THE EFFECTIVE EVALUATION OF TRUCK SAFETY FOR AN ALTERNATIVE PARALLEL SOUTH AFRICAN PBS LEGISLATION

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A research report submitted to the Faculty of Engineering and the Built Environment, of the University of the Witwatersrand, in partial fulfilment of the requirements for the degree of Master of Science in Engineering.

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DECLARATION

I declare that this research report is my own unaided work. It is being submitted to the Degree of Master of Science to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

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(Signature of Candidate)

……….. day of …………….., ……………

(day) (month) (year)

ABSTRACT

The National Transport Commission have shown that implementation of Performance Based Standards (PBS) improves companies' productivities by minimizing the transportation costs. This in turn has a positive effect on the South African economy. The development of PBS in Australia was identified and developed in South Africa. Computational modelling plays an important role in evaluating a truck's performance and dynamics for PBS adherence. This is because computational modelling can be done quicker, safer, and cheaper than conducting physical evaluation tests. In order to effectively evaluate vehicle performance, it is necessary to use an effective software package. The following software packages were analysed in this study: ADAMS/View 2011, TruckSim 8.0, and Yaw/Roll. Although the National Transport Commission has found accurate agreement of results by software comparison, this research looks at the ease-of-use (user effort required), cost, output agreement and features (e.g. driver models, tyre models, integrators, etc.) of the different software. This will assist other vehicle dynamicists wanting to evaluate PBS designs.

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ABBREVIATIONS

ABS	Antilock Braking System
ADAMS	Automatic Dynamic Analysis of Mechanical Systems
CAD	Computer Aided Design
CSIR	Council for Scientific and Industrial Research
DADS	Dynamic Analysis Design System
GUI	Graphical User Interface
HAVSIN	Haversine
MSC	McNeil Schindler Corporation
NRTC	National Road Transport Commission
NTC	National Transport Commission
PBS	Performance Based Standards
SAE	Society of Automotive Engineers
SI	International System of Units
UMTRI	University of Michigan Transportation Research Institute
Wits	University of the Witwatersrand

1 INTRODUCTION

1.1 The Need to Address Road Problems in South Africa

South Africa’s productivity is directly affected by the efficiency of its freight logistics system, to transport raw materials and manufactured goods. Many of the manufacturing areas in South Africa are situated at great distances from sea ports and airports. A great portion of the costs of manufactured goods are tied up in the transport of the goods from the point of their manufacture to their final destination [1].

Further, the Department of Transport [2] (in particular the transport minister) has stated that the South African economy has been taking strain from the exorbitant costs of road accidents. The Automobile Association estimated that more than R100 billion has been spent on dealing with collisions and fatalities during the 2010 financial year. Between years 2001 and 2008, the number of trucks involved in accidents has been above 1,200 (with more than 700 deaths per year) between 2001 and 2006, and over 500 per year (with more than 330 deaths per year) in 2007 and 2008. These figures exclude the statistics for articulated trucks [2].

The amount of road wear in South Africa is a further concern, which also involves high road maintenance costs. According to the CSIR, 20% of all heavy trucks on the road at any one time are overloaded. These trucks are responsible for 60% of road damage [3].

Performance Based Standards (PBS) is a possible solution to reduce the costs of the transportation of goods, to reduce collisions and fatalities, and to reduce road wear.

1.2 Performance Based Standards (PBS)

Current standards for vehicles have focused on their ability to adequately haul their loads up inclines, to ensure that their braking systems adequately decelerate the vehicle when fully loaded, to negotiate curves, and to undertake certain manoeuvres without becoming unstable. Loading legislation focuses on axle and axle unit loading, the maximum vehicle and combination mass, and the carrying capacity of bridges (using the bridge formula). These standards do address a range of safety issues; however, there are some aspects of heavy vehicle safety performance which are not controlled adequately by these standards.

The PBS approach, on the other hand, addresses factors such as the highly important aspect of a vehicle’s stability and dynamic performance. PBS ensures that trucks are stable on the road and can be manoeuvred in a safe manner. Introducing PBS vehicles does not only improve transport productivity by reducing the costs associated with transporting raw materials and minimizing the cost of delivery to the customer, but also has road safety benefits as well. PBS is a set of standards which specify the minimum requirements of a heavy vehicle before the vehicle can be considered to be safe. A vehicle which is designed according to the PBS standards conforms to performance measures which directly assess the vehicle’s safety. Introducing these standards enables productivity gains, and encourages technological improvements in heavy vehicles. The standards focus on what a heavy vehicle is meant to be able to do rather than what the vehicle should look like, at the same time meeting safety, road asset protection, and environmental requirements [4, 5].

Implementation of PBS is, therefore, advantageous to the South African economy, safety and road asset protection. It is thus necessary to determine how to evaluate the adherence of heavy duty trucks to PBS, in an effective manner.

1.3 Effective Evaluation of Vehicle Dynamics

In order to effectively implement and evaluate PBS on heavy vehicles, computational modelling is often used since it has a number of advantages over physical testing of vehicles. Physical testing is time consuming due to instrumentation, test set-up and repetition of unsuccessful tests. It also costs a lot more to conduct a physical test since precision instrumentation is expensive. Physical testing is hazardous since there is potential for damage to equipment, property, and humans. Computational modelling is less time consuming, costs a fraction of a physical test, and has zero risk. Another benefit of computational modelling is that a vehicle can be assessed, and design improvements may be made, before the vehicle is built.

There have been numerous cases of validation of computational test results with results from physical testing which gives computational modelling credibility for evaluating PBS. However, there is a research need to determine which software are the most effective ones to use for PBS evaluation and what is the agreement in results determined by modelling using these software packages.

1.4 Objectives

The objective of this study was to assess ADAMS/View 2011 (ADAMS), Yaw/Roll, and TruckSim 8.0 as suitable modelling packages for the effective evaluation of PBS in South Africa. The project focused on comparing the *ease-of-use, cost, and agreement* of the software packages.

Although other software packages exist, the three mentioned here have been identified by the NTC and have been identified as the most reputable.

2 LITERATURE SURVEY

2.1 PBS Development in Australia

In 1999, Australia made the first steps to passing PBS legislation and was funded by Austroads and the NRTC (National Road Transport Commission). The first step in the PBS project was to determine which performance standards were most appropriate for the regulation of heavy vehicles in Australia. This involved documenting the entire field of potential performance measures relevant to heavy vehicles, in NTRC reports [6] and [7]. Next, several steps were taken to select the initial set of regulatory performance measures. This was accomplished by using procedures in [8], the NTRC 2000a document. Over 100 potential performance measures were reduced to a set of 25, being sufficient to cover safety and infrastructure issues.

The set of potential regulatory performance measures were presented for review and comment by the stakeholders. It was decided that some of the standards needed to be reviewed, and it was requested that two more performance measures be included. Many of the potential regulatory performance measures were considered to be prescriptive in nature rather than being truly performance based. Performance measures that were deemed to fall in this category were primarily related to infrastructure issues. They were reframed and outcome specific performance measures were formulated. For example, three pavement related measures were replaced by a single, reframed, performance measure. In this way, the total number of proposed performance standards was reduced from a total of 25 to 23 [9].

The next phase of the PBS project aimed at evaluating and reviewing the proposed performance standards by testing them against a set of representative heavy vehicles from the Australian heavy vehicle fleet, to measure the safety and infrastructure related performance of the selected fleet vehicles against the proposed standards, and to recommend a final set of performance-based standards for heavy vehicle regulation. A total of 139 representative heavy vehicles from the Australian fleet were evaluated against the performance standards, using computer based modelling. Results from field studies on these vehicles were used to verify the modelling results. The agreements between the measurements and the computer-based predictions were accurate and acceptable. It was found that a large number of existing vehicles already met the performance standards proposed for unrestricted access to the Australian road network. The study indicated that a range of design features that, with adjustment, would enable more vehicles to meet the standards and take advantage of the PBS flexibility. From the results of the performance evaluation and feedback received from stakeholders, the proposed performance measures were reviewed. After further rigorous analysis, 20 performance measures were selected and 15 were considered useable and suitable for performing heavy vehicle assessments for regulatory purposes, while the other 5 require further research. Table 1 summarizes the final proposed set of performance measures [10].

Table 1: Proposed final set of performance measures [10]

Performance Measures	
#	**Safety Related**
	Longitudinal Performance (Low Speed):
1	Startability
2	Gradeability
3[b]	Acceleration Capability
	Longitudinal Performance (High Speed):
4[a]	Overtaking Time
5	Tracking Ability on a Straight Path
6[a]	Ride Quality (Driver Comfort)
	Directional Performance (Low Speed):
7	Low-Speed Offtracking

Performance Measures	
8	Frontal Swing
9	Tail Swing
10	Steer Tyre Friction Demand
	Directional Performance (High Speed):
11	Static Rollover Threshold
12	Rearward Amplification
13	High-Speed Transient Offtracking
14	Yaw Damping Coefficient
15[a]	Handling Quality (Understeer/Oversteer)
16[a]	Braking Stability in a Turn
	Infrastructure Related
	Pavements:
17	Gross Mass per Standard Axle Repetition
18	Horizontal Tyre Forces
19[a]	Tyre Contact Pressure Distribution
	Bridges:
20[b]	Maximum Effect Relative to Reference Vehicles

a) These are considered essential but require further research and development. [10]

b) "*Acceleration Capability*" and "*Maximum Effect Relative to Reference Vehicles*" are designed to replace, respectively, "*Intersection Clearance Time*" and "*Maximum Bridge Stress*". [10]

The reason why driver comfort is essential, as indicated in Table 1, is because the level of vibration, that a driver is exposed to during a working shift, leads to reduced comfort and decreased proficiency which contributes to fatigue [10].

Mainly, minor revisions were made to many of the performance standards (in order to clarify and remove any ambiguity rather than change the meaning or intent of the performance measure); however, a major revision was made to the performance level for the specification for the rearward amplification. This change allowed a significantly larger number of vehicles to meet the performance requirement of rearward amplification, particularly truck/trailers and road trains. Two of the original performance measures, namely, load transfer ratio and high-speed steady-state offtracking, were found to be redundant and were removed from further consideration. These redundant performance measures were found to be highly correlated with other existing performance measures. After a parametric study, parameters that were found to be highly related to the performance measures were: engine power/torque, driveline gear ratio, centre of gravity height, axle loads, wheelbase dimensions, tyre cornering stiffness (which is the slope of the linear portion of the tyre's lateral force vs. slip angle characteristic), and speed.

2.2 Computer-Based Modelling of Vehicle Dynamics

Further work performed by the NTRC in the PBS project included a comparison of modelling systems to determine whether there is acceptable agreement between simulations from computer-based models of heavy vehicles created by different modelling packages. This work was also done to address concerns raised by stakeholders about the reliability of the performance predictions from different computer-based models used by different service providers, since PBS is intended to encourage and foster innovation in road transport, and computer-based modelling will play a central role in both the development and initial demonstration of innovative vehicles and concepts. Computer based models of two heavy vehicles were created by two consultants (Road and Transport Dynamics, and Transport Engineering Research New Zealand) using three separate computer-based modelling packages, namely, ADAMS, UMTRI's constant velocity Yaw/Roll program, and AUTOSIM [11]. Each consultant was provided with the same input datasets and the same test manoeuvres were performed (comprising of a pulse steer, step steer, standard SAE lane change and a

90˚ low speed turn) in each model. It was found that simulations involving only vehicle responses were very close in agreement. Simulations involving a driver controller (a controller that is designed within the software packages to carry out the function of a real driver) were found to be in good agreement. Agreement in the outputs from the simulations in all manoeuvres was generally better than 7% for the performance measures considered. Prem *et al* believed that acceptable agreement can be expected from computer-based modelling and simulations provided the same input datasets are used and accurate models are created [11].

Vehicle performance can be evaluated by either physical testing and/or computer-based modelling. Field testing of vehicles, although necessary for validation is neither desirable, convenient, nor affordable. In addition, testing vehicles that have low stability thresholds for rollover or rearward amplification in near limit manoeuvres is a high risk activity which requires careful planning and additions to the vehicle such as outriggers. In the case where a broad range of performance characteristics are required, many field tests would be required to be performed that would require sophisticated instruments to record numerous variables. Computer-based modelling of vehicles is an attractive alternative to physical testing because it does not require a vehicle to be manufactured and then physically tested. A number of proposed vehicle designs can be studied in a wide range of situations and manoeuvres, and any number of variables in the model can be viewed and studied. There is no safety and property risk involved with computer-based modelling compared to physical testing of vehicles. Computer models can be used to identify problems or performance deficiencies and correct them during the design phase. Computer-based modelling, when compared to physical testing, is a very useful tool and provides a comprehensive, cost effective, safe and efficient way for studying heavy vehicle performance under a wide range of conditions [11].

2.3 PBS in South Africa

As a result of the potential benefits of PBS (such as safety, efficiency, and road protection) that have been identified in Australia, New Zealand and Canada, the introduction of a pilot project of PBS in South Africa was proposed by the CSIR as a research project [12]. It was found that experience in PBS vehicles, especially regarding design, manufacturing, and operation, was needed in South Africa. Due to this, demonstration PBS vehicles were commissioned by Mondi and Sappi, in the forestry industry. The standards used to design the two PBS demonstration vehicles included: startability, gradeability, acceleration capability, frontal swing, tail swing, slow speed swept path, tracking ability on a straight path, static rollover threshold, rearward amplification, yaw damping, and high-speed transient offtracking.

After commissioning, the two PBS demonstration vehicles were monitored. This involved recording data such as payload per trip, average trip speeds, kilometres travelled per month, average monthly fuel consumption, maintenance costs and records of incidents and accidents. The observed improvements were noted from the results of monitoring of the two PBS vehicles compared to the baseline vehicle. These improvements are summarized in Table 2.

Table 2 Improvements of the PBS demonstration vehicles [**12**]

Performance indicator	**Measured result**
Payload	Average improvement: 19.3%
Payload Efficiency Factor (Payload/Gross Combination Mass x 100)	Increase from 69.3% to 70.5%
Tons transported per month	Average increase: 19.3%
Fuel consumption	Average savings: 12.7%
Fuel savings (based on 700 000 tons/annum contract)	485 000 litres per annum
Fleet size	Reduction of 17%
Incident/accidents*	Reduction from 3.1 to 1.1 per month
CO_2 emissions (based on 700 000 tons/annum contract)	Reduction of 1 280 tons of CO_2 per annum
Road wear	Reduction varies from 2 to 23%

* Based on a fleet of 45 new vehicle combinations incorporating a number of PBS design features [12]

Due to these improvements, the KwaZulu-Natal department of transport has approved 30 additional permits for PBS demonstration vehicles in the forestry industry. By December 2009, 15 of these vehicles had already been commissioned [12].

Further PBS expertise was developed in South Africa when a contract was concluded between the University of the Witwatersrand and Hall Longmore in 2009 to design a PBS vehicle to transport pipes. So far, the University of the Witwatersrand has completed the initial conceptual development, vehicle configuration selection, and simulations to determine conformance to the Australian PBS measures. The design approach has been based on the performance measures that were developed in Australia. The design also conforms to South African axle load and bridge formula legislation. According to Dessein *et al*. [5], eight performance measures were considered necessary and sufficient for a safe vehicle in the context of the project. These eight measures were:

yaw damping coefficient, static rollover threshold, rearward amplification, high-speed transient offtracking, tracking ability on a straight path, low-speed swept path, tail swing, and frontal swing. Using an optimisation model, an A-Double design was shown to have met all of the PBS requirements with a 50% increase in payload compared to the baseline vehicle. The optimisation model was verified using a detailed model that was developed in TruckSim 8.0. In comparison to the optimised model, the simulation results from the software-based analysis proved to be accurate.

Although the proposed PBS standards have been defined for the Australian context, and may vary from country to country, most of them are applicable for evaluating PBS in South Africa. The long term goal of PBS in South Africa is to review the applicability of some of the PBS standards for South Africa. It may be required that new measures or requirements be introduced for the South African context.

2.4 Literature Review Summary and Focus of this Research

Since the time that the National Road Transport Commission and Austroads, in Australia, had initiated PBS legislation in 1999, over 100 potential performance measures were reduced to a set less than 25 measures, by NTRC review procedures, being sufficient to cover safety and infrastructure issues [8]. These proposed performance measures were evaluated and reviewed by testing them against a set of representative Australian heavy vehicle fleet.

Further work that has been carried out on PBS includes the determination of acceptable agreement between simulations from computer-based models of heavy vehicles created by different modelling packages [11]. This was to address concerns raised by stakeholders about the reliability of performance predictions from different modelling packages. The simulations performed by different consultants using different modelling packages were in very close agreement (generally better than 7%), according to Prem *et al.* [11].

As a result of the initiatives made in Australia, there was a need to gain experience in PBS vehicle design, manufacturing, and operation for the South African context. Thus, two demonstration PBS vehicles were commissioned by Mondi and Sappi. After commissioning, the vehicles were monitored by analysing data such as average monthly fuel consumption, maintenance costs and records of road accidents. Many improvements of the vehicles were noted which resulted in further permit approvals for PBS demonstration vehicles. More experience in PBS was gained in South Africa when the University of the Witwatersrand had designed a PBS vehicle, for Hall Longmore, to transport large pipes. Eight key PBS measures were sufficient for the design of the PBS vehicle.

The objective of the current research is focused on the effective evaluation of PBS in heavy duty trucks, in the South African context. The benefits of computer-based modelling for PBS evaluation have already been discussed. Although the NTC has already looked at the accuracy of computational modelling, this research is an extension of the NTC software comparison study. It looks at the various features of each software (e.g. the different mathematical solvers; the different means of creating driver controllers, speed controllers, and tyre models); the flexibility of each software; the ease-of-use (user effort required); and the cost of each software (which includes both initial and support costs).

