& load_front_axle_single_sine_steer(i,j,k,l) < 10000*g...
& load_dolly_single_sine_steer(i,j,k,l) < 18000*g
& load_tridem1_single_sine_steer(i,j,k,l) < 24000*g ...
& load_tridem2_single_sine_steer(i,j,k,l) < 24000*g
& load_tractor_single_sine_steer(i,j,k,l) < 26000*g   ...
& load_front_axle_single_sine_steer(i,j,k,l)> ...
0.2*load_tractor_single_sine_steer(i,j,k,l) ...
& load_driven_axle_single_sine_steer(i,j,k,l)> 0.20*Overall_mass(i,j,k,l)*g
disp('Configuration has passed the test')
 allowed_range_post_single_sine_steer_pass{i,j,k,l} =
 [5.6+0.2*i,3+0.2*j,-3.1-0.3*k,-2.8-0.2*l];
 allowed_range_post_single_sine_steer_fail{i,j,k,l} = [0,0,0,0];
 else
  disp('Configuration has failed the test')
   allowed_range_post_single_sine_steer_pass{i,j,k,l} = [0,0,0,0];
   allowed_range_post_single_sine_steer_fail{i,j,k,l} =
   [5.6+0.2*i,3+0.2*j,-3.1-0.3*k,-2.8-0.2*l];
end

             end
         end
    end
end
```

..............Pre-check...........

Pre check - This part of the script is used to get values for differentparameters

```
trackwidth_single_sine_steer = fmu_obj1.getValue('paramSet.w[1,1]');
% Get value for the trackwidth (tractor)
tractor_wheelbase_single_sine_steer(i,j,k,l) =
fmu_obj1.getValue('paramSet.L[1,2]');
% Obtain the wheelbase of the tractor
semitrailer_wheelbase_single_sine_steer(i,j,k,l) =
fmu_obj1.getValue('paramSet.A[2]');
drawbar_length_single_sine_steer(i,j,k,l) =
fmu_obj1.getValue('paramSet.A[3]');
semitrialer_DTH_single_sine_steer(i,j,k,l)=
fmu_obj1.getValue('paramSet.B[2]');
Semitrailer_precheck_single_sine_steer(i,j,k,l) =
```

```
semitrailer_wheelbase_single_sine_steer(i,j,k,l) ...
-semitrialer_DTH_single_sine_steer(i,j,k,l);
Clash_single_sine_steer(i,j,k,l) =
-1*semitrialer_DTH_single_sine_steer(i,j,k,l) ...
+drawbar_length_single_sine_steer(i,j,k,l)-2.6;
%
fmu_obj1.setValue('paramSet.Cc[1,1]',6);
fmu_obj1.setValue('paramSet.Cc[1,2]',6);
fmu_obj1.setValue('paramSet.Cc[1,3]',6);
fmu_obj1.setValue('paramSet.Cc[2,1]',6);
fmu_obj1.setValue('paramSet.Cc[2,2]',6);
fmu_obj1.setValue('paramSet.Cc[2,3]',6);
fmu_obj1.setValue('paramSet.Cc[3,1]',6);
fmu_obj1.setValue('paramSet.Cc[3,2]',6);
fmu_obj1.setValue('paramSet.Cc[4,1]',6);
fmu_obj1.setValue('paramSet.Cc[4,2]',6);
fmu_obj1.setValue('paramSet.Cc[4,3]',6);
%
fmu_obj1.setValue('paramSet.L[1,3]', ...
tractor_wheelbase_single_sine_steer(i,j,k,l)-1.37);
% This makes sure the tandem axle spread on tractor is always 1.37 m;
fmu_obj1.setValue('paramSet.L[2,2]',-1.3);
% This sets the semitrailer i tridem spread to 1.3m, nominal value.
fmu_obj1.setValue('paramSet.L[2,3]',-2.6);
% This sets the semitrailer i tridem spread to 2.6m, nominal value.
fmu_obj1.setValue('paramSet.L[3,2]',-1.3);
% This sets the dolly wheelbase to 1.3m, nominal value.
fmu_obj1.setValue('paramSet.L[4,2]',-1.3);
% This sets the semitrailer ii tridem spread to 1.3m, nominal value.
fmu_obj1.setValue('paramSet.L[4,3]',-2.6);
% This sets the semitrailer ii tridem spread to 2.6m, nominal value.
fmu_obj1.setValue('paramSet.B[3]',-0.65);
% This sets the semitrailer ii hitch point on dolly to be in center of
%wheelbase 0.65m, nominal value.
fmu_obj1.setValue('paramSet.X[1]',-1.4315);
fmu_obj1.setValue('paramSet.X[3]',-0.7447);

