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# GENERIC FRAMEWORK FOR ASSESSMENT AND EXTRACTION OF ENVELOPES FOR LONG COMBINATION VEHICLES



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## Abstract

This work presents a generic framework to assess the dynamic behaviour of Long Combination Vehicles (LCV). This framework is applied to determine allowed ranges, envelopes, for vehicle's geometrical and inertial parameters. The vehicles that comply with these allowed ranges will be permitted on the road. The various constraints incorporated in the framework are performance-based standards (PBS), geometrical and legal constraints. The performance based standard constraints include longitudinal, lateral high-speed and low-speed characteristics of LCVs. Practical constraints such as maximum length, width, and clash between units are also considered. Legal constraints on road damage and safety are included. This framework was applied on an A-double combination vehicle to obtain envelopes or allowed ranges

**Keywords:** *Performance based standards, long combination vehicles, envelopes, A-double vehicle, and vehicle dynamics.*

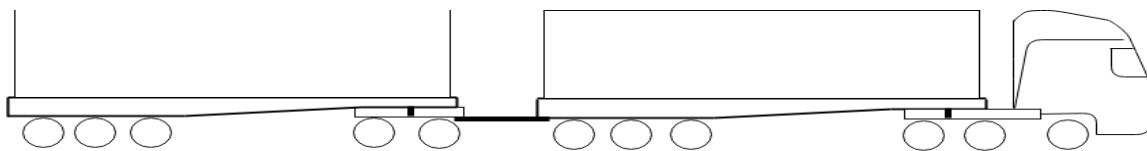
## 1. Introduction

In the era of technology, the major developments in vehicular technology 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 [1], transportation sector solely contributed to 27% of overall greenhouse gas emissions. Another study [2] suggests the contribution by Europe towards global carbon dioxide emissions by burning fossil fuels was 9% of the total emissions. International energy agency [3] 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 million of oil per day. The strategies used by commercial vehicle industry for sustainable transportation 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 adopted to reduce emissions and efficiently transport goods, by truck industries in Canada and Australia is the dispensation of LCV [4], [5]. Safety and traffic congestion of the vehicles is the key aspect to be considered for an LCV. In 1983 a European directive, was passed to harmonize vehicle lengths and weights. Under this directive, the length of a conventional heavy vehicle was fixed to 18.75 m. However, the legislation allowed the usage of LCV's if they are based on the modular system. According to [6], trial dispensations of heavier and longer vehicles for Sweden have resulted in significant increase in transport efficiency, reduction in CO<sub>2</sub> emissions and fuel economy. Currently,

there are two approaches to implementing the PBS strategy in the industry. One method is to allow 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 with these ranges. This work only investigates the second approach by presenting the framework to obtain permissible vehicle ranges, envelopes, like Canadian PBS.

Due to large number of vehicle parameters covering geometry of vehicle, tyre parameters, load distribution and design criteria. The parameters that will be studied in this work are a subset of the larger parameter set. After extensive study of the literature, it was observed that there were no studies dedicated to address the issue of envelopes. In studies [7] and [8], 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 [9] was performed to simulate different combination vehicles to evaluate the performance metrics. The work done in [10] is focused towards the evaluation of vehicle a-double for the PBS defined in above sections. An example of the envelope can be found at [11] implemented by Canadian PBS. The drawback is that there is no paper or document or framework which provides information to be able to regenerate similar envelopes and this was the gap in the literature. The main goal of this work was to develop a framework for the assessment of long combination vehicles to be permitted in Sweden. The framework is generic while considering legal, physical and as many, if not all, practical constraints. One of the limitations of this work, is that is focussed only on an A-double combination vehicle.



**Figure 1: A-double Combination Vehicle**

## **2. Performance Based Standards**

As mentioned above the truck length was limited to 18.75m with 40tons load carrying capacity. 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. To allow LCVs on the road, an extensive study on the stability and safety of such vehicles is imperative. According to [6] a performance-based standard has three aspects, a performance measure, an acceptable performance level and a test maneuver to assess performance measure. It is important that the LCVs allowed on roads to fulfill requirements broadly in all aspects of vehicle dynamics, environmental and traffic safety. The work performed in [6], culminated in identifying the most important vehicle performance measures to be considered under PBS for LCVs.