Although discussing the ease-of-use may be subjective, there is useful insight gained from the author’s experience while conducting the software comparison. Ease-of-use of each software has been broken down to cover: the time and effort required to create models in each software, how long it takes for the solver in each software to complete a simulation, animation capability, and the systems of units that are available in each package.

There are other software packages available to evaluate vehicle dynamics, such as Recurdyn and DADS, however, the reasons for evaluating the mentioned software are as follows: The software have been evaluated by the NTC, and have already been identified as a reputable software. ADAMS is also the most widely used software for multi-body dynamics and motion analysis in the world [13]. Although the NTC has evaluated AutoSim, this software is no longer available on the market. However, TruckSim has been developed from AutoSim. This is why TrukSim was chosen to be analysed. Although ADAMS/View was chosen for the analysis, ADAMS/Car is another package that could be used, since it has drivers, event builders, road builders, test rigs, and comes standard with truck-trailer assemblies.

This research has been presented at an international, peer-reviewed, conference, at the 12th Heavy Vehicle Transport Technology Symposium (HVTT12) in Stockholm, Sweden [14].

3 METHODOLGY

In order to evaluate the effectiveness of truck safety for PBS, three different types of software were utilised and compared. The reference B-double simulated by Prem *et al.* [11] was modelled to perform four standard manoeuvres: an SAE lane change, a 90° low speed turn, a pulse steer input, and a step steer input. These four standard manoeuvres were selected by Prem *et al.* [11] because they were designed to test for specific performance attributes and, thereby, revealing different aspects of the vehicle models and controllers (both open-loop control and closed-loop control). The three software packages ADAMS/View, Yaw/Roll and TruckSim 8.0 (as discussed in Section 2) were used.

The ease-of-use of the software packages was evaluated by an engineering graduate with no prior experience of working with the software packages, in order to remove bias from the comparison. Software quotations were obtained from the local software agents in South Africa in order to compare software costs. The output agreement of the software packages was determined by plotting and comparing the results as calculated by each software package. The following two sections give brief descriptions of the standard modelled manoeuvres [11] and the software packages.

3.1 Modelled Manoeuvres

SAE Lane Change

The SAE lane change is used to evaluate rearward amplification and high-speed transient offtracking. The manoeuvre was conducted at a speed of 88 km/h [11]. The lateral displacement was 1.46 m over a longitudinal distance of 61 m. A closed-loop control was used for this simulation.

90° Low Speed Turn

The 90° low speed turn is used to evaluate low-speed swept path, tail swing, and frontal swing. The centre of the steer axle is required to follow a path comprising of a straight entry segment, 11.25 m radius, 90° arc and a straight exit segment. The manoeuvre was conducted at a speed of 10 km/h.

Pulse Steer Input

The pulse steer input is used to evaluate yaw-damping. The steer angle was increased from 0° to 10° and then back to 0° over a 0.5 s period. The manoeuvre was conducted at a speed of 100 km/h.

Step Steer Input

The step steer input is not required for PBS assessment [15] but has been used in previous validation studies by Prem *et al*. [11] and Sayers and Riley [16]. The steer angle was increased from 0° to 1° over a 0.25 s period and then held steady. The manoeuvre was conducted at a speed of 100 km/h.

3.2 Software Packages

The following sections give a background to each of the software packages that were analysed in this research.

3.2.1 ADAMS/View

ADAMS is the most widely used multibody dynamics and motion analysis software in the world [13]. The ADAMS user is required to either build a geometric model or else import CAD geometries of the system. The bodies can be rigid or flexible and the interconnections between bodies relating the motion of body A to body B must be defined. From these geometrical inputs, ADAMS generates the mathematical equations that describe the kinematic and kinetic motion of the system. The ADAMS solver integrates the differential equations providing a solution that can be viewed in the post-processor: a number of integrator algorithms are offered. ADAMS is used extensively in the automotive industry and any mechanical system can be modelled and analysed.

3.2.2 Yaw/Roll

Yaw/Roll was developed at the University of Michigan Transport Research Institute (UMTRI) to predict the directional and roll response of generalized articulated vehicles. It is the predecessor of TruckSim. The program can be used for stability, rollover as well as low-speed turn simulations. The turning behaviour of the vehicle can be controlled either by defined steering inputs or by a driver model following a prescribed trajectory. The equations defining the vehicle response are hardcoded, limiting any extension of the model to account for specific requirements e.g. a steering trailer axle. The differential equations are solved using a predictor-corrector integration method [17].

3.2.3 TruckSim

TruckSim is a dedicated software tool for simulating and analysing the dynamic behaviour of medium to heavy trucks, buses and articulated vehicles [18]. The truck data and control inputs defining the manoeuvre concerned are entered using data screens with a graphical user interface (GUI). An extensive variety of axle, suspension, tyre, brake, steering, payload and trailer configurations can be selected. TruckSim can be linked with Matlab Simulink if the required truck component, feature or input cannot be modelled using the data screens offered.

4 MODEL DEVELOPMENT

Although the B-double vehicle model was already developed in [11], there was no information about the effort and the methods that were used to model the vehicle and road paths in the different software packages, with mechanical properties, geometry, controllers, etc. This section describes how the B-double truck was developed and modelled in each software package. It includes how the:

- Tyre models,
- Suspensions systems,
- Roll centres,
- Fifth wheels,
- Prime mover,
- Trailers,
- Steer controllers,
- Speed controllers, and
- Manoeuvre paths/inputs,

were developed in each software package.

4.1 Tyre Models

The tyre properties describing how lateral force and self-aligning moment varies with slip angle, for different vertical loads, have been provided [11]. Appendix A [11] tabulates the tyre properties used on the NTC B-double truck.

In ADAMS/View, input files containing all tyre data needed to be created. In TruckSim and Yaw/Roll, the tyre properties were completely specified within the Graphical User Interface (GUI).

4.1.1 Creating a Tyre Model in ADAMS/View

The Pacejka ’89 Magic Formula [19] was used to develop the tyre model in ADAMS/View, since it is most applicable to the given tyre data in Prem *et al*. [11]. The Magic Formula is defined in Equation (1) [19].

$$\begin{gathered} y(x) = D\sin\left(C \cdot \arctan\left\{Bx - E\left(Bx - \arctan\left(Bx\right)\right)\right\}\right) \\ Y(X) = y\left(x\right) + S_v \\ x = X + S_h \end{gathered} \tag{1}$$

In Equation (1), $Y(X)$ is the lateral tyre force, F_y; X is the tyre lateral slip angle, α; B is the stiffness factor, C is the shape factor; D is the peak factor ; E is the curvature factor; S_h is the horizontal shift; and S_v is the vertical shift. Each of these terms are dependent on the tyre vertical load and camber angle. Coefficients B, C, D and E are each dependent on coefficients a_0 to a_{13}.

Equation (1) is also used for fitting the longitudinal force vs. longitudinal slip curves as well as the self-aligning moment vs. slip angle curves of the tyre i.e. $Y(X)$ can represent the longitudinal force, F_x, for the case of the longitudinal force curves (along with the longitudinal coefficients b_0 to b_{10}; or $Y(X)$ can be the self-aligning moment, M_z, for the case of the self-aligning moment curves (along with aligning coefficients c_0 to c_{17}). The method for determining the coefficients for each case is defined by Bakker *et al*. [19].

In this study, a regression analysis was performed to determine the various coefficients for the tyres’ lateral characteristics and self-aligning characteristics, since longitudinal tyre properties were not necessary for the manoeuvres that were simulated. After performing a regression analysis, the coefficients for the lateral force and self-aligning moment magic formulae were determined, while using the fact that the camber angle was zero for the B-double vehicle. The curve fits were in close agreement with the tyre properties given (as shown in Appendix A.1). The coefficients were entered into the ADAMS/View 2011 Pacejka ’89 tyre file (as shown in Appendix A.2). Figure 1 and Figure 2 show the curve fits for the lateral tyre characteristics and the self-aligning tyre characteristics, respectively.

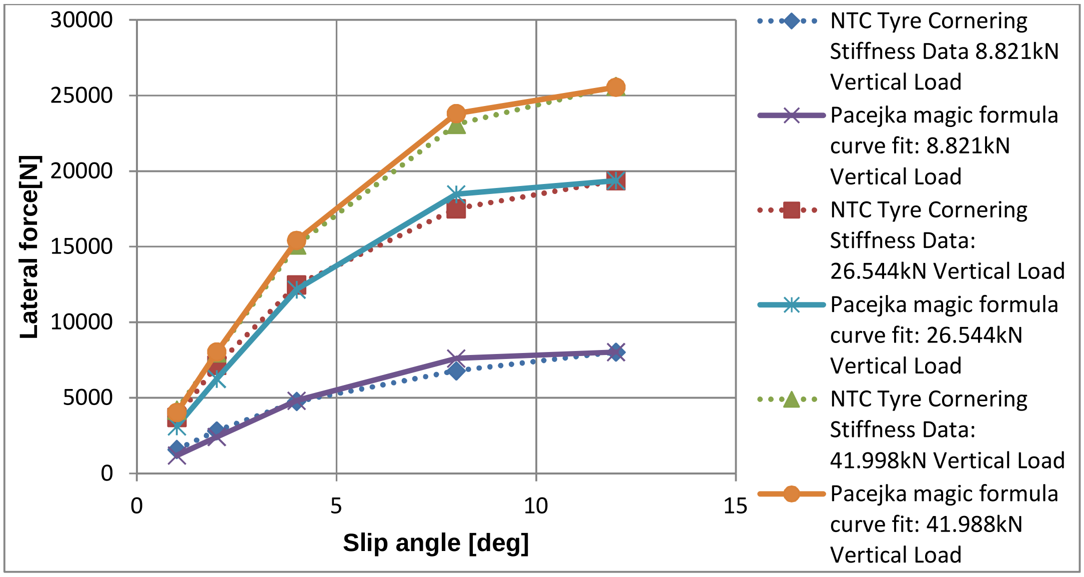


Figure 1: Lateral force vs. slip angle Pacejka ’89 curve fit

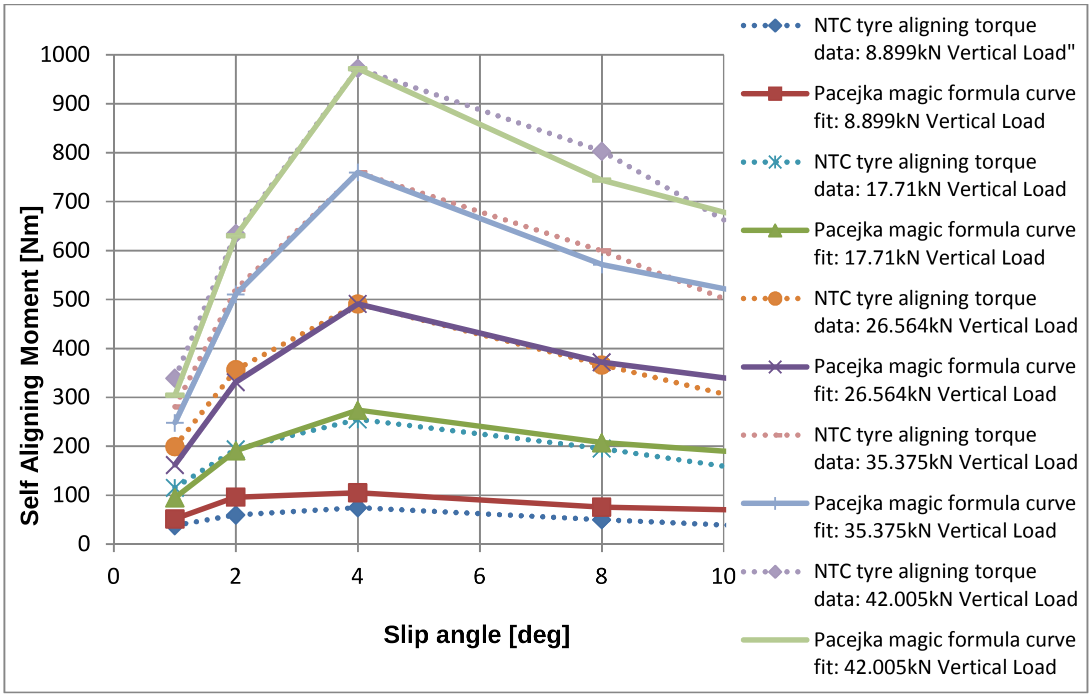
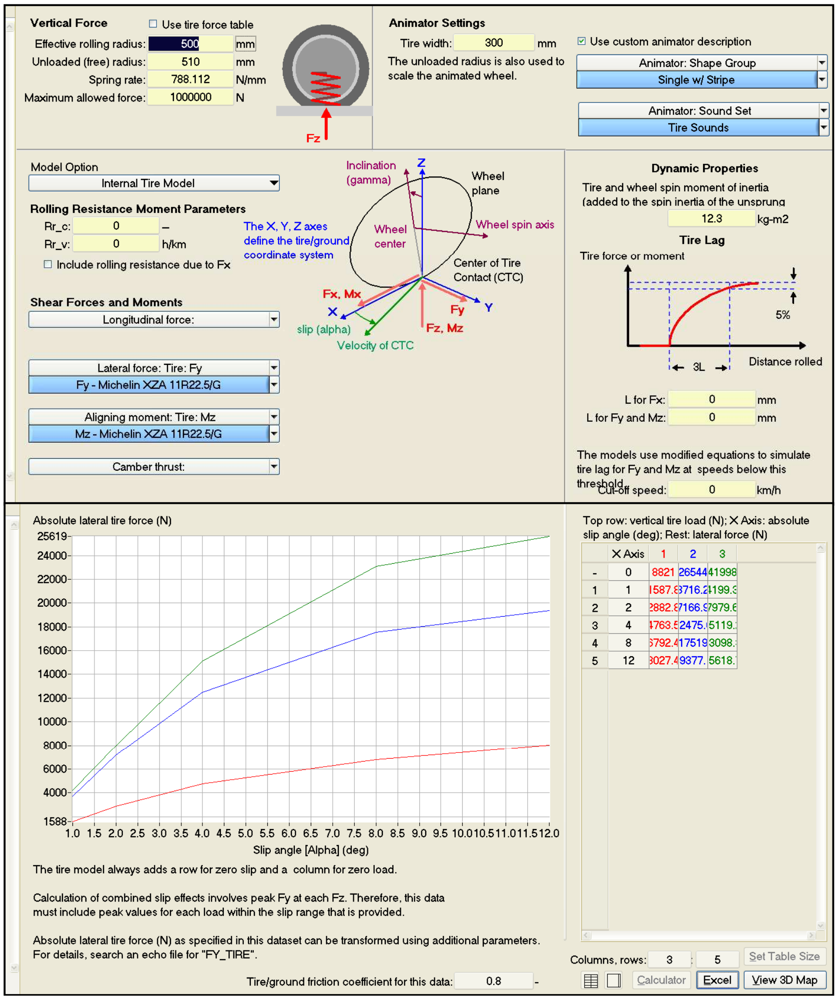


Figure 2: Self-aligning moment vs. slip angle Pacejka '89 curve fit

4.1.2 Creating a Tyre Model in TruckSim

It was not necessary to perform a Magic Formula curve fit, or to create a tyre input file, to define a tyre in TruckSim. All the tyre characteristics and properties were directly inserted onto the TruckSim GUI. This is shown in Figure 3. The bottom half of Figure 3, which corresponds to Figure 1, shows the curves of Lateral Tyre Force vs. Slip Angle, which are created by directly entering the tyre characteristics, as they are in Appendix A, onto the GUI.



Vertical Force ☐ Use tire force table

Effective rolling radius: 500 mm
Unloaded (free) radius: 510 mm
Spring rate: 788.112 N/mm
Maximum allowed force: 1000000 N

Animator Settings

Tire width: 300 mm
The unloaded radius is also used to scale the animated wheel.

☑ Use custom animator description
Animator: Shape Group
Single w/ Stripe
Animator: Sound Set
Tire Sounds

Model Option
Internal Tire Model

Rolling Resistance Moment Parameters

Rr_c: 0 –
Rr_v: 0 h/km
☐ Include rolling resistance due to Fx

The X, Y, Z axes define the tire/ground coordinate system

Shear Forces and Moments

Longitudinal force:
Lateral force: Tire: Fy
Fy - Michelin XZA 11R22.5/G
Aligning moment: Tire: Mz
Mz - Michelin XZA 11R22.5/G
Camber thrust:

Dynamic Properties

Tire and wheel spin moment of inertia (added to the spin inertia of the unsprung
12.3 kg-m2

Tire Lag

L for Fx: 0 mm
L for Fy and Mz: 0 mm

The models use modified equations to simulate tire lag for Fy and Mz at speeds below this threshold.
Cut-off speed: 0 km/h

Absolute lateral tire force (N)

The tire model always adds a row for zero slip and a column for zero load.

Calculation of combined slip effects involves peak Fy at each Fz. Therefore, this data must include peak values for each load within the slip range that is provided.

Absolute lateral tire force (N) as specified in this dataset can be transformed using additional parameters. For details, search an echo file for "FY_TIRE".

Tire/ground friction coefficient for this data: 0.8 -

Top row: vertical tire load (N); X Axis: absolute slip angle (deg); Rest: lateral force (N)

	X Axis	1	2	3
-	0	8821	26544	41998
1	1	1587.8	3716.2	4199.3
2	2	2882.8	7166.9	7979.6
3	4	4763.5	2475.	5119.
4	8	5792.4	17519	3098.
5	12	3027.4	9377.	5618.