%
A1_1(i,j,k,l)=fmu_obj1.getValue('paramSet.A[1]');
% Get value for the front coupling point of unit 2 (tractor)
A2_1(i,j,k,l)=fmu_obj1.getValue('paramSet.A[2]');
% Get value for the front coupling point of unit 2 (semitrailer i)
A3_1(i,j,k,l)=fmu_obj1.getValue('paramSet.A[3]');
% Get value for the front coupling point of unit 3 (Dolly)
A4_1(i,j,k,l)=fmu_obj1.getValue('paramSet.A[4]');
% Get value for the front coupling point of unit 2 (semitrailer ii)
```

```
B1_1(i,j,k,l)=fmu_obj1.getValue('paramSet.B[1]');
% Get value for the Rear coupling point of unit 2 (tractor)
B2_1(i,j,k,l)=fmu_obj1.getValue('paramSet.B[2]');
% Get value for the Rear coupling point of unit 2 (semitrailer i)
B3_1(i,j,k,l)=fmu_obj1.getValue('paramSet.B[3]');
% Get value for the Rear coupling point of unit 3 (dolly)
B4_1(i,j,k,l)=fmu_obj1.getValue('paramSet.B[4]');
% Get value for the Rear coupling point of unit 4 (semitrailer ii)

%
fmu_obj1.setValue('paramSet.FOH[1]',1.4)
fmu_obj1.setValue('paramSet.FOH[2]', ...
semitrailer_wheelbase_single_sine_steer(i,j,k,l)+1.6)
fmu_obj1.setValue('paramSet.FOH[3]',0.5);
fmu_obj1.setValue('paramSet.FOH[4]', ...
semitrailer_wheelbase_single_sine_steer(i,j,k,l)+1.6)
fmu_obj1.setValue('paramSet.ROH[1]', ...
tractor_wheelbase_single_sine_steer(i,j,k,l)-2.17)
fmu_obj1.setValue('paramSet.ROH[3]',-1.8)
%
fmu_obj1.setValue('paramSet.ROH[2]', ...
-(13.6-semitrailer_wheelbase_single_sine_steer(i,j,k,l)-1.6));
fmu_obj1.setValue('paramSet.ROH[4]', ...
-(13.6-semitrailer_wheelbase_single_sine_steer(i,j,k,l)-1.6));

ROH2_1(i,j,k,l)=fmu_obj1.getValue('paramSet.ROH[2]');
ROH4_1(i,j,k,l)=fmu_obj1.getValue('paramSet.ROH[4]');
Check_semtrialer_length1_single_sine_steer(i,j,k,l) =
13.6-(1.6+A2_1(i,j,k,l)-ROH2_1(i,j,k,l));
Check_semtrialer_length2_single_sine_steer(i,j,k,l) =
13.6-(1.6+A4_1(i,j,k,l)-ROH4_1(i,j,k,l));
%setting masses
fmu_obj1.setValue('paramSet.m[1]',9500);
fmu_obj1.setValue('paramSet.m[2]',31000);
fmu_obj1.setValue('paramSet.m[3]',2500);
fmu_obj1.setValue('paramSet.m[4]',31000);
%
fmu_obj1.setValue('paramSet.I[1]',4.1341e+04);
fmu_obj1.setValue('paramSet.I[2]',3.6244e+05);
fmu_obj1.setValue('paramSet.I[3]',0.0728e+05);
fmu_obj1.setValue('paramSet.I[4]',3.6244e+05);
%
m1_1(i,j,k,l)=fmu_obj1.getValue('paramSet.m[1]');
m2_1(i,j,k,l)=fmu_obj1.getValue('paramSet.m[2]');
m3_1(i,j,k,l)=fmu_obj1.getValue('paramSet.m[3]');
m4_1(i,j,k,l)=fmu_obj1.getValue('paramSet.m[4]');
```