**Table 1: PBS Threshold Values**

Performance Based Standards	Threshold Value
Startability (SA)	12%
Gradeability (GA)	1% maintaining 70 km/h speed
Acceleration Capability (AC)	-
Low Speed Swept 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 <sup>2</sup> -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 Tires (FDST)	Max 0.25
Braking Stability in a Turn (BST)	-

The study in [6] also provides a detailed explanation of which maneuver to be used to measure the performance levels. A brief description of the same is provided in table 2.

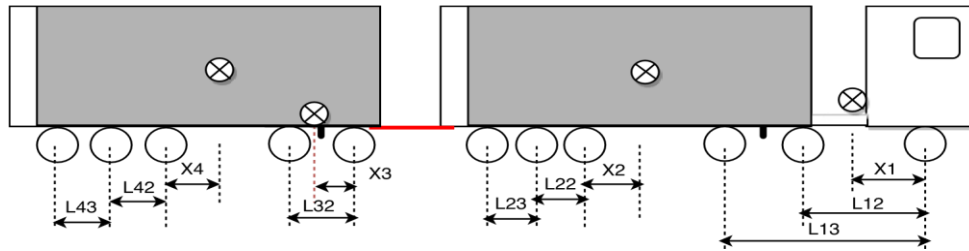
**Table 2: Table describing the maneuvers**

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 and Tail swing	Low speed curve 90 degree, 12.5m radius @ 1 m/s
Friction demand on tires	Low speed curve 90 degree, 12.5m radius @ 1 m/s

## 2.1. Parameterization

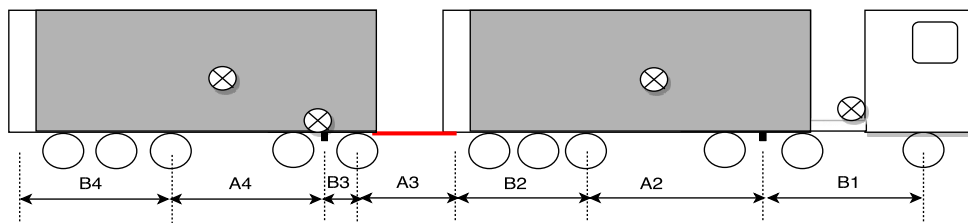
The parameterization developed for PBS models is generic; it can be used to define any type of combination vehicle. This is crucial to cover all the different configurations of LCVs. The two major inputs to the parameterization are the number of modular units and a maximum number of axles on any of the units. The parameterization uses the first axle of each unit as

the reference for that unit. The distance is defined with respect to the first axle of each modular unit. The figure 2 shows parameterization for each modular unit and their notations used in the models.



**Figure 2: A schematic representation of parameterization for distance between axles**

The coupling points on modular units are important for force and moment balances. Again, the parameterization 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: A schematic representation of parameterization for coupling points**

The parameterization of a long combination vehicle with different modular units has been performed. The equation of motions for a single-track model is developed for the parameterized model. The geometrical constraints at the coupling points are defined completely in [12].

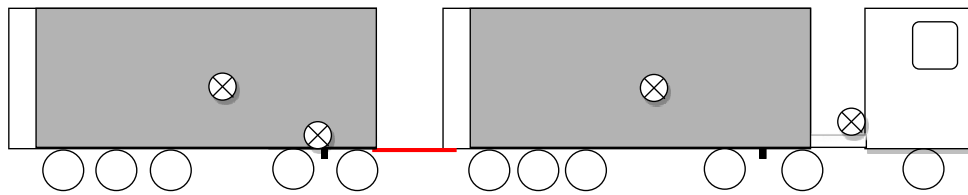
## 2.2. Loading

The important factors affecting the performance of a combination vehicle are geometrical dimensions and the way the payload is distributed. In this work, it was observed that it was crucial to consider different types of loading. The semitrailer kerb weight is a cuboidal shape with 6600 kg 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 center of gravity position of the semitrailer is determined from these above assumptions and applying basics of solid mechanics. In the report [13], the author observes that the vertical forces on driven axles of an A-double are lower than the threshold when both the semitrailers are loaded uniformly. To provide good traction, a requirement on vertical forces of driven axle was set, refer to table 1. The report [13], suggests that, loading the semitrailers more to the front eliminates this issue.