Columns, rows: 3 : 5

Figure 3: TruckSim GUI for defining tyre forces vs. slip

4.1.3 Creating a Tyre Model in Yaw/Roll

In Yaw/Roll, tyre cornering properties and self-aligning table properties are entered into the data input file, which must be in the required format. The format is discussed in detail by Gillespie *et al*. [17]. At each line, a particular dataset needs to be defined (e.g. in line 151, the number of tyre cornering forces needs to be entered).

Linear or non-linear tyre models can be defined. Linear tyre models can be defined by a single tyre stiffness value that is entered (as pounds/degree) for each tyre on the different axles. Non-linear tyres can be represented by a tabular input in the input file. The same needs to be done when defining tyre aligning moments. Multiple tyre cornering force tables can be defined for different tyres on different axles. The same applies for tyre aligning moment tables.

4.2 Creating the Sprung and Unsprung Masses

This section describes how the dimensions, mass properties and mechanisms were created for various parts of the B-double vehicle, such as axles, sprung masses, suspension springs, roll centres, and fifth wheels. All the dimensions, masses, inertias and other vehicle properties of the B-double vehicle were obtained from Prem *et al*. [11] and are presented in Appendix B. These data were used for developing the vehicles in the software.

4.2.1 ADAMS/View 2011

The first step in creating the ADAMS model was to select the preference of units and to define in which direction gravity is acting. The axles were the first parts created, after the tyre models were prepared, in the ADAMS model. Each axle was created using a cylindrical shape, using the ADAMS standard geometries from the toolbar. The axles were correctly sized and spaced, for each unit, and were given masses and moments of inertia at the correct locations.

The tyre parts were attached to the axles by using revolute joints. Dual tyres were coupled together. Once the tyres were attached to the axles, the tyre property files, which contained the detailed information about the tyres such as dimensions and other properties discussed in Section 3.1.1, were imported and loaded for each tyre. In addition, the road was created by importing the appropriate road file. In this case, a 2-D flat road was imported (from the standard ADAMS road files) and was specified for each tyre. The road was fixed to ground and thus would not fall by gravitational force. The tyres were attached to the steer axle in a similar way to the other axles, except that there was an extra revolute joint to allow for the steer action. The steer tyres were connected to the steer axle by two revolute joints (since the steering mechanism was a basic parallelogram [11]). One revolute joint allowed the rotation of the tyre about the axis of the tyre. The other revolute joint allowed the steering angle rotation of the tyre. These two revolute joints were connected in series. Figure 4 shows how the steer joint mechanism was created in ADAMS. The steer tyres were connected to the wheel revolute joint, described in Figure 4.

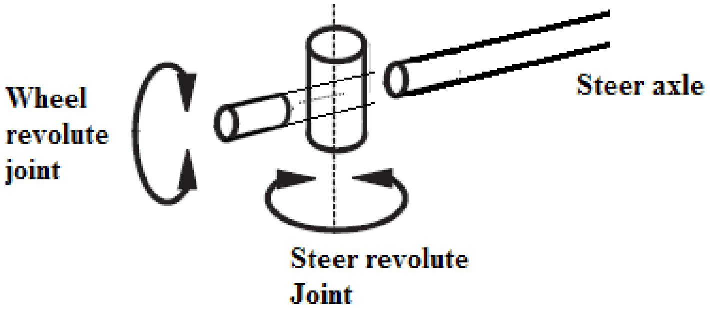


Figure 4: Schematic diagram of steer mechanism created in ADAMS

Once the axles and wheels were created, sprung masses were created by creating block-shaped parts for the tractor sprung mass and each trailer. They were dimensioned correctly, and were given masses and moments of inertia, which were specified at the location of the centre of gravity of each sprung mass. To connect each sprung mass to the suspension system, combined springs and dampers were used. They were correctly located and spaced and splines were specified to define each spring's force-displacement curves. The damping coefficients of the dampers were also defined at each axle.

In order to cater for rotation about the roll centre of the vehicle and to cater for vertical translation of the sprung masses, a mechanism was created that is similar to what is shown in Figure 5. Figure 5 shows how a revolute joint (which allows rotation parallel to the longitudinal axis of the vehicle) is connected in series to a vertical translation joint to simulate the vehicle's roll centres. At each revolute joint, a torsional spring was created to allow the effect of axle roll stiffness (with the correct magnitude of stiffness defined on the torsional spring). This mechanism was created at each axle of the vehicle.

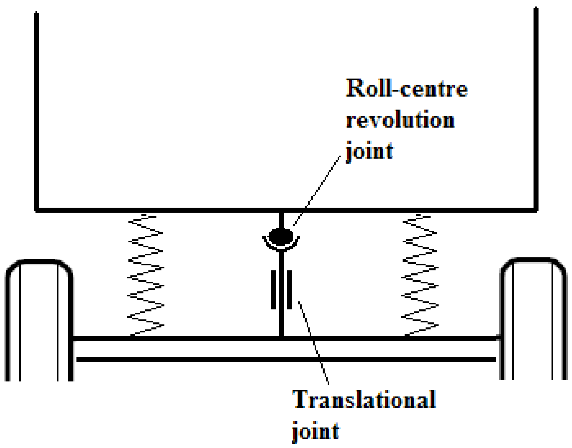


Figure 5: Schematic diagram showing the roll centre mechanism

Each unit of the vehicle, i.e. the prime mover, trailer one and trailer two, were connected to each other at the hitch point (i.e. the fifth wheels). This was done by connecting the units with a ball joint. Torsion springs were created at the hitch points to create roll stiffness between the units. Figure 6 shows the B-double model that was created in ADAMS, with a rendered view.

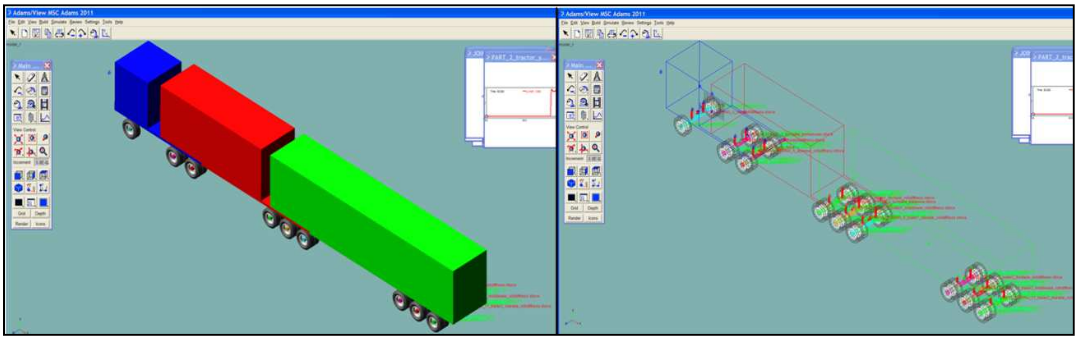
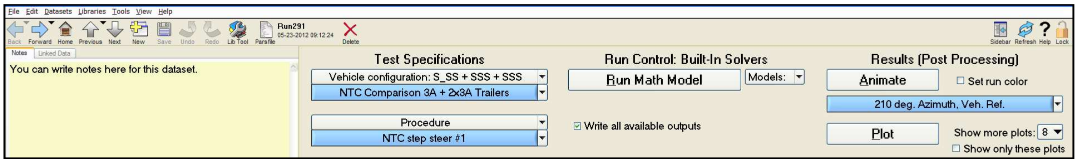


Figure 6: The ADAMS/View B-double model

4.2.2 TruckSim [20]

When starting TruckSim, a new database is selected to create a new model on the TruckSim Run Control screen. Under the “Test Specifications” heading, there are two areas which link to datasets that define the properties of the vehicle and procedure in the simulated test. TruckSim has a drop-down menu with various vehicle configuration options on the Run Control (home) screen, which is the first screen to appear when TruckSim is started up. The first step in creating the vehicle was to select a three axle tractor with two of three axle B-trailers, since a B-double was used for the study. Figure 7 shows a portion of the Run Control screen.



Run291
05-23-2012 09:12:24

You can write notes here for this dataset.

Vehicle configuration: S_SS + SSS + SSS
NTC Comparison 3A + 2x3A Trailers

Procedure
NTC step steer #1

Models:

☑ Write all available outputs

☐ Set run color
210 deg. Azimuth, Veh. Ref.

Show more plots: 8
☐ Show only these plots

Figure 7: TruckSim Run Control screen (“home” screen)

The TruckSim standard package offers thirteen configurations, as shown in Table 3. However, more configurations can be purchased for additional flexibility.

Table 3 Standard TruckSim Configurations

TruckSim designation	SAE designation	Common name
s_s	11	2-axle truck
s_ss	12	3-axle truck
ss_s	21	3-axle truck
ss_ss	22	4-axle truck
s_s + s	11s1	2-axle tractor & 1-axle semi-trailer
s_s + ss	11s2	2-axle tractor & 2-axle semi-trailer
s_s + sss	11s3	2-axle tractor & 3-axle semi-trailer
s_ss + s	12s1	3-axle tractor & 1-axle semi-trailer
s_ss + ss	12s2	3-axle tractor & 2-axle semi-trailer
s_ss + sss	12s3	3-axle tractor & 3-axle semi-trailer
s_ss + ss + ss	12s2s2	7-axle B-double
s_ss + sss + sss	12s3s3	9-axle B-double (used in this study)
s_s + s + ds + s	11s1-1s1	5-axle A-double

Once the vehicle configuration was selected, the details of the vehicle were defined by clicking on the first blue tab under the Test Specifications heading (as shown in Figure 6). Within this area, the lead unit and the trailers were specified in detail.

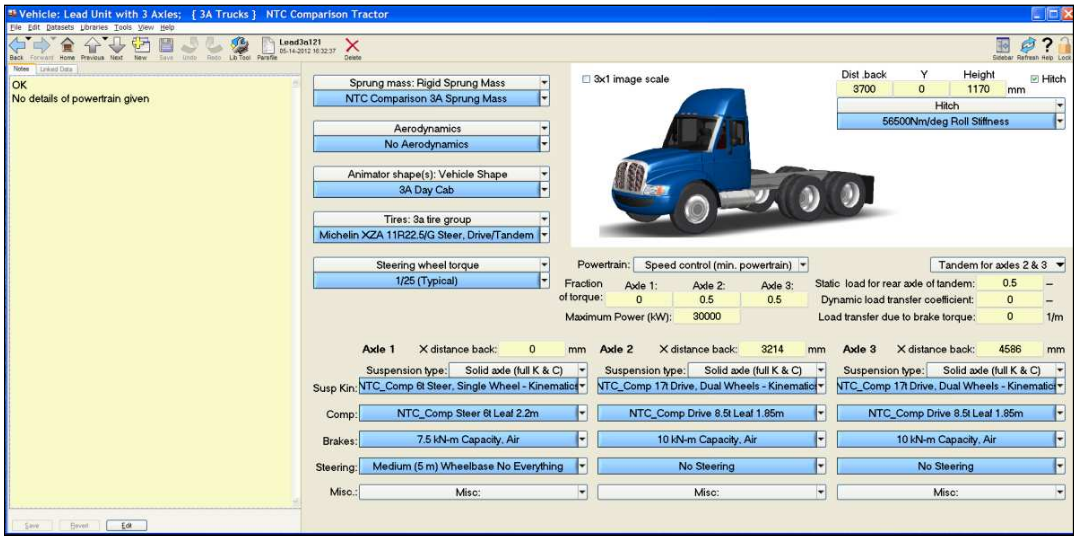
Under the lead unit area, there are various sub-sections which are used to define the lead unit, namely:

- The *lead unit* sprung mass. This is where the dimensions, mass, and inertia properties of the lead unit sprung mass are defined. The position of the centre of gravity is defined here.
- *Tyres*. This is where the tyres can be specified for each axle, as discussed in Section 3.1.2 and shown in Figure 3. All properties of the tyres can be defined on the GUI, such as: effective rolling radius, unloaded radius, spring rate, spin moments of inertia, rolling resistance moment parameters, tyre models, lateral

force variation with slip angles, longitudinal force variation with slip angles, aligning torque variation with slip angles, and others.

- *Steering wheel torque*. The steering ratio can be specified here, i.e. total steering wheel torque / total kingpin moment.
- *Engine power* and *torque fraction* of power per axle. This includes specifying speed control.
- *Hitch* (i.e. fifth wheel) location and stiffness.
- *Axle spacing*. This is the distance between each axle.
- *Suspension kinematics*. This is where the wheel centre height, location of the centre of gravity of the axles, axle masses and moments of inertia, jounce, roll-steer, roll centre location, toe and camber are defined.
- *Axle compliances*. This is where the force-displacement splines for each spring; shock absorbers (dampers); rebound stops; axle roll stiffness; and the lateral displacement between the springs and dampers, are defined.
- *Aerodynamics*. Aerodynamics effects (drag and lift) are defined here.
- *Brakes*. ABS control and other brake system parameters can be defined.
- *Steering*. Steering kinematics can be defined under this section within the TruckSim GUI.

The main lead unit specification screen is shown in Figure 8. It shows different blue buttons where are the main sub-sections can be edited when defining a unit of the vehicle.



Lead3a121
05-14-2012 16:32:37

OK
No details of powertrain given

Sprung mass: Rigid Sprung Mass
NTC Comparison 3A Sprung Mass

Aerodynamics
No Aerodynamics

Animator shape(s): Vehicle Shape
3A Day Cab

Tires: 3a tire group
Michelin XZA 11R22.5/G Steer, Drive/Tandem

Steering wheel torque
1/25 (Typical)

☐ 3x1 image scale

Dist .back: 3700; Y: 0; Height: 1170 mm ☑ Hitch

Hitch
56500Nm/deg Roll Stiffness

Powertrain: Speed control (min. powertrain)

Fraction of torque:	Axle 1:	Axle 2:	Axle 3:
	0	0.5	0.5

Maximum Power (kW): 30000

Tandem for axles 2 & 3
Static load for rear axle of tandem: 0.5 –
Dynamic load transfer coefficient: 0 –
Load transfer due to brake torque: 0 1/m

	Axle 1	Axle 2	Axle 3
X distance back:	0 mm	3214 mm	4586 mm
Suspension type:	Solid axle (full K & C)	Solid axle (full K & C)	Solid axle (full K & C)
Susp Kin:	NTC_Comp 6t Steer, Single Wheel - Kinematics	NTC_Comp 17t Drive, Dual Wheels - Kinematics	NTC_Comp 17t Drive, Dual Wheels - Kinematics
Comp:	NTC_Comp Steer 6t Leaf 2.2m	NTC_Comp Drive 8.5t Leaf 1.85m	NTC_Comp Drive 8.5t Leaf 1.85m
Brakes:	7.5 kN-m Capacity, Air	10 kN-m Capacity, Air	10 kN-m Capacity, Air
Steering:	Medium (5 m) Wheelbase No Everything	No Steering	No Steering
Misc.:	Misc:	Misc:	Misc:

Figure 8: Lead unit specification screen in TruckSim

The same subsections, except for the steering wheel and engine specifications, exist to define the other units of the vehicle (i.e. for trailer one and trailer two).

4.2.3 Yaw/Roll [17]

The Yaw/Roll program uses a list of input parameters. The program starts by reading the input parameter list which contains the vehicle configuration, initial conditions, and steer inputs. The input data are "echoed" on the first page of output. The program runs by solving the differential equations of motion for the vehicle until the vehicle reaches a default stop or until the required maximum simulation time has been reached. At various points during the run, simulation output is printed which contains data about the time-based dynamics and forces of the vehicle. This simulation run is completed within approximately one or two seconds.

The input data are identified only by position in the input list and, therefore, the vehicle data must be ordered exactly. The Yaw/Roll user-manual [17] defines the format of the input data, line by line.

The input data list will contain the following elements:

- Title line (up to 80 characters)
- Simulation operation parameters
- Sprung mass parameters for each vehicle
- Axle loading parameters
- Unsprung mass parameters for each axle
- Suspension parameters for each axle
- Hitch parameters
- Suspension spring tables (optional)
- Tyre cornering force tables
- Tyre aligning torque tables
- Steering system parameters
- Steering control parameters (driver model or time/steer angle control).

Appendix C shows the input data .DAT file that was created to model the NTC B-double vehicle in for the SAE lane change simulation in the Yaw/Roll program. The data were inserted sequentially according to the format specified in the Yaw/Roll user manual. The vehicle parameter data were taken from Prem *et al*. [11] and are reproduced in Appendix B. All the parameters were converted from SI units to English units before being inserted in the input file, shown in Appendix C. Appendix C also contains the .OUT file that contains the “echoed” input data as well as the tabulated output results.

4.3 Vehicle Controllers

Once all the parameters, parts, and dynamic mechanisms of the vehicle were created, controllers were created to move the vehicle. A velocity controller was required to ensure that the vehicle was moving at the correct speed. Steer controllers were needed for the vehicle to execute the open loop control manoeuvres and the closed loop control manoeuvres.

4.3.1 ADAMS/View Vehicle Controllers

Velocity controller

In order to accelerate the B-double from static equilibrium to a desired speed, a velocity controller was created. The controller was based on a force function that was applied to the centre of the drive axles on the tractor. The magnitude of the driving force was a function of the desired velocity of the vehicle and the actual measured velocity of the vehicle. The controller was a proportional-integral one, and the function, which defined the magnitude of the driving force, is described in Equation 2.

$$F_d = K_P \cdot (V_d - V_a) + K_I \cdot \int_0^t (V_d - V_a)\,dt \qquad (2)$$

In Equation (2), F_d is the driving force, K_I is the integral gain, K_P is the proportional gain, V_a is the actual/measured speed of the vehicle, and V_d is the desired/set speed that the vehicle is to attain and, thereafter, maintain. Figure 9 shows a schematic diagram of the velocity controller that was developed in ADAMS/View.