```
%
FOH1_1(i,j,k,l)=fmu_obj1.getValue('paramSet.FOH[1]');
% Get value for the front coupling point of unit 2 (tractor)
FOH2_1(i,j,k,l)=fmu_obj1.getValue('paramSet.FOH[2]');
% Get value for the front coupling point of unit 2 (semitrailer i)
FOH3_1(i,j,k,l)=fmu_obj1.getValue('paramSet.FOH[3]');
% Get value for the front coupling point of unit 3 (Dolly)
FOH4_1(i,j,k,l)=fmu_obj1.getValue('paramSet.FOH[4]');
% Get value for the front coupling point of unit 2 (semitrailer ii)
ROH1_1(i,j,k,l)=fmu_obj1.getValue('paramSet.ROH[1]');
% Get value for the Rear coupling point of unit 2 (tractor)
ROH2_1(i,j,k,l)=fmu_obj1.getValue('paramSet.ROH[2]');
% Get value for the Rear coupling point of unit 2 (semitrailer i)
ROH3_1(i,j,k,l)=fmu_obj1.getValue('paramSet.ROH[3]');
% Get value for the Rear coupling point of unit 3 (dolly)
ROH4_1(i,j,k,l)=fmu_obj1.getValue('paramSet.ROH[4]');
% Get value for the Rear coupling point of unit 4 (semitrailer ii)
%
Overall_mass(i,j,k,l)=m1_1(i,j,k,l)+m2_1(i,j,k,l)+m3_1(i,j,k,l)+m4_1(i,j,k,l)
total_length_single_sine_steer(i,j,k,l) = FOH1_1(i,j,k,l)-B1_1(i,j,k,l) ...
+A2_1(i,j,k,l)-B2_1(i,j,k,l)+A3_1(i,j,k,l)-B3_1(i,j,k,l) ...
+A4_1(i,j,k,l)-ROH4_1(i,j,k,l);
%
%it is important remember that all axle positions are found w.r.t first
%axle hence the values are negative,the same can be seen above when we set
%dolly wheelbase,tractor tandem axle spread
%

% We calculate the overall length of the combination in order to filter all
% modular combinations above certain length,check the main simulation file
% for more details refer to report.
%
```

..............Post-check......

Postcheck - this is done to satisfy the legal and geometrical constraints. For more details look into the report.

```
Fz11_single_sine_steer(i,j,k,l) = max(yout1(:,4));  % Fz- unit 1 axle 1
Fz12_single_sine_steer(i,j,k,l) = max(yout1(:,5));  % Fz- unit 1 axle 2
Fz13_single_sine_steer(i,j,k,l) = max(yout1(:,6));  % Fz- unit 1 axle 3
Fz21_single_sine_steer(i,j,k,l) = max(yout1(:,7));  % Fz- unit 2 axle 1
Fz22_single_sine_steer(i,j,k,l) = max(yout1(:,8));  % Fz- unit 2 axle 2
Fz23_single_sine_steer(i,j,k,l) = max(yout1(:,9));  % Fz- unit 2 axle 3
```