**Table 3: Table describing Unit masses including payload**

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

In the first case, the semitrailer is loaded such that the entire payload is assumed to be placed uniformly in the front 80% of the container as depicted in figure 4. The envelopes are obtained for all three loading cases namely 80%, and 90% front loading and Even loading.



**Figure 4: 80% front loading of the vehicle**

### 3. Framework

The introduction of an LCV would result in different configurations with different properties of the same combination vehicle. Envelopes are ranges for the geometrical and inertial properties of a vehicle. 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

#### 3.1. Pre-Check

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. There are mainly 6 different checks which are implemented under pre-check filter in this work namely: check on Overall length of the combination vehicle, track width, semitrailer consistency, and clash between modular units, number of units and maximum number of axles on any modular unit.

#### 3.2. PBS Check

Under the PBS check the vehicle configurations performance is compared with the threshold values provided in table 1. If the performance measures are satisfied, the vehicle configuration is considered to pass.

#### 3.3. Post Check

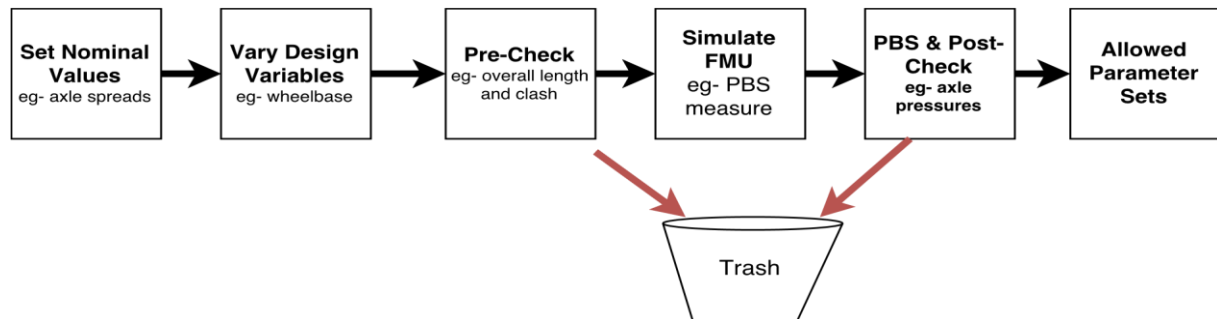
In post check, all vehicle combinations need to satisfy certain conditions on vertical loads of axles. By The vehicle stability can be assessed by vertical loads and road friction. The vertical loads must be below a certain value for mechanical integrity of the modular unit. If the load experienced is 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 prescribed to keep the road damage minimal.

**Table 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
Tractor	Max Sum of load on all axles	24 tons if wheelbase is 3m 25 tons if wheelbase is 3.2m 26 tons if wheelbase is 3.4m 27 tons if wheelbase is 3.4-3.8m
Semitrailer	Max tri-dem axle load	24 tons
Dolly	Max dolly load	18 tons

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.



**Figure 5: A schematic representation of overall framework**

#### 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 [14] 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

**Table 5: Nominal Values for Parameters**

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 w.r.t 1 <sup>st</sup> driven axle	0.25 m
Tractor	Front overhang	1.4 m
Tractor	Rear overhang w.r.t 1st axle	5.17 m
Tractor	Position of COG w.r.t 1st driven axle	1.4315 m



Semitrailer	Load length	13.6 m
Semitrailer	Tri-dem axle spread	2.6 m
Semitrailer	Front Overhang	1.6 m
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
Tire	Cornering Coefficient	6 (1/Rad)

The sensitivity 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 here provide a motivation to choose the important parameters for an A-double combination vehicle.