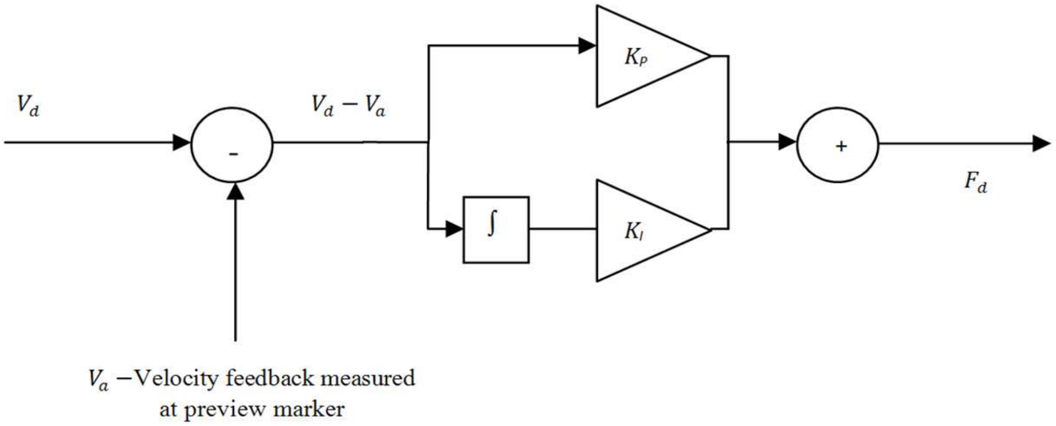


Figure 9: Schematic of velocity controller developed in ADAMS/View

To create the velocity controller, a marker was defined on the vehicle. A measure was created at this marker to measure the actual vehicle speed. A variable was created and defined to be equal to the desired velocity of the vehicle. A force was created at the centre of the two drive axles, in the forward longitudinal direction of the vehicle that was as given by Equation 1. The difference between V_d and V_a is the error which causes the actuation (or driving force) i.e. the driving force is applied proportionally to the magnitude of the error between the desired velocity and the actual/measured velocity, $(V_d - V_a)$. The magnitudes for the gains, K_P and K_I, were found by trial-and-error until the best velocity control was observed. Although it is possible to implement proportional control to control the vehicle speed, proportional-integral control was used to gradually increase the vehicle speed to the desired speed in a more critically damped manner in a shorter time.

The method followed in ADAMS/View when building the velocity controller was as follows:

- A *design variable* was created and was called “desired_velocity”, stored with the desired value for the speed.

- A *state variable* was created and was called “actual_velocity”. This variable stored the measured velocity of the tractor at the marker created on the tractor.
- An *explicit differential* equation, named “velocity_error”, was created to store the difference between the desired velocity and the actual velocity.
- A *design variable* was created, called “Proportional_gain”. Various values were defined for this until the velocity controller was optimised (as visualised in the post-processor).
- A *design variable*, called “Integral_gain” was created and was defined with various values until the controller was optimised.
- A drive-force function was created at the drive axles as shown in Equation (3):

$$\begin{aligned} Function &= Proportional\_gain \cdot DIF1(velocity\_error) + Integral\_gain \cdot \\ & DIF(velocity\_error) \end{aligned} \tag{3}$$

In Equation (3), *DIF*1 (a function used in ADAMS for manipulating differential equations) returns the function belonging to the referenced differential equation. In this case, it returns the error/difference of the actual and desired velocities. *DIF* integrates the function belonging to the referenced differential equation. In this case, it integrates the velocity error.

Open loop steer controllers

Two of the simulations were open loop control manoeuvres and the other two simulations were closed loop control manoeuvres. The two open loop control manoeuvres were the pulse steer and the step steer. In open loop control, no feedback is required, so the required motion was directly imposed on the steer revolute joints of each steer tyre with no feedback measures in the control algorithm. For the step steer manoeuvre, Equation (4) describes the motion imposed on the steer revolute joints.

$$\delta = \begin{cases} \delta_0 & t \le t_0 \\ \dfrac{\delta_0 + \delta_1}{2} + \dfrac{\delta_1 - \delta_0}{2} sin\left[\left(\dfrac{t - t_0}{t_1 - t_0}\right)\pi - \dfrac{\pi}{2}\right] & t_0 < t < t_1 \\ \delta_1 & t \ge t_1 \end{cases} \qquad (4)$$

In Equation (4), t is time (s), t_0 is the commencement time of the steer application (s), t_1 is the termination time of steer application (s), δ is the steer angle (deg), δ_0 is the initial value of the steer angle (deg) and δ_1 is the final value of the steer angle (deg). The function shown in Equation (4) is known as the Haversine function. The Haversine function is one of the common functions within the list of mathematical functions available within ADAMS/View function builder. It has the format: "HAVSIN (x, x0, h0, x1, h1)". The variable "x" is replaced by time, with "x0" being the numerical value of t_0; "x1" being the numerical value of t_1; "h0" being the initial value of the steer angle, δ_0, and "h1" being the final value of the steer angle, δ_1. For the simulation, the steer angle was increased from 0°to 1° in a time duration of 0.25 s. The Haversine function ("HAVSIN (x, x0, h0, x1, h1)") was used at each steer revolute joint, but with different signs for the left and right steer wheels. The step steer manoeuvre was simulated at a vehicle speed of 100 km/h. Figure 10 shows the shape of the step steer input that was imposed on the steer revolute joints.

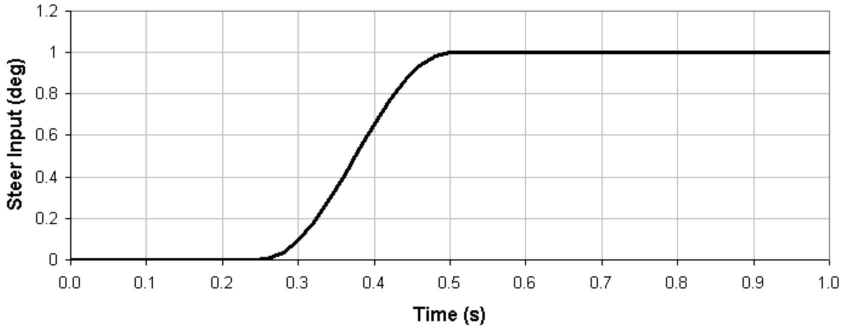


Figure 10: Step steer input based on the Haversine function [11]

For the pulse steer manoeuvre, two Haversine functions, of the format “HAVSIN (x, x0, h0, x1, h1)”, were added together, in order to produce the pulse shape. The steer angle was increased from 0˚ to 10˚ and then from 10˚ to 0˚ over a 0.5 s time duration. The pulse steer manoeuvre was simulated at a speed of 100 km/h. The shape of the pulse steer motion that was implemented on the steer revolute joints is shown in Figure 11 [11].

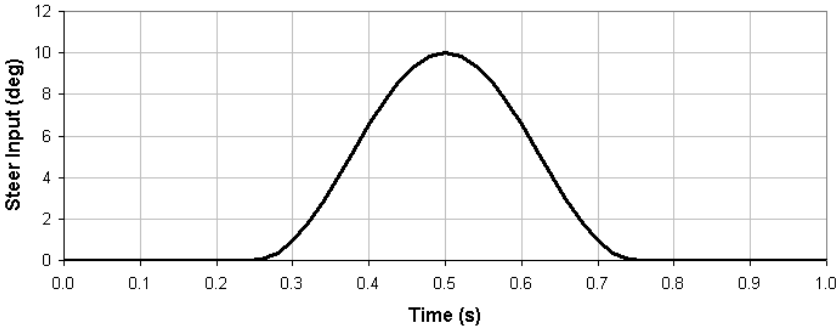


Figure 11: Pulse steer input based on the Haversine function [11]

Closed loop controllers

The two closed loop control manoeuvres that were simulated were the SAE lane change and the 90˚ low speed turn. For the SAE lane change [21], the vehicle must follow the path described in Figure 12.

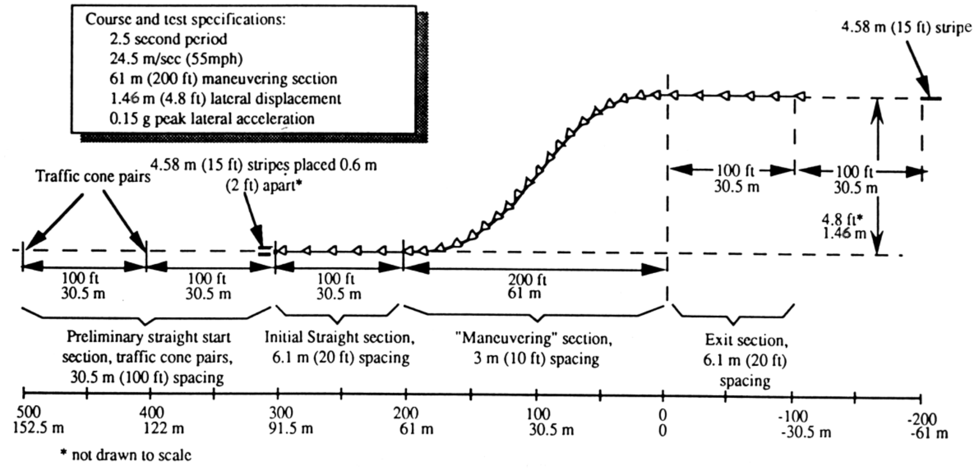


Figure 12: SAE J2176 single lane change manoeuvre [21]

The vehicle is driven at a speed of 88 km/h (by the velocity controller) on a straight segment that is approximately 100 m in length. The vehicle is required to execute a lane change manoeuvre from a precisely prescribed path over a distance of 61 m. The lateral displacement for the lane change manoeuvre is 1.46 m. The controller used to execute this manoeuvre was a lateral position comparator i.e. the lateral position of the tractor of the vehicle was measured and compared to the desired prescribed SAE lane change path that is described in Figure 12, at regular longitudinal positions. This was accomplished by creating a spline of the desired SAE lane change path co-ordinates and importing it into ADAMS/View. A measure was created on the preview marker to measure the vehicles x and y co-ordinates. The actual and desired lateral co-ordinates of the vehicle were subtracted from each other. The resulting difference is the error which was used to change the steer angle at the steer revolute joints. Equation (5) describes the control algorithm for the SAE lane change manoeuvre.

$$\delta = K_{LC} \cdot (y_a - y_d) \tag{5}$$

In Equation (5), δ is the controlled steer angle; K_{LC} is the lane change proportional gain; y_a is the measured (actual) lateral co-ordinate of the tractor (measured at the preview marker); and y_d is the desired lateral co-ordinate of the tractor from the spline that was created for the SAE lane change. The lateral co-ordinates are compared at the same longitudinal positions.

For the 90˚ low speed turn, the centre of the steer axle must follow a path that is made of a straight segment that leads into a circular 90˚ arc with an 11.25 m radius (which is tangent to the straight segment). The curve then leads onto a straight exit segment. The vehicle was maintained at a speed of 10 km/h. A similar controller to the SAE lane change was developed but was different in that the yaw angle of the vehicle was also controlled. The control algorithm for the 90˚ low speed turn is given by Equation (6).

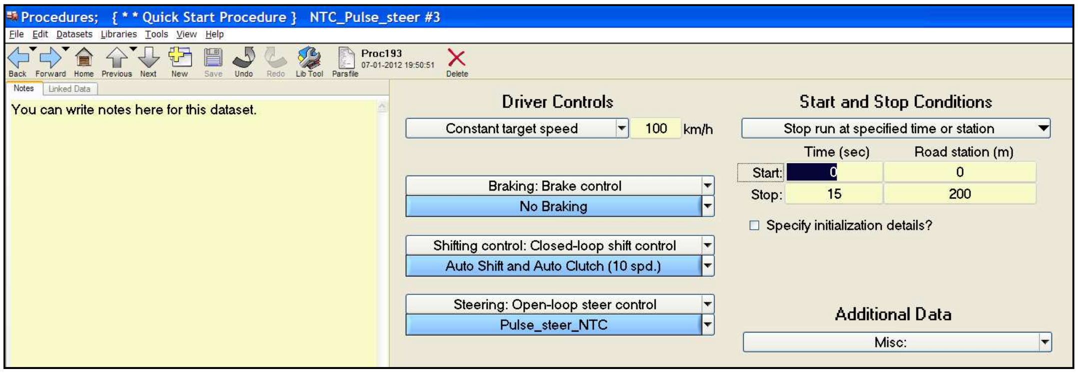
$$\delta = K_{LS} \cdot (y_a - y_d) + K_{yaw} \cdot (\varphi_a - \varphi_d) \tag{6}$$

In Equation (6), all symbols have the same definition as mentioned in Equation (5), except that K_{LS} is the proportional gain for the lateral co-ordinate error; K_{yaw} is the proportional gain for the yaw angle comparison; φ_a is the actual (measured) yaw angle of the tractor; and φ_d is the desired yaw angle which was determined from the slope (tangent) of the desired path spline.

4.3.2 TruckSim Vehicle Controllers

Velocity controller

It was not necessary to create a velocity controller in TruckSim from scratch. The velocity required was simply specified within the "Procedure" area (found on the TruckSim "Run Control" screen). Within this area, the vehicle velocity can be defined under "Driver Controls", as shown in Figure 13.



You can write notes here for this dataset.

Driver Controls

Constant target speed 100 km/h

Braking: Brake control
No Braking

Shifting control: Closed-loop shift control
Auto Shift and Auto Clutch (10 spd.)

Steering: Open-loop steer control
Pulse_steer_NTC

Start and Stop Conditions

Stop run at specified time or station

	Time (sec)	Road station (m)
Start:	0	0
Stop:	15	200

☐ Specify initialization details?

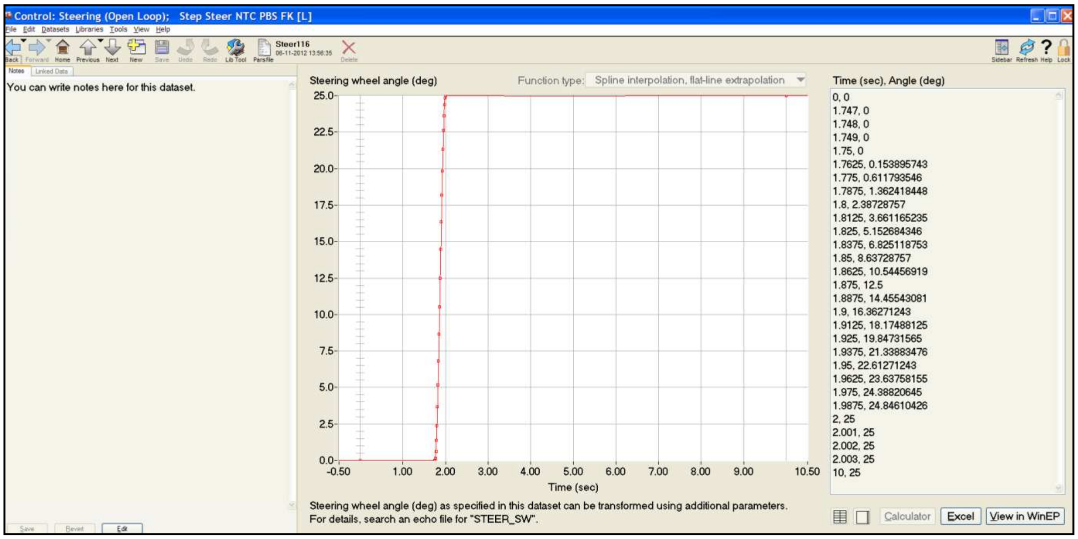
Additional Data

Misc:

Figure 13: Velocity control in TruckSim

Open loop steer controllers

The two open loop manoeuvres have already been discussed in Section 3.3.1. To simulate a step steer input in TruckSim, an open-loop control steering procedure was selected under the “Driver Controls” section. A step-steer was selected by defining a spline for the steer angle. This was done directly within TruckSim. This is shown in Figure 14.



You can write notes here for this dataset.

Function type: Spline interpolation, flat-line extrapolation

Time (sec), Angle (deg)

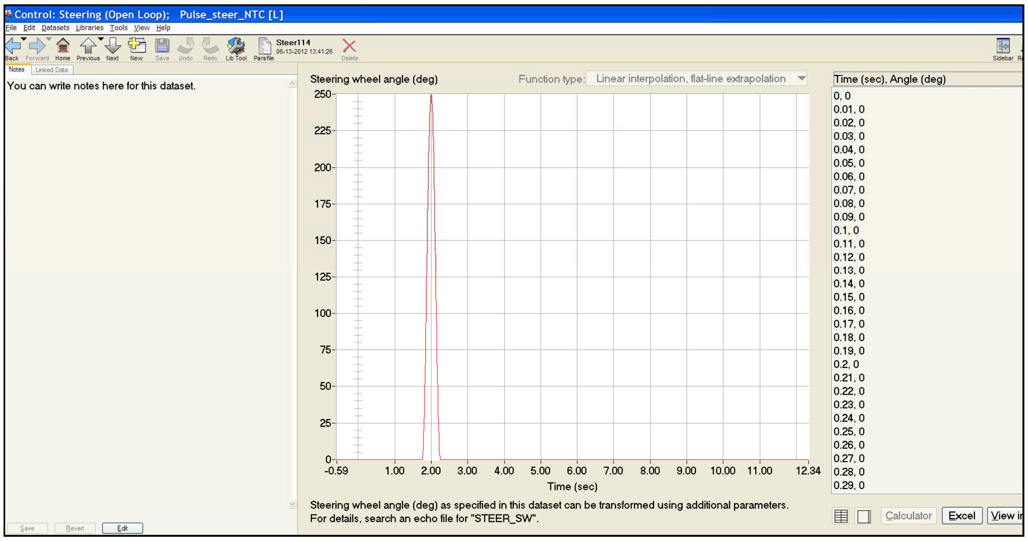
0, 0
1.747, 0
1.748, 0
1.749, 0
1.75, 0
1.7625, 0.153895743
1.775, 0.611793546
1.7875, 1.362418448
1.8, 2.38728757
1.8125, 3.661165235
1.825, 5.152684346
1.8375, 6.825118753
1.85, 8.63728757
1.8625, 10.54456919
1.875, 12.5
1.8875, 14.45543081
1.9, 16.36271243
1.9125, 18.17488125
1.925, 19.84731565
1.9375, 21.33883476
1.95, 22.61271243
1.9625, 23.63758155
1.975, 24.38820645
1.9875, 24.84610426
2, 25
2.001, 25
2.002, 25
2.003, 25
10, 25

Steering wheel angle (deg) as specified in this dataset can be transformed using additional parameters.
For details, search an echo file for "STEER_SW".