```
Fz31_single_sine_steer(i,j,k,l) = max(yout1(:,10)); % Fz- unit 3 axle 1
Fz32_single_sine_steer(i,j,k,l) = max(yout1(:,11)); % Fz- unit 3 axle 2
Fz33_single_sine_steer(i,j,k,l) = max(yout1(:,12)); % Fz- unit 3 axle 3
Fz41_single_sine_steer(i,j,k,l) = max(yout1(:,13)); % Fz- unit 4 axle 1
Fz42_single_sine_steer(i,j,k,l) = max(yout1(:,14)); % Fz- unit 4 axle 2
Fz43_single_sine_steer(i,j,k,l) = max(yout1(:,15)); % Fz- unit 4 axle 3
%
%These are some of the variables that have to be constrianed to certain
%values for the combination to be legal.Check the main code for the
%constraint values
%
load_front_axle_single_sine_steer(i,j,k,l)=Fz11_single_sine_steer(i,j,k,l);
% Load on the first axle of the combination(only steered axle)
load_driven_axle_single_sine_steer(i,j,k,l)=Fz12_single_sine_steer(i,j,k,l) ...
+ Fz13_single_sine_steer(i,j,k,l); % Load on the driven axles
load_tractor_single_sine_steer(i,j,k,l) =  Fz11_single_sine_steer(i,j,k,l) ...
+ Fz12_single_sine_steer(i,j,k,l) + Fz13_single_sine_steer(i,j,k,l);
load_tridem1_single_sine_steer(i,j,k,l) =  Fz21_single_sine_steer(i,j,k,l) ...
+ Fz22_single_sine_steer(i,1i,k,l) + Fz23_single_sine_steer(i,j,k,l);
% Load on the semitrailer I axles
load_dolly_single_sine_steer(i,j,k,l) =    Fz31_single_sine_steer(i,j,k,l) ...
+ Fz32_single_sine_steer(i,j,k,l) + Fz33_single_sine_steer(i,j,k,l);
% Load on the dolly axles
load_tridem2_single_sine_steer(i,j,k,l) =  Fz41_single_sine_steer(i,j,k,l) ...
+ Fz42_single_sine_steer(i,j,k,l) + Fz43_single_sine_steer(i,j,k,l);
% Load on the semitrailer II axles
```

A.6 Center of gravity for payload

This code is to determine the cg position and yaw moment of inertia for semitrailer along with the payload

These calculations done below are assumed that the semitrailer wheelbase is 6.9 m which is the sum of distance from front coupling point to center axle of tri-dem (We assume a starting value for A2 as 5.6 m). Mass of the container is 9000 kg but the axle masses are considered separately, each with a mass of 800 kg.

```
m_chassis= 9000-2400;
m_payload= 22000;
m_axis1=800;
m_axis2=800;
m_axis3=800;
chassis_dist_length = 13.6; % the chassis is assumed equally spread over
%the length of 13.6
per_loading = 1-0.9; % The percent of front loading, for instance90%
payload_dist_length = chassis_dist_length-per_loading*chassis_dist_length ;
% the payload is assumed equally spread from front to 90% of length
load_width = 2.5;
% using simple math the cgx for chassis n payload are calculated as
% following with respect to first axle of the semitrailer
cgx_chassis=0.4;   % with respect to the first axle of the semitrailer
cgx_payload=1.08;  % with respect to the first axle of the semitrailer
cgx_axis1 = 0;
cgx_axis2 = -1.3;
cgx_axis3 = -2.6;
%cgx_payload2= -0.16; % with respect to the first axle of the semitrailer
m_total= m_chassis + m_payload + m_axis1 + m_axis2 + m_axis3;
cgx_total = (m_chassis*cgx_chassis + m_payload*cgx_payload ...
+ m_axis1*cgx_axis1 + m_axis2*cgx_axis2 + m_axis3*cgx_axis3)/m_total

Izz_chassis = m_chassis*(chassis_dist_length*chassis_dist_length ...
+load_width*load_width)/12;
Izz_payload= m_payload*(payload_dist_length*payload_dist_length ...
+load_width*load_width)/12;
Izz_total = Izz_chassis + Izz_payload
+ m_chassis*(cgx_chassis-cgx_total)*(cgx_chassis-cgx_total)...
+ m_payload*(cgx_payload-cgx_total)*(cgx_payload-cgx_total)...
+ m_axis1*(cgx_axis1 - cgx_total)*(cgx_axis1 - cgx_total)...
+ m_axis2*(cgx_axis2 - cgx_total)*(cgx_axis2 - cgx_total)...
+ m_axis3*(cgx_axis3 - cgx_total)*(cgx_axis3 - cgx_total)
```