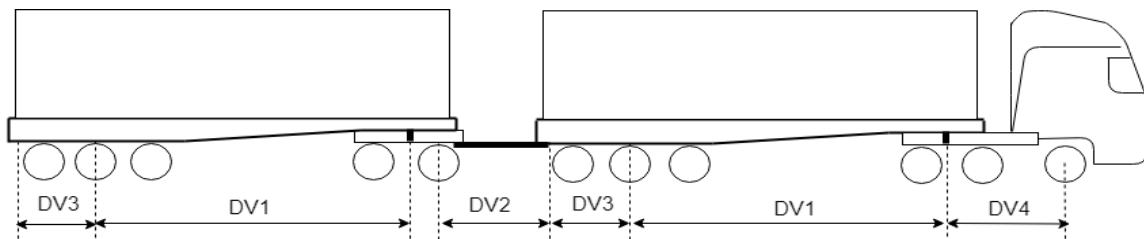
**Table 6: Results for Sensitivity Analysis**

Module	Parameters	RWA	1/YD	HSTO	TASP	LSSP	FS	TS	Step (m)
Tractor	Wheelbase	increase	increase	decrease	decrease	increase	increase	decrease	0.2
Tractor	Tandem spread	-	increase*	decrease*	-	-	increase	increase	0.1
Tractor	Front overhang	-	-	-	-	-	increase	-	0.1
Tractor	5 <sup>th</sup> wheel position	increase*	decrease*	-	-	decrease	-	increase	0.1
Semitrailer	Wheelbase	decrease	decrease	decrease	increase	decrease	-	decrease	0.2
Semitrailer	Front overhang	-	-	-	-	-	increase	increase	0.1
Semitrailer	Distance to rear hinge point	increase	increase*	increase	increase	decrease	-	-	0.2
Semitrailer	Tri-dem spread	decrease	decrease	decrease	-	increase*	decrease*	increase	0.1
Dolly	Wheelbase	decrease	decrease	decrease	-	increase*	increase*	decrease*	0.1
Dolly	Drawbar length	decrease	decrease*	decrease*	increase	decrease	decrease*	increase*	0.2
Tire	Cornering Coef	decrease	decrease	decrease	decrease	-	increase	increase	1



- increase/decrease– change in the value of PBS measure w.r.t nominal value for a step change in the parameter value is  $>25\%$
- increase\*/decrease\*– change in the value of PBS measure w.r.t nominal value for a step change in the parameter value is  $<25\%$
- - No affect

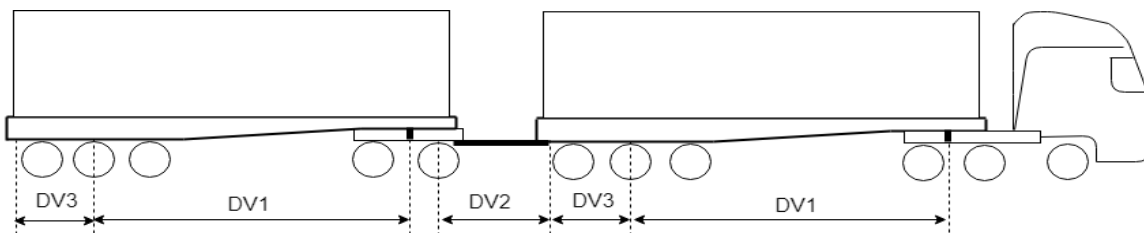
The front overhang of tractor and semitrailer does not have any influence on PBS measures, except for frontal and tail swing. The tandem axle spread and fifth wheel position on the tractor have influence on 4 different PBS measures. Whereas the most important parameters that influence all PBS measures 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. The parameters that are chosen to study are semitrailer wheelbase, distance from first axle of semitrailer to rear coupling point, drawbar length and tractor wheelbase.



**Figure 6: Design Variables**

#### 4.2. Three-Dimensional Sweep

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 7.