Figure 14: Creating a step-steer input in TruckSim

In Figure 14, it can be seen that the steering wheel angle was increased from 0° to 25°in a time period of 0.25 s. Since the steering ratio was specified at 25:1, the steer angle on the wheels was actually increased from 0° to 1° in 0.25 s.

The pulse steer manoeuvre was defined in a similar way to the step steer manoeuvre. The spline created for this is shown in Figure 15.



Control: Steering (Open Loop); Pulse_steer_NTC [L]

Steer114
06-13-2012 13:41:26

You can write notes here for this dataset.

Function type: Linear interpolation, flat-line extrapolation

```
Time (sec), Angle (deg)
0, 0
0.01, 0
0.02, 0
0.03, 0
0.04, 0
0.05, 0
0.06, 0
0.07, 0
0.08, 0
0.09, 0
0.1, 0
0.11, 0
0.12, 0
0.13, 0
0.14, 0
0.15, 0
0.16, 0
0.17, 0
0.18, 0
0.19, 0
0.2, 0
0.21, 0
0.22, 0
0.23, 0
0.24, 0
0.25, 0
0.26, 0
0.27, 0
0.28, 0
0.29, 0
```

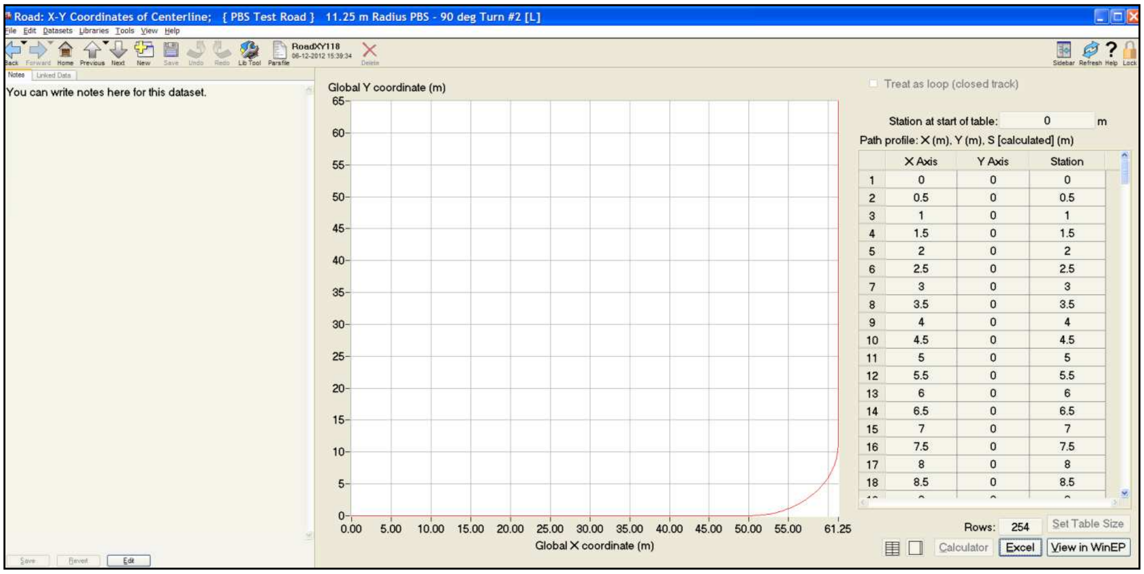
Steering wheel angle (deg) as specified in this dataset can be transformed using additional parameters.
For details, search an echo file for "STEER_SW".

Figure 15: Creating a pulse-steer input in TruckSim

Again, since the steer ratio is 25:1, the actual steer wheel angle is changed from 0° to 10°to 0° in 0.5 s, although the input steering wheel angle changes from 0° to 250°to 0°in 0.5 s.

Closed-loop steer controllers

For the closed-loop controllers, the user defines the driver path follower (as opposed to defining the steer motion described for the open-loop control). Splines were imported to define the paths. In addition, the preview distance for the controller was defined directly on the user interface. Figure 16 shows the driver path follower that was created in TruckSim for the 90° low speed turn.



Road: X-Y Coordinates of Centerline; { PBS Test Road } 11.25 m Radius PBS - 90 deg Turn #2 [L]

RoadXY118 06-12-2012 15:39:34

You can write notes here for this dataset.

☐ Treat as loop (closed track)

Station at start of table: 0 m

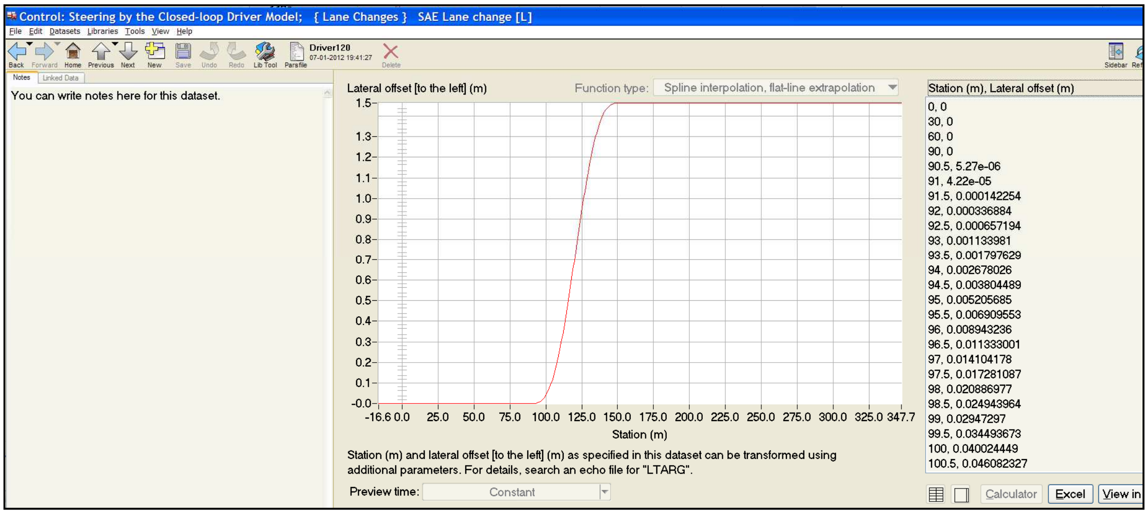
Path profile: X (m), Y (m), S [calculated] (m)

	X Axis	Y Axis	Station
1	0	0	0
2	0.5	0	0.5
3	1	0	1
4	1.5	0	1.5
5	2	0	2
6	2.5	0	2.5
7	3	0	3
8	3.5	0	3.5
9	4	0	4
10	4.5	0	4.5
11	5	0	5
12	5.5	0	5.5
13	6	0	6
14	6.5	0	6.5
15	7	0	7
16	7.5	0	7.5
17	8	0	8
18	8.5	0	8.5

Rows: 254

Figure 16: TruckSim driver path follower for the 90˚ low speed turn

Similarly, the driver path follower for the SAE lane change was created as shown in Figure 17.



Control: Steering by the Closed-loop Driver Model; { Lane Changes } SAE Lane change [L]

Driver120 07-01-2012 19:41:27

You can write notes here for this dataset.

Function type: Spline interpolation, flat-line extrapolation

Station (m), Lateral offset (m)

0, 0
30, 0
60, 0
90, 0
90.5, 5.27e-06
91, 4.22e-05
91.5, 0.000142254
92, 0.000336884
92.5, 0.000657194
93, 0.001133981
93.5, 0.001797629
94, 0.002678026
94.5, 0.003804489
95, 0.005205685
95.5, 0.006909553
96, 0.008943236
96.5, 0.011333001
97, 0.014104178
97.5, 0.017281087
98, 0.020886977
98.5, 0.024943964
99, 0.02947297
99.5, 0.034493673
100, 0.040024449
100.5, 0.046082327

Station (m) and lateral offset [to the left] (m) as specified in this dataset can be transformed using additional parameters. For details, search an echo file for "LTARG".

Preview time: Constant

Figure 17: TruckSim driver path follower SAE single lane change

4.3.3 Yaw/Roll Vehicle Controllers

Yaw/Roll is only capable of constant velocity manoeuvres. It was not necessary to develop any velocity controller. The forward velocity required (in feet/second) is specified exactly in the third line of code in the input code.

The steering of the vehicle can be controlled in two ways [17]:

- Steer angle: The steering input can be controlled by definition of a time versus steer angle table. If this option is used, a positive value equal to the number of lines in the time/steer angle table is entered in the 377th line. The 378th line is skipped and the first line of entry starts on the 379th line of the input code. The required steer angle is entered alongside the time value, line by line.
- Driver model: This method makes use of specifying the prescribed path which the vehicle is to follow. This option is activated by entering a negative number on the 377th line of the input code, with the numerical value equal to the number of lines in the table defining the desired trajectory. The path is defined by entering two values (a longitudinal co-ordinate and corresponding lateral co-ordinate, consecutively) per line from the 379th line of code. The units for the values are to be entered in feet. The table should begin with 0, 0 and extend for a longitudinal distance equal to or greater than the distance the vehicle will travel during the simulation, plus the distance equivalent to the driver preview interval (which is defined in line 378 of the input code).

In Yaw/Roll, the preview distance as well as the driver transport lag can be defined for the vehicle controllers. Again, this is done by entering the numerical values in the correct position within in the Yaw/Roll input file.

5 MATHEMATICAL SOLVER COMPARISON

The following sections describe the various mathematical solvers that are available in ADAMS/View, TruckSim and Yaw/Roll.

5.1 ADAMS/View

ADAMS makes use of differential algebraic equations for the model formulation. This means that ADAMS/View deals with a large number of variables compared to solvers for ordinary differential equations (ODEs). This also means that ADAMS/View takes longer to complete a simulation than a software package that deals with ODEs. A benefit of ADAMS/View using differential algebraic equations is that every force, displacement, velocity, and acceleration can be simulated in the model. The step size of the solver can be adjusted for the accuracy and time required for the simulation. ADAMS/View has a number of options for integrators that can be used in the solver and each have their individual advantages. There are options for forward explicit integrators and also backward implicit integrators [22]. Generally, explicit integrators tend to be less stable than the implicit integrators.

The integrators available in ADAMS/View are stiff integrators. A system is classified as stiff when $\frac{\textit{highest overdamped eigenvalue}}{\textit{highest underdamped eigenvalue}} > 200$.

Each integrator has various indices, which can be selected. The integrator index defines the amount of times the equations are to be differentiated to get a system of ordinary differential equations. The higher the index, the more challenging it is for the solver to converge. For some solvers there is an option that reduces the original index-3 (I3) problem to an analytical equivalent index-2 (I2) problem. Index-2 is a slower option, but is more robust and accurate.

Although the different integrators are described in the MSC ADAMS help files, Figure 18 classifies the various integrators that are available in ADAMS/View according to solver speed, robustness and accuracy, which will not be seen in the help files. The classification has been given by an MSC ADAMS software representative at an ADAMS/Solver advanced modelling seminar [22]. The GSTIFF and WSTIFF integrators are quite similar.

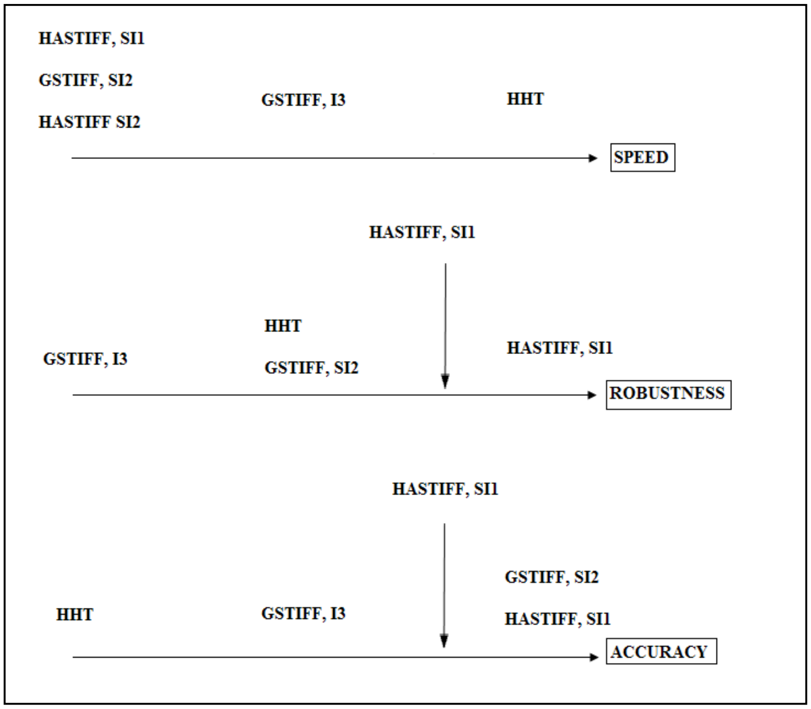


Figure 18: Integrator classification in ADAMS/View [22]

A GSTIFF, SI2 numerical integrator was selected, with a time step of 1e-03 seconds for the simulation of the B-double truck in this study.

5.2 TruckSim

TruckSim makes use of ordinary differential equations for the model formulation, which means that the solver has to deal with less variables at each iteration of the simulation. The benefit of this is that it would take less time to run a simulation in TruckSim than in a package which uses differential algebraic equations for the model formulation. The drawback of this is that the evaluator does not have access to as many variables (in the results) as one would have in a package which solves differential algebraic equations.

5.3 Yaw/Roll

Yaw/Roll being the predecessor of TruckSim, also solves differential equations of motion and uses a predictor corrective integration method for solving the equations of motion [17]. There are no options to select different solver/integrator methods within Yaw/Roll.

6 SOFTWARE COST COMPARISON

Table 4 is a comparison of the costs of the three different software, used in this research. The costs are from quotations provided by credible software distribution companies. Yaw/Roll is freely available. The costs for TruckSim 8.0 and ADAMS/View 2011 and software support, for one year, are shown in Table 4. TruckSim is vehicle modelling specific, less flexible, requires less user effort, but has a higher cost. On the other hand, ADAMS/View, is used for general mechanical systems dynamic analysis, more flexible, requires more user effort for vehicle modelling, but has a slightly lower cost. Although Yaw/Roll is freely available, it requires a larger amount of user effort and is not as flexible. There are a number of simplifications that were made when designing the software [17].

Table 4 Software Package Purchase Costs

Yaw/Roll	ADAMS/View	TruckSim 8.0
$0	$31,673	$32,625

7 SOFTWARE OUTPUT COMPARISON

In this section, the software packages' outputs are compared to evaluate the agreement of the results from the four manoeuvres that have been simulated. As noted in Section 3, these four manoeuvres were selected (as discussed by Prem *et al.* [11]) because they were designed to test for specific performance attributes of a vehicle and thus reveal the different aspects of the vehicle models and controllers. I.e. to evaluate the software packages, it was not necessary to simulate every PBS manoeuvre.

7.1 SAE Lane Change

Figure 19 and Figure 20 show the respective yaw rate and lateral acceleration of the vehicle units during the SAE lane change. The results show good agreement between the three software packages.

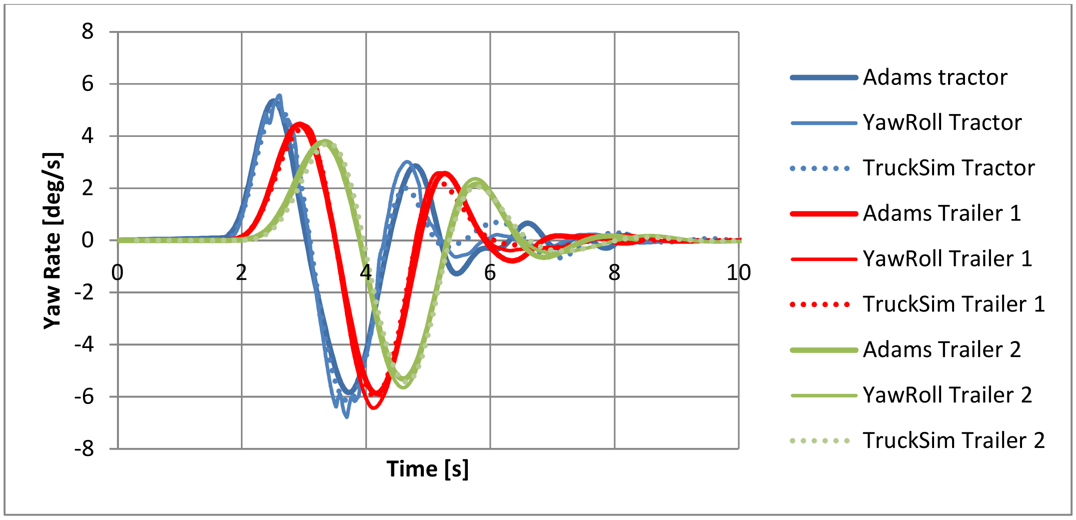


Figure 19: SAE lane change: yaw-rate

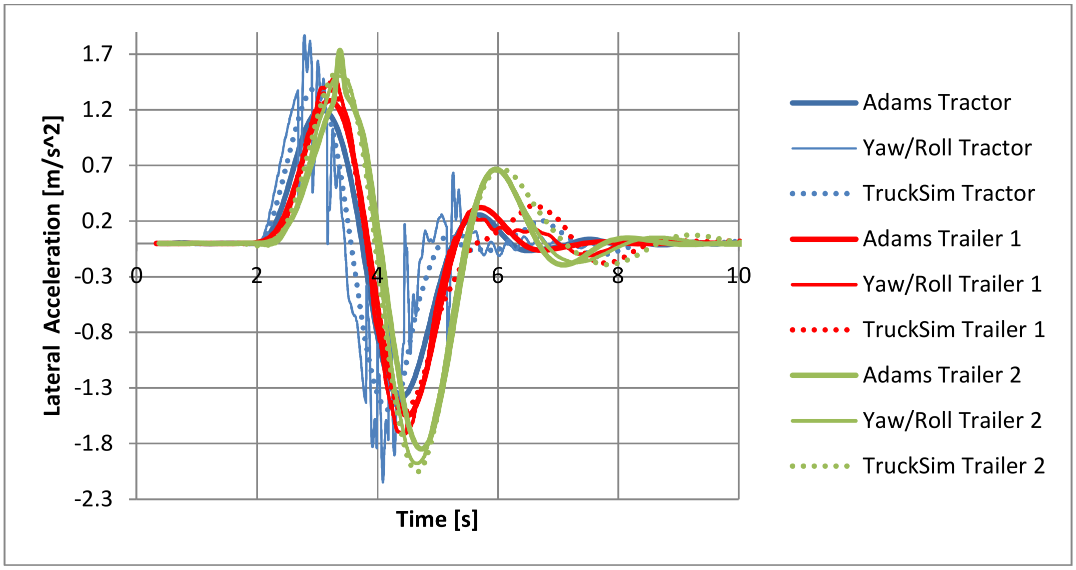


Figure 20: SAE lane change: lateral acceleration

7.2 90˚ Low Speed Turn

Figure 21 shows the paths of the steer, drive, and trailer axles during the 90° low speed turn. The centre points of the axles are plotted and the trailer axles are for the rearmost axle. There is excellent agreement between the software packages.

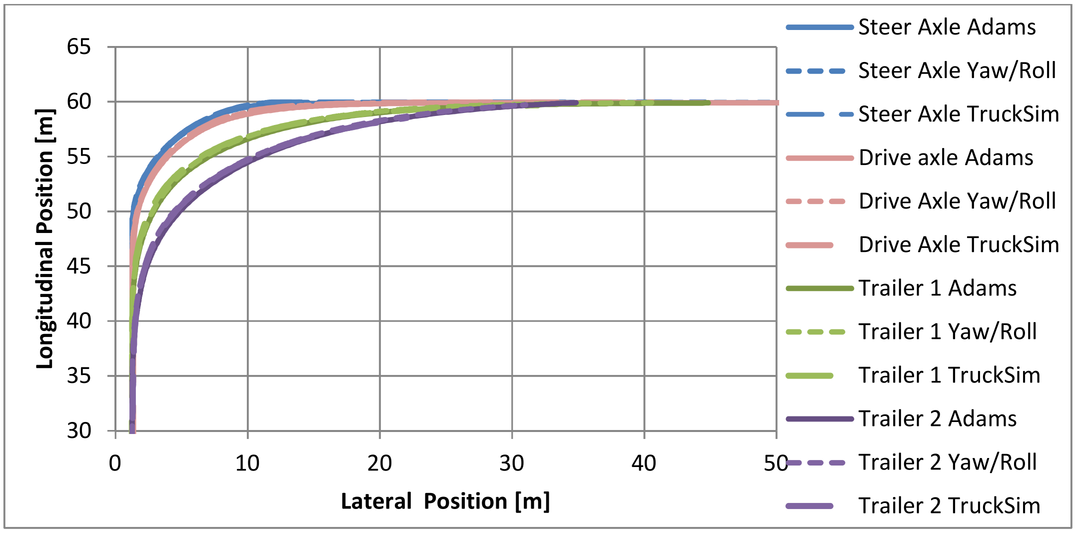


Figure 21: 90˚ low speed turn

7.3 Pulse Steer

Figures 21 to 24 show the respective articulation angles between the units of the vehicle, yaw rates, lateral accelerations, and lateral tyre slip of the vehicle. There is good agreement between the software packages as shown by how similar the output curves are.

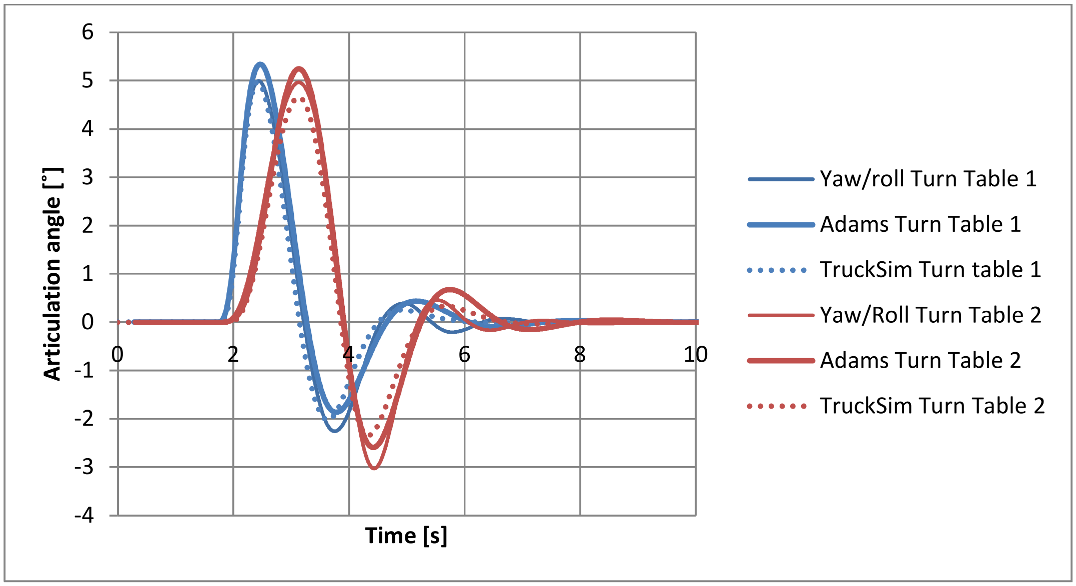


Figure 22: Pulse steer: articulation angle

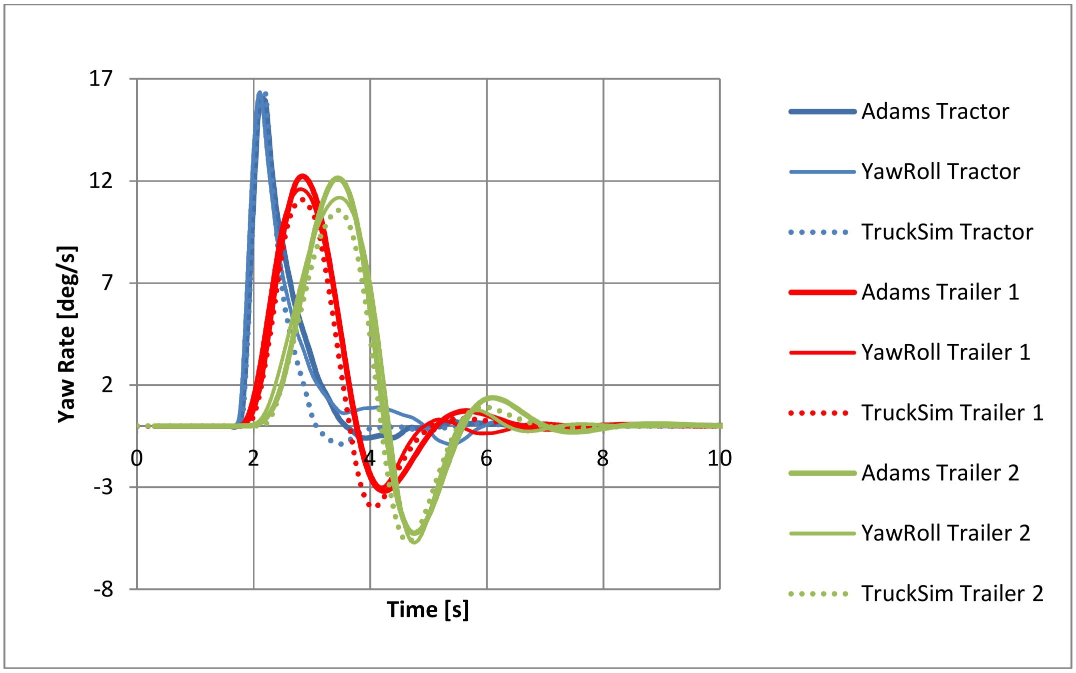


Figure 23: Pulse steer: yaw-rate

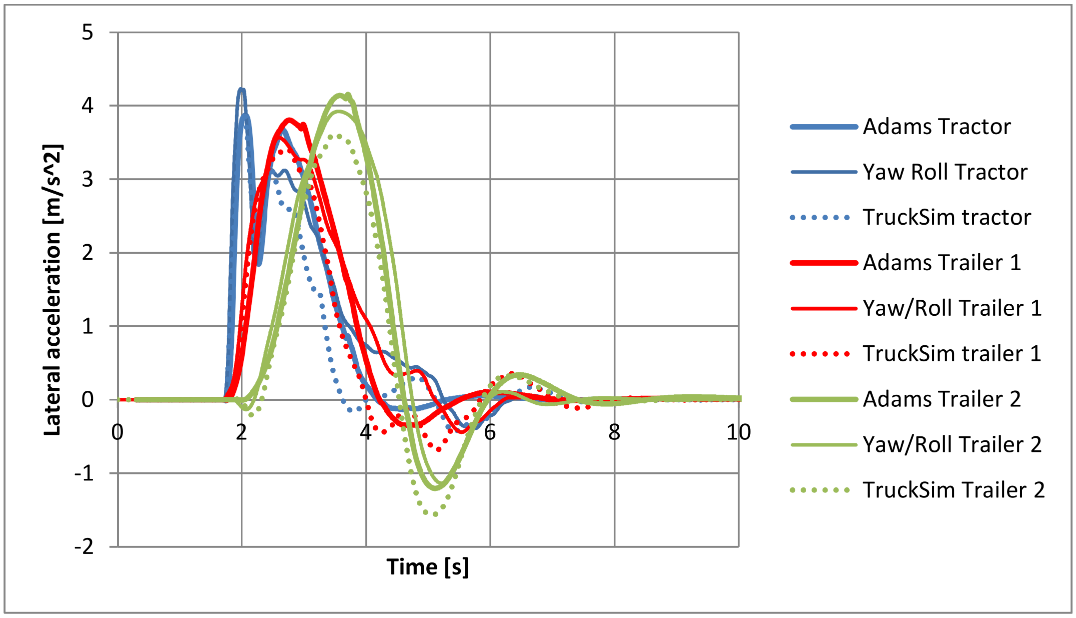


Figure 24: Pulse steer: lateral acceleration

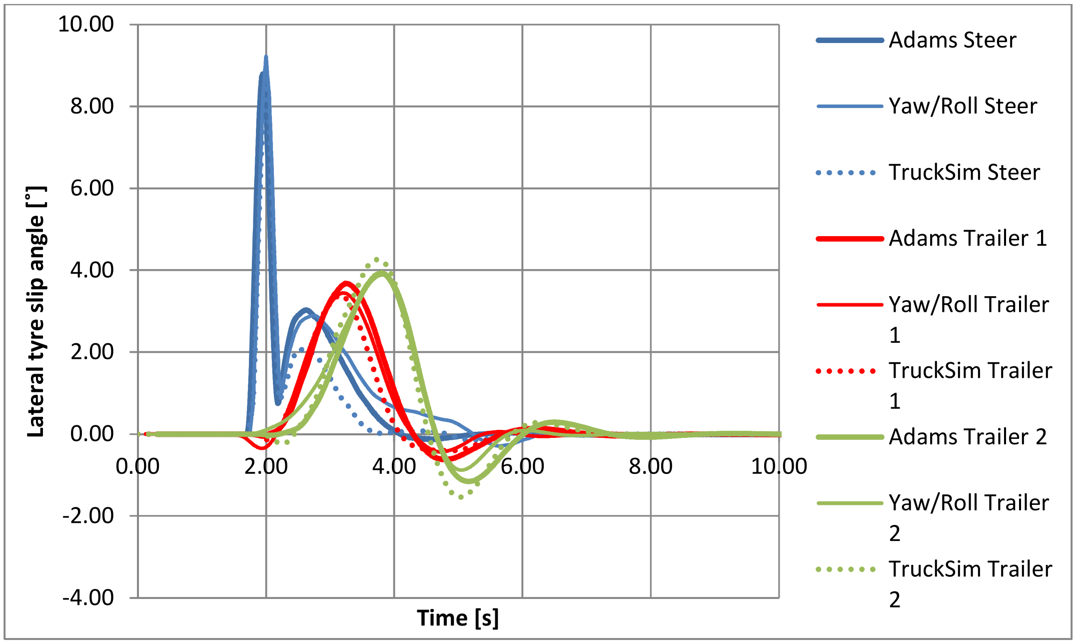


Figure 25: Pulse steer: lateral tyre slip angle

7.4 Step Steer

Figure 26 shows the yaw rates of the vehicle units during the step steer input. There is excellent agreement between the software packages.

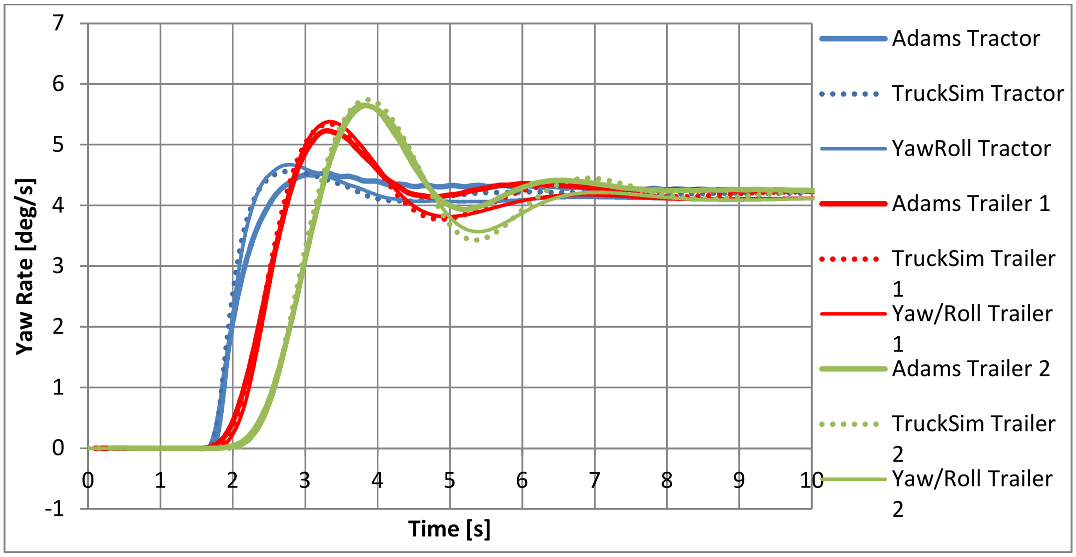


Figure 26: Step steer: yaw-rate

8 DISCUSSION

8.1 Ease-of-use

The ease-of-use of the software focused on the time and effort to build a model, the solver time, animation, system of units and the flexibility of the package.

Of the three software packages evaluated, ADAMS/View required the most user effort to build a vehicle model able to evaluate PBS compliance. The geometry of the truck defining the relationships between the moving bodies of the truck system needed to be developed. The gains and structure for a longitudinal speed controller and driver model needed to be designed by defining the mathematical relationships of the drive torque and steering in terms of the vehicle states. ADAMS/View provides a number of tyre models, which require tyre parameter or coefficients to be entered. The package was not able to directly read in the tyre side force and tyre aligning moment tables presented by Prem *et al*. [11]. A regression analysis was performed on these tables to determine the coefficients of the magic tyre formula which were entered into ADAMS. The Pacejka 89' model [19] was used.

The ADAMS software developers, MSC Software, have developed a module, ADAMS/Car, specifically for vehicle dynamics studies. The module includes speed controllers, driver models, event builders, road builders, and preconfigured vehicle configurations including a truck and trailer assembly. The module addresses the significant effort required to build a vehicle model using ADAMS/View. However, the ADAMS/Car software package costs more than the ADAMS/View software package. The ADAMS/View package (i.e. ADAMS/View and the required ADAMS/Solver) is approximately half the cost of the ADAMS/Car package (i.e. ADAMS/Solver, ADAMS/View, ADAMS/Tire and ADAMS/Car). ADAMS/View is required for ADAMS/Car.

Yaw/Roll required an intermediate user effort. The need to convert parameters from metric to Imperial units to analyse the vehicle and converting the results back into metric units was time-consuming. Furthermore, the text input files, DOS operating system, and rigid rules governing number formatting were difficult to work with. The text file input must conform exactly to the input format requirements i.e. even an extra trailing zero added to an input parameter or a spurious space will cause an error. Substantial care was required to correctly enter the vehicle data into the text file. Yaw/Roll was the most limited of the software packages evaluated: the modelled vehicle was limited to a maximum of four vehicle units and eleven axles and the road surface was constrained to be flat. The latter restriction precludes the use of Yaw/Roll to calculate the tracking ability on a straight path PBS measure, which requires the vehicle to traverse an uneven surface.