**Figure 7: Design Variables for 3D study**

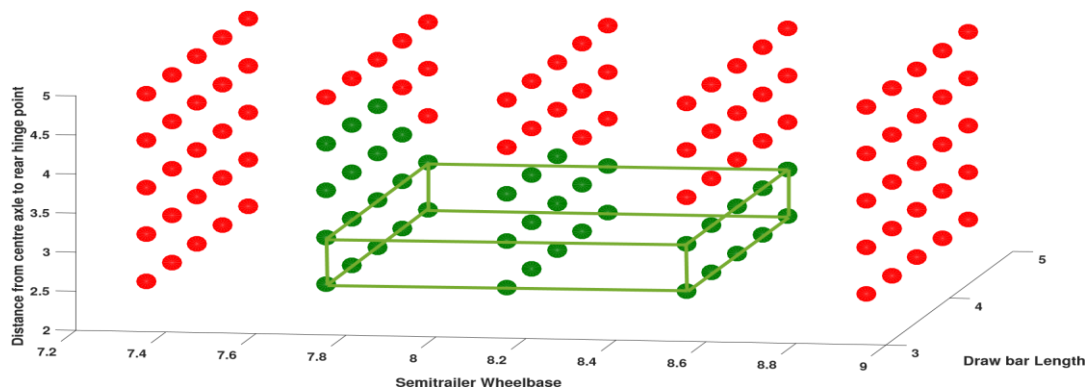
The variables chosen to study are the ones that have most influence on the PBS. The design variables are semitrailer wheelbase, distance from center axle to rear hinge point on semitrailer and draw bar length. The following table provides a range of variation of each variable in the study. These ranges were provided by Volvo Group Trucks Technology.

**Table 7: Table providing information on range of variation**

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

### Results

As mentioned above the main reason behind studying three variables was to be able to visualize the envelopes. It is crucial for the end user to interpret the results to build allowable combination vehicles. One problem could be the optimal cuboid in the 3D space. There could be many cuboids which can be inscribed in parameter space. Industrial expertise was used to choose the final envelopes.



**Figure 8: Envelopes for 3D combined sweep for 80% front loading**

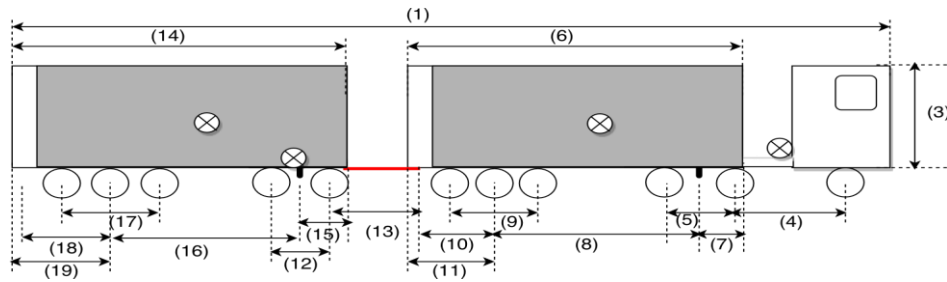
Figure 8, depicts the envelope space for this study. It is observed, there are no separate isolated spaces of allowed ranges hence making it easy to inscribe a cuboid. The cuboid covering the maximum area is chosen.

### 4.3 Four-Dimensional Sweep

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 4 different parameters. The following table provides ranges to vary for the design variables

### Results

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.



**Figure 9: A-Double: Description and Dimensions**

**Table 8: 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 9: Allowed ranges for the design variables for 80% front loading**

Tractor wheelbase [m]	Trailer wheelbase[m]	Distance 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
3.6	7.7 - 8.5	2.4	3.0 - 5.0
	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 are summarized in tables 8 and 9. There are many cuboids that can be inscribed into permissible design space. The permitted cuboids which can be formed are provided in table 9. The results provided in table 9 are the 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.

## 5. Conclusion

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 8-9. The vehicle combinations realized out of these ranges will be stable for the PBS measures and other constraints considered in this study.

It was also observed that for an A-double vehicle combination, even load, i.e., loading the semitrailer such that the payload is uniformly distributed along the entire length is not preferable because the vertical loads on axle is not above the threshold for any configuration.

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