TruckSim required the least user effort to build a vehicle model compared to ADAMS and Yaw/Roll. The vehicle details were captured in easy to use data screens. The modelled vehicle was limited to thirteen vehicle and axle configurations (See Section 4.2.2); although add-on modules expanding the vehicle configurations could be purchased.

Using a standard PC of average computational power (with 3.24 GB of RAM at 1.17 GHz and a 280 GHz processor), the ADAMS/View model solved in approximately two to five minutes, the TruckSim model in half a minute and the Yaw/Roll model in approximately two seconds.

Both ADAMS and TruckSim offer sophisticated post-processor animation capabilities which allow the vehicle motion to be viewed as a video. Yaw/Roll cannot animate the vehicle motion. The animations were found to be extremely useful in debugging models as well as convincing the South African road authorities and truck operators of the benefits of PBS and the fidelity of the simulation results.

8.2 Flexibility

ADAMS offers a choice of systems of units (including metric and Imperial). TruckSim uses metric units. The vehicle model in Yaw/Roll must be entered in British- American units. This was found to be particularly frustrating as the vehicle input parameters needed to be converted.

Of the software packages evaluated, ADAMS/View offered the most flexibility. There are no limitations in ADAMS on the number of vehicle units or axles that can be modelled. Yaw/Roll is limited to modelling a maximum of four vehicle units (including dollies) and eleven axles. The Yaw/Roll user-manual, [17], lists a number of assumptions made by Yaw/Roll. The most important of these is that the road surface must be flat and horizontal, damping in the tyre is assumed to be small with no tyre relaxation length being modelled, the suspension damping is considered to be linear and no load sharing occurs between axles. A further drawback is that Yaw/Roll must be run using the DOS operating system or else a DOS emulator must be used. The TruckSim solvers are optimised for each vehicle and axle configuration. The standard package offers the thirteen configurations shown in Table 3. If a vehicle and axle configuration not listed in Table 3 is required then this configuration must be purchased as an add-on.

The Yaw/Roll restrictions on vehicle configurations and the need to buy expanded vehicle configurations as add-on modules in TruckSim are factors to consider when evaluating the software's cost effectiveness for PBS analyses. PBS encourages innovation to improve vehicle safety and productivity and the innovative vehicle solutions may not conform to standard configurations.

8.3 Mathematical Solver Comparison

ADAMS/View solves differential algebraic equations when simulating a multi-body dynamic system. This means that ADAMS/View deals with more variables than an ordinary differential equation solver. This allows the user to have access to every force, displacement, velocity, and acceleration for each component in the model.

TruckSim solves ordinary differential equations when simulating a manoeuvre. It deals with less variables than a differential algebraic equation solver. This means that it takes less time to solve the equations of motion. However, the drawback is that the user cannot view every force, displacement, velocity, or acceleration.

Yaw/Roll also solves differential equations of motion and uses a predictor corrective integration method for solving the equations of motion. The user cannot view every force, displacement, velocity, or acceleration for each component of the model.

8.4 Software Output Comparison

There is good agreement between the software packages as seen from the results of the yaw rate, lateral accelerations, tyre slip angles, and articulation angles of the vehicle units for the SAE lane change, pulse steer input and step steer input; and the positions of the steer axle, drive axle, trailer 1 and trailer 2 for the 90° low speed turn. For the SAE lane change, the high frequency variation of the Yaw/Roll results (See Figure 20) is due to the irregular and rough steering of the Yaw/Roll driver model.

It is important to note that the accuracy of a computational model is highly dependent on the quality of the vehicle input data used when defining the vehicle parameters. It is thus recommended that the PBS evaluator take great care that the vehicle input dataset is complete and is accurate before conducting a computational model.

8.5 Cost

The purchase cost of either ADAMS or TruckSim is just over $30,000. This includes software support for one year. Yaw/Roll is freely available. This is the main advantage of the Yaw/Roll software. The beginner PBS analyst, evaluating the best choice of software package must decide if the increased flexibility and ease-of-use justifies the cost of commercial software.

8.6 General

It is left to the vehicle dynamics analyst to decide whether increased flexibility and ease-of-use are justifiable. Again, it should be noted that the accuracy of any computational model is highly dependent on the accuracy of the input data of the vehicle. It is, therefore, important to ensure that the input data of the vehicle are accurately known.

9 CONCLUSIONS

- Three software packages (ADAMS, Yaw/Roll and TruckSim) were successfully evaluated for the suitability to evaluate PBS compliance of vehicles. The evaluation was in part subjective but it is hoped the study provided useful insight. In summary, the evaluation results are that:
  - ADAMS is the most flexible
  - Yaw/Roll is the cheapest
  - TruckSim is the easiest to use

- There is good agreement between each of the software packages.

- ADAMS and TruckSim are capable of evaluating all the PBS measures required for an assessment. Yaw/Roll is able to evaluate almost all PBS performance measures; the Yaw/Roll limitation that the road must be flat would preclude its use to evaluate tracking ability on a straight path.

- In developing vehicle models in ADAMS, Yaw/Roll and TruckSim, the expertise to evaluate PBS compliance in South Africa has been extended. The results of this study will assist the beginner PBS analyst in evaluating the best software package for analysis.

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APPENDIX A: Tyres

A.1. Tyre characteristics

Table A.1 and Table A.2 tabulate the tyre side force and self-aligning moment characteristics that were used on the B-double vehicle by the NTC.

Table A.1: Tyre side force characteristics [11]

Slip Angle (deg)	Vertical Force (N)		
	8,821	26,544	41,998
	Lateral Force(N)		
1.00	1,587.8	3,716.2	4,199.3
2.00	2,822.8	7,166.9	7,979.6
4.00	4,763.5	12,475.6	15,119.2
8.00	6,792.4	17,519.0	23,098.8
12.00	8,027.4	19,377.1	25,618.7

Table A.2: Tyre Aligning torque characteristics [11]

Slip Angle (deg)	Vertical Force (N)				
	8,899	17,710	26,564	35,375	42,005
	Aligning Torque (Nm)				
1.00	38.0	115.3	199.4	280.7	339.1

2.00	59.7	193.9	356.7	520.8	634.7
4.00	74.6	255.0	491.0	759.5	972.4
8.00	50.2	195.3	366.2	599.5	802.9
12.00	28.5	123.4	246.8	404.2	522.2

A.2 ADAMS/View Tyre property file

The text below is the tyre property file that was modified to be an input into ADAMS/View 2011 for the B-double vehicle. The coefficients determined by the curve fit (from a regression analysis using the Pacejka ’89 tyre model) are shown within this file:

```
$---------------------------------------------------------------------MDI_HEADER
[MDI_HEADER]
 FILE_TYPE     =  'tir'
 FILE_VERSION  =  2.0
 FILE_FORMAT   =  'ASCII'
(COMMENTS)
{comment_string}
'Tire      - XXXXXX'
'Pressure  - XXXXXX'
'Test Date - XXXXXX'
'Test tire'
'New File Format v2.1'
$--------------------------------------------------------------------------UNITS
```

```
[UNITS]
 LENGTH              = 'mm'
 FORCE               = 'newton'
 ANGLE               = 'radians'
 MASS                = 'kg'
 TIME                = 'sec'
$---------------------------------------------------------------------MODEL
[MODEL]
! use mode    1   2   3   4    11   12   13   14
! ------------------------------------------------------------------
! smoothing          X   X             X    X
! combined       X       X        X         X
! transient              X    X    X    X
!
 PROPERTY_FILE_FORMAT    = 'PAC89'
 USE_MODE                = 14.0
 TYRESIDE                = 'LEFT'
$------------------------------------------------------------------DIMENSION
[DIMENSION]
 UNLOADED_RADIUS         = 525
 WIDTH                   = 300.0
 ASPECT_RATIO            = 0.75
$------------------------------------------------------------------PARAMETER
[PARAMETER]
 VERTICAL_STIFFNESS      = 788.112
```

```
 VERTICAL_DAMPING        = 0.0
 LATERAL_STIFFNESS       = 190
 ROLLING_RESISTANCE      = 0.0
$------------------------------------------------------------------------shape
[SHAPE]
{radial width}
 1.0    0.0
 1.0    0.2
 1.0    0.4
 1.0    0.5
 1.0    0.6
 1.0    0.7
 1.0    0.8
 1.0    0.85
 1.0    0.9
 0.9    1.0
$---------------------------------------------------------LATERAL_COEFFICIENTS
[LATERAL_COEFFICIENTS]
 a0  =  1.3
 a1  = -10.158
 a2  =  999.633
 a3  =  4419.32
 a4  =  64.25803
 a5  =  0
 a6  =  0.0385
```

```
 a7  =  -3.29155
 a8  =  0
 a9  =  -0.01176
 a10 =  0.38915
 a11 =  0
 a12 =  -4.90888
 a13 =  395.8012
$--------------------------------------------------------------longitudinal
[LONGITUDINAL_COEFFICIENTS]
 b0  =  1.65
 b1  =  2
 b2  =  354
 b3  =  7
 b4  =  13.5
 b5  =  0.00954
 b6  =  -0.0173
 b7  = -0.06391
 b8  =  0.199864
 b9  =  0.0299
 b10 = -0.17600
$-----------------------------------------------------------------aligning
[ALIGNING_COEFFICIENTS]
 c0  =  1.7
 c1  =  0.338806
 c2  =  9.483614
```

c3 = -0.04675

c4 = 2.941738

c5 = -0.04698

c6 = 0

c7 = 0.001705

c8 = -0.14752

c9 = -2.645129483

c10 = 0

c11 = 0

c12 = -0.17024

c13 = 46.6223

c14 = 0

c15 = 0

c16 = -0.0112

c17 = 0.56516

APPENDIX B: B-double (Input Dataset) [11]

B.1 Layout Drawing

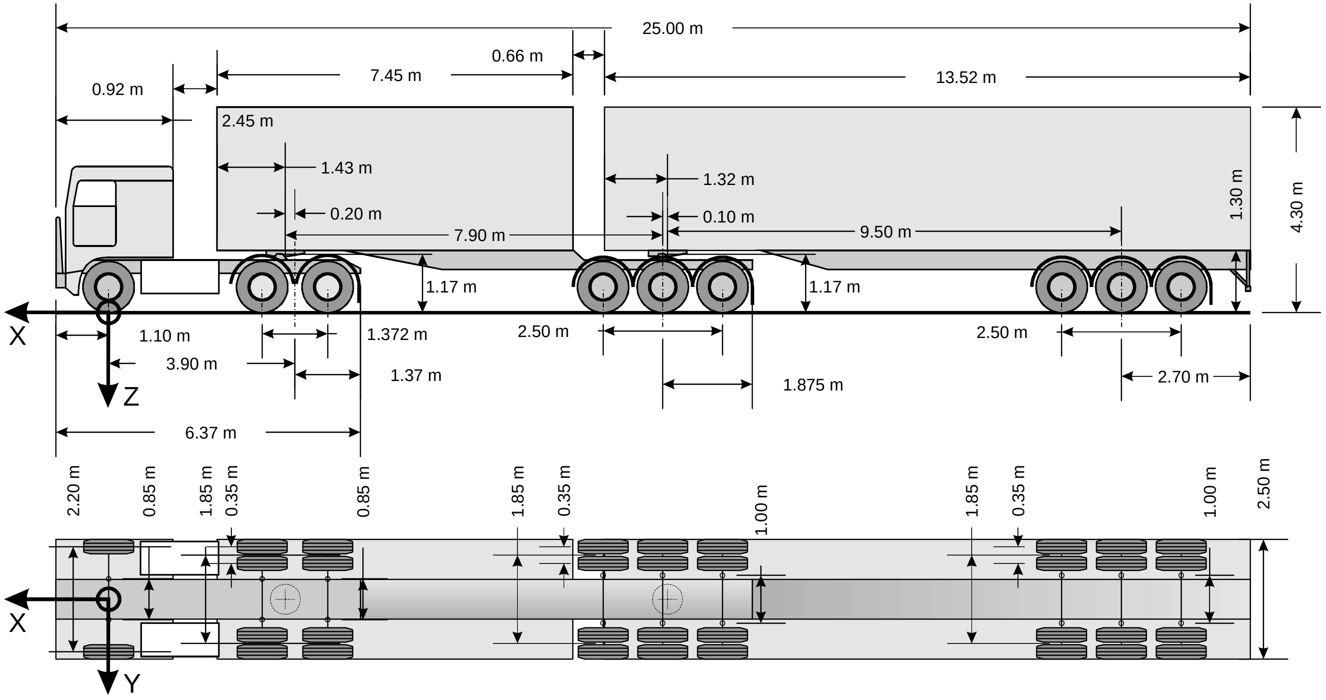


Fig. B1 Layout drawing for the reference B-double.

B.2 Dimensions

B.2.1 Sprung Masses

Table B2.1 – Key Dimensions for Sprung Masses (B-double)

Dimension	Prime Mover	Trailer 1	Trailer 2	Vehicle
Front overhang (m)	1.10	1.43	1.32	
Wheelbase and S-dimension (m)	3.90	7.90	9.50	
Kingpin lead (m)	0.20	-0.10		
Rear overhang (m)	1.37	1.875	2.70	
Overall length (m)	6.37	11.205	13.52	25.00
Cabin and load length (m)	2.45	7.45	13.52	
Space between units (m)	0.92	0.66		
Kingpin to rear (m)				20.20
Width (m)	2.50	2.50	2.50	
Height (m)	3.30	4.30	4.30	
Deck height (m)		1.30	1.30	
Load volume (m^3)		55.875	101.4	157.275
Number of pallets (1170 mm x 1170 mm)		12	22	34

B.2.2 Unsprung Masses (Axles)

Table B2.2 – Key Dimensions for the Unsprung Masses (B-double)

Dimension	Steer	Drive	Trailer 1	Trailer 2
Axle spacing (m)		1.372	1.250	1.250
Spring and damper half-track (m)	0.425	0.425	0.500	0.500

B.2.3 Wheels

Table B2.3 – Key Dimensions for the Wheels (B-double)

Dimension	Steer	Drive	Trailer 1	Trailer 2
Tyre width (m)	0.300	0.300	0.300	0.300
Dual-tyre spacing (m)		0.350	0.350	0.350
Tyre half-track (m)	1.100	0.925	0.925	0.925

B.3 Mass Properties

B.3.1 Sprung Masses

Table B3.1 – Mass Properties of the Sprung Masses (B-double)

Mass Parameter	Prime Mover	Trailer 1	Trailer 2
Number of Masses	1	1	1
Mass (kg)	6,400	20,100	34,100
Mass moment of inertia, I_{xx}, (kgm²)	7,883	31,540	53,509
Mass moment of inertia, I_{yy}, (kgm²)	39,713	332,371	647,646
Mass moment of inertia, I_{zz}, (kgm²)	38,497	321,768	629,658
Inertia products (kgm²)	0	0	0
CG height above ground (m)	1.250	2.000	2.000
CG position aft of steeraxle/king-pin (m)	1.049	2.327	5.600

B.3.2 Unsprung Masses

B.3.2.1 Axles

Table B3.2.1 – Masses Properties of the Axles (B-double)

Mass Parameter	Steer	Drive	Trailer 1	Trailer 2
Number of axles	1	2	3	3

Mass per axle (kg)	404.0	608.0	408.0	408.0
Mass moment of inertia, I_{xx}, per axle (kgm^2)	145.3	238.8	87.8	87.8
Mass moment of inertia, I_{yy}, per axle (kgm^2)	20.4	33.9	2.1	2.1
Mass moment of inertia, I_{zz}, per axle (kgm^2)	163.7	238.8	87.8	87.8
Inertia products (kgm^2)	0.0	0.0	0.0	0.0
CG height above ground (m)	0.500	0.511	0.514	0.514

B.3.2.2 Wheels

Table B3.2.2 – Mass Properties of the Wheels (B-double)

Mass Parameter	Steer	Drive	Trailer 1	Trailer 2
Number of wheels per axle group	2	8	12	12
Mass per wheel (kg)	98.0	98.0	98.0	98.0
Mass moment of inertia, I_{xx}, per wheel (kgm^2)	6.9	6.9	6.9	6.9
Mass moment of inertia, I_{yy}, per wheel (kgm^2)	12.3	12.3	12.3	12.3
Mass moment of inertia, I_{zz}, per wheel (kgm^2)	6.9	6.9	6.9	6.9
Inertia products (kgm^2)	0.0	0.0	0.0	0.0

B.3.1 Axle Group Loads

Table B3.1 – Axle Group Loads (B-double)

Design Parameter	Steer	Drive	Trailer 1	Trailer 2	GCM
Axle group load (kg)	6,000	17,000	22,500	22,500	68,000

B.4 Turntables (Fifth Wheel)

Table B4 – Mechanical Properties of the Turntables (B-double)

Design Parameter	Prime Mover	Trailer 1
Roll stiffness (Nm/deg)	56,500	56,500
Pitch stiffness (Nm/deg)	0.0	0.0
Yaw stiffness (Nm/deg)	0.0	0.0
Longitudinal compliance (m/N)	0.0	0.0
Lateral compliance (m/N)	0.0	0.0
Vertical compliance (m/N)	0.0	0.0

B.5 Suspensions

B.5.1 Springs

B.5.1.1 Geometry

Table B5.1.1 – Suspension Spring Geometry (B-double)

Design Parameter	Steer	Drive	Trailer 1	Trailer 2
Alignment of springs	vertical	vertical	vertical	vertical
Roll centre height (m)	0.700	0.600	0.714	0.714
Roll-steer angle (deg)	5.0	5.0	5.0	5.0

B.5.1.2 Spring Properties

Table B5.1.2 – Spring Properties (B-double)

Design Parameter	Steer	Drive	Trailer 1	Trailer 2
Load-deflection characteristics (see Spring Tables below)	Steer	Drive	Trailer 1	Trailer 2
Coulomb friction (Hysteresis)	0.0	0.0	0.0	0.0
Auxiliary roll stiffness per axle (Nm/deg)	432	1,695	9,380	9,380

B.5.1.3 Spring Tables

The following tables give the force/deflection characteristics of springs used in the suspensions. These were derived from data presented in the comprehensive truck size and weight study managed by the Roads and Transportation Association of Canada (RTAC) and reported in Ervin and Guy (1986). The values in the tables shown below are simply the average of the compression and extension envelopes from the spring tables given in Ervin and Guy (1986). The name of the spring file from the RTAC study from which the force/deflection curves were derived are given in the headings for each axle. For example, the RTAC data from spring file *ST6T:Sp.IHRef.Frt* was used to create the force/deflection curve for the steer axle, as shown below.

a) Steer – ST6T:Sp.IHRef.Frt

Table B5.1.3(a) – Steer-Axle Spring Force/Deflection Curve (B-double)

Force (N)	Deflection (mm)
-91,440	-381.0
-5,206	-19.1
-667	0.0
5,562	25.4
11,347	50.8
17,020	76.2
32,215	139.7
49,513	215.9
89,333	393.7

b) Drive – ST6T:Sp.ARD244.16

Table B5.1.3(b) – Drive-Axle Spring Force/Deflection Curve (B-double)

Force (N)	Deflection (mm)
-172,535	-76.2
22,693	-31.8
26,753	-12.7
29,924	0.0
33,539	12.7
37,989	25.4
153,012	76.2

c) Trailers 1 and 2 - ST6T:Sp.AR9517.16

Table B5.1.3(c) – Spring Force/Deflection Curve for Axles on Trailers 1 and 2 (B-double)

Force (N)	Deflection (mm)
-92,330	-63.5
22,693	-34.9
28,478	-12.7
31,147	0.0
34,429	12.7
41,993	38.1
125,785	76.2

B.5.2 Dampers

Table B5.2 – Dampers (B-double)

Design Parameter	Steer	Drive	Trailer 1	Trailer 2
Alignment of damper	vertical	vertical	vertical	vertical
Bump and rebound damping coefficient (Ns/m)	3,502	13,658	13,658	13,658

B.6 Tyres

The same tyres are used on the steer, drive and trailer axles.

Tyre side force and aligning torque characteristics due to slip angle at zero longitudinal slip are based on data presented in Ervin and Guy (1986) and El-Gindy and Kenis (1998), respectively. Tyre relaxation length and vertical damping have been modified for this study; both have been set to zero.

B.6.1 General

Table B6.1 – General Tyre Characteristics (B-double)

Design Parameter	Steer	Drive	Trailer 1	Trailer 2
Number of tyres per axle	2	4	4	4
Rolling resistance (%)	0.0	0.0	0.0	0.0
Tyre relaxation length (m)	0.0	0.0	0.0	0.0
Peak friction value (-)	0.8	0.8	0.8	0.8
Locked wheel friction value (-)	0.7	0.7	0.7	0.7

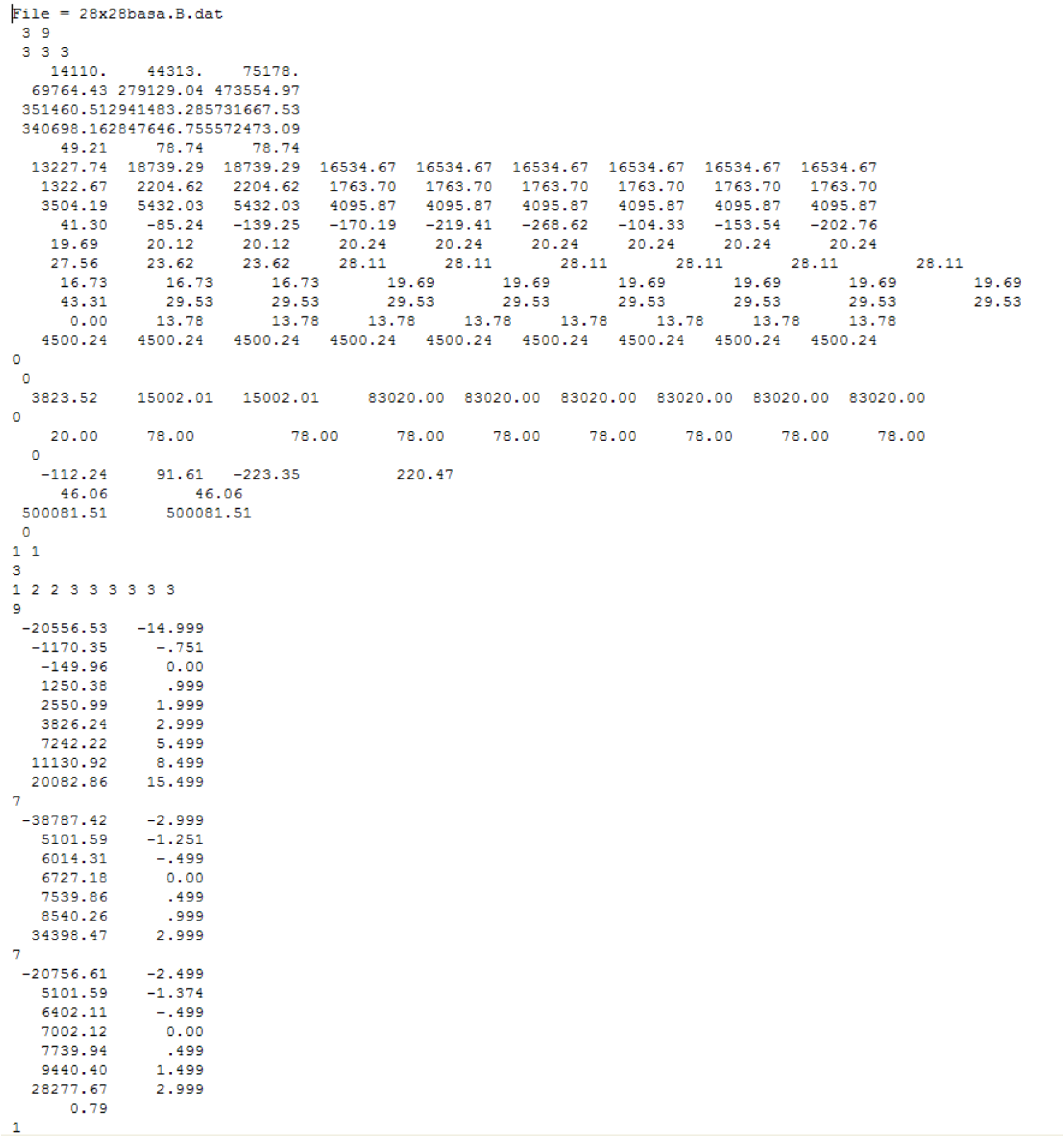
B.6.2 Ride Characteristics

Table B6.2 – Tyre Ride Characteristics (B-double)

Design Parameter	All locations
Vertical stiffness (N/m)	788,112
Vertical damping (Ns/m)	0.0
Loaded radius (m)	0.500

APPENDIX C: Yaw Roll Model

C.1 Input .DAT File for B-double SAE Lane Change Simulation



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 340698.162847646.755572473.09
     49.21     78.74     78.74
  13227.74  18739.29  18739.29  16534.67  16534.67  16534.67  16534.67  16534.67  16534.67
   1322.67   2204.62   2204.62   1763.70   1763.70   1763.70   1763.70   1763.70   1763.70
   3504.19   5432.03   5432.03   4095.87   4095.87   4095.87   4095.87   4095.87   4095.87
     41.30    -85.24   -139.25   -170.19   -219.41   -268.62   -104.33   -153.54   -202.76
    19.69     20.12     20.12     20.24     20.24     20.24     20.24     20.24      20.24
    27.56     23.62     23.62     28.11      28.11       28.11       28.11       28.11        28.11
     16.73      16.73      16.73       19.69       19.69       19.69       19.69       19.69        19.69
     43.31      29.53      29.53       29.53       29.53       29.53       29.53       29.53        29.53
      0.00     13.78       13.78     13.78     13.78     13.78     13.78     13.78     13.78
   4500.24   4500.24   4500.24   4500.24   4500.24   4500.24   4500.24   4500.24   4500.24
0
 0
  3823.52   15002.01  15002.01       83020.00  83020.00  83020.00  83020.00  83020.00  83020.00
0
    20.00     78.00          78.00      78.00     78.00     78.00     78.00     78.00     78.00
  0
   -112.24     91.61   -223.35          220.47
     46.06         46.06
 500081.51      500081.51
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1 2 2 3 3 3 3 3 3
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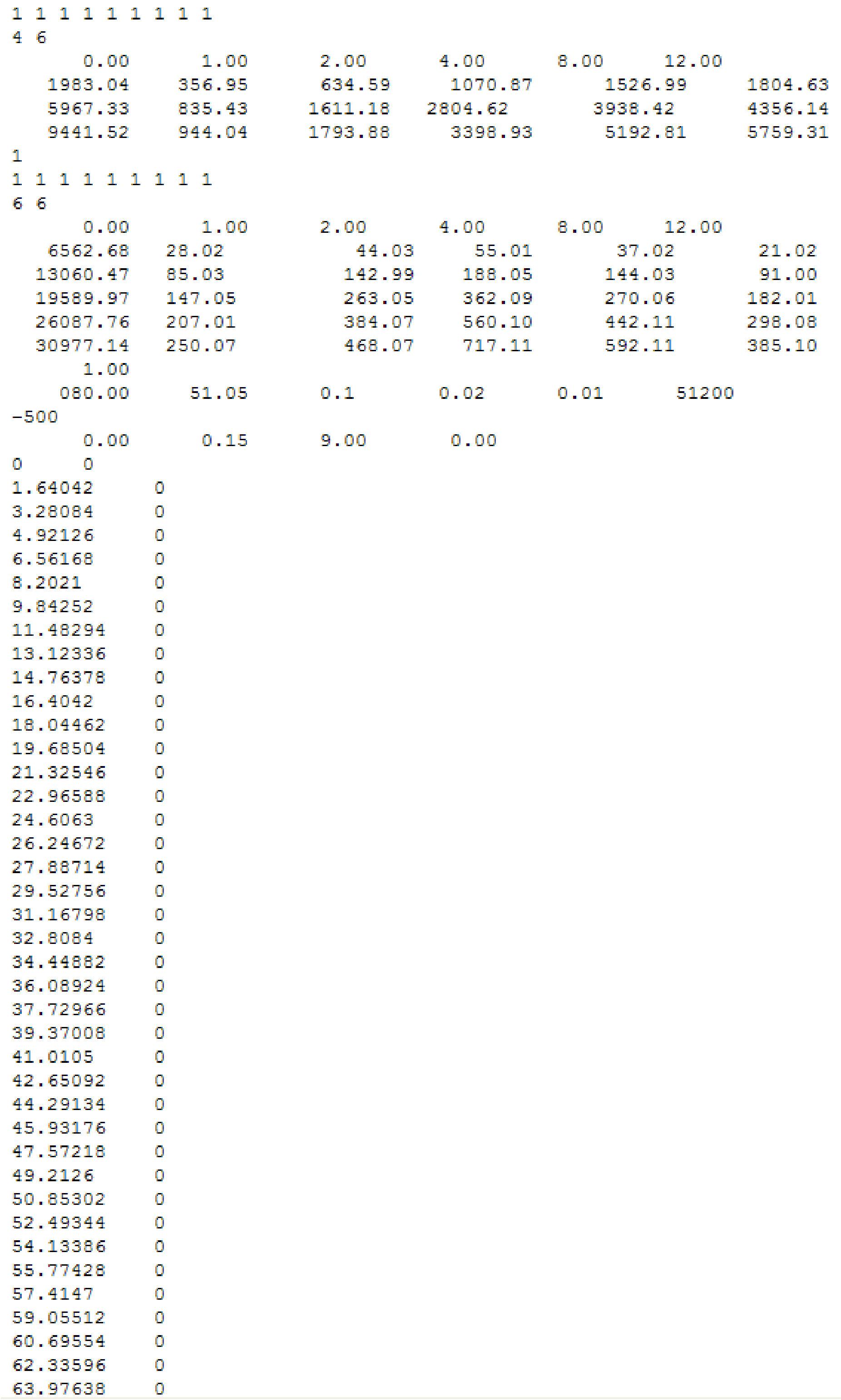

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   5967.33    835.43    1611.18   2804.62      3938.42      4356.14
   9441.52    944.04    1793.88     3398.93      5192.81     5759.31
1
1 1 1 1 1 1 1 1 1
6 6
      0.00      1.00      2.00      4.00      8.00     12.00
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  13060.47   85.03         142.99    188.05      144.03       91.00
  19589.97   147.05        263.05    362.09      270.06      182.01
  26087.76   207.01        384.07    560.10      442.11      298.08
  30977.14   250.07        468.07    717.11      592.11      385.10
      1.00
    080.00     51.05      0.1       0.02      0.01      51200
-500
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0     0
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3.28084     0
4.92126     0
6.56168     0
8.2021      0
9.84252     0
11.48294    0
13.12336    0
14.76378    0
16.4042     0
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24.6063     0
26.24672    0
27.88714    0
29.52756    0
31.16798    0
32.8084     0
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37.72966    0
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41.0105     0
42.65092    0
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45.93176    0
47.57218    0
49.2126     0
50.85302    0
52.49344    0
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63.97638    0
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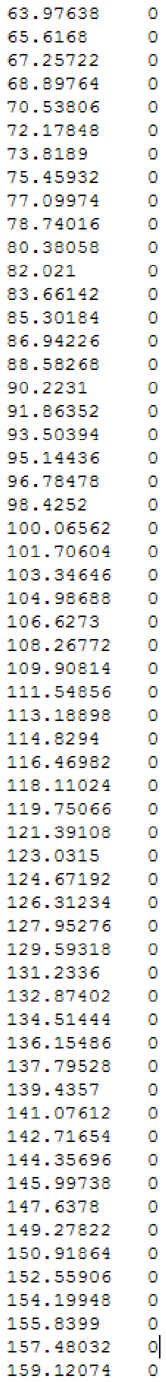

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98.4252	0
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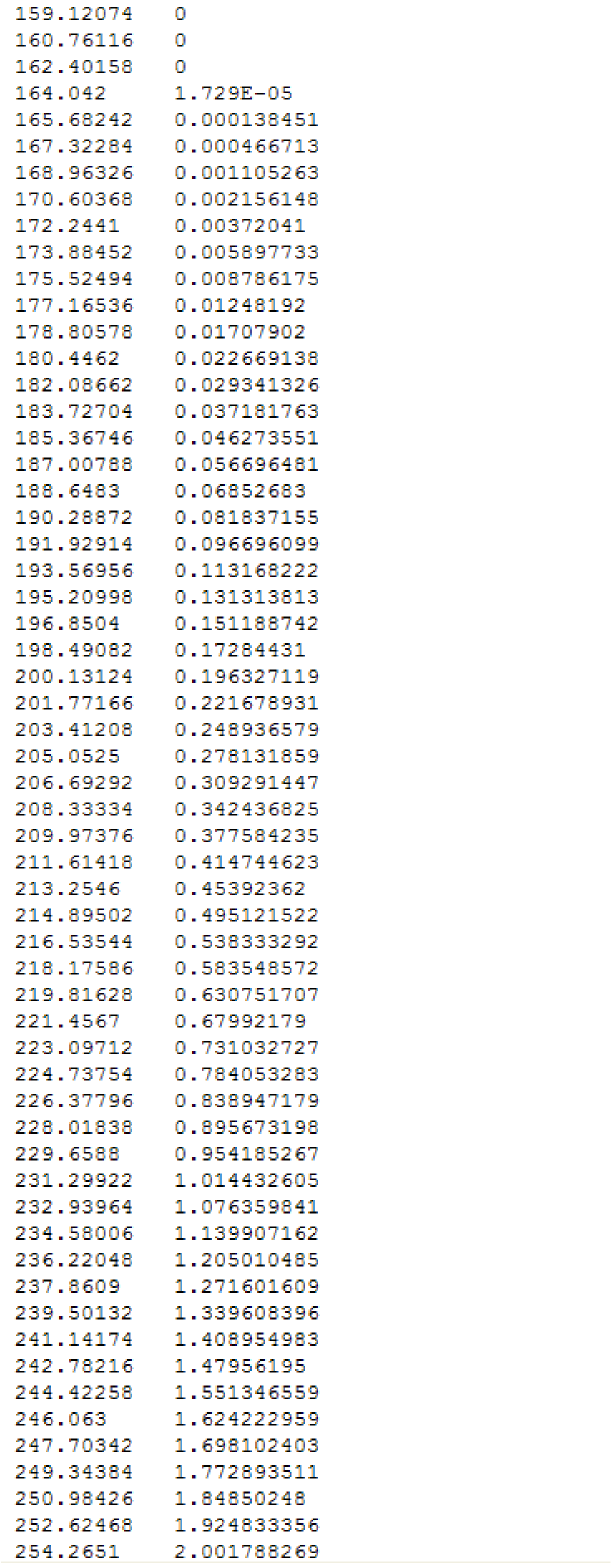

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213.2546    0.45392362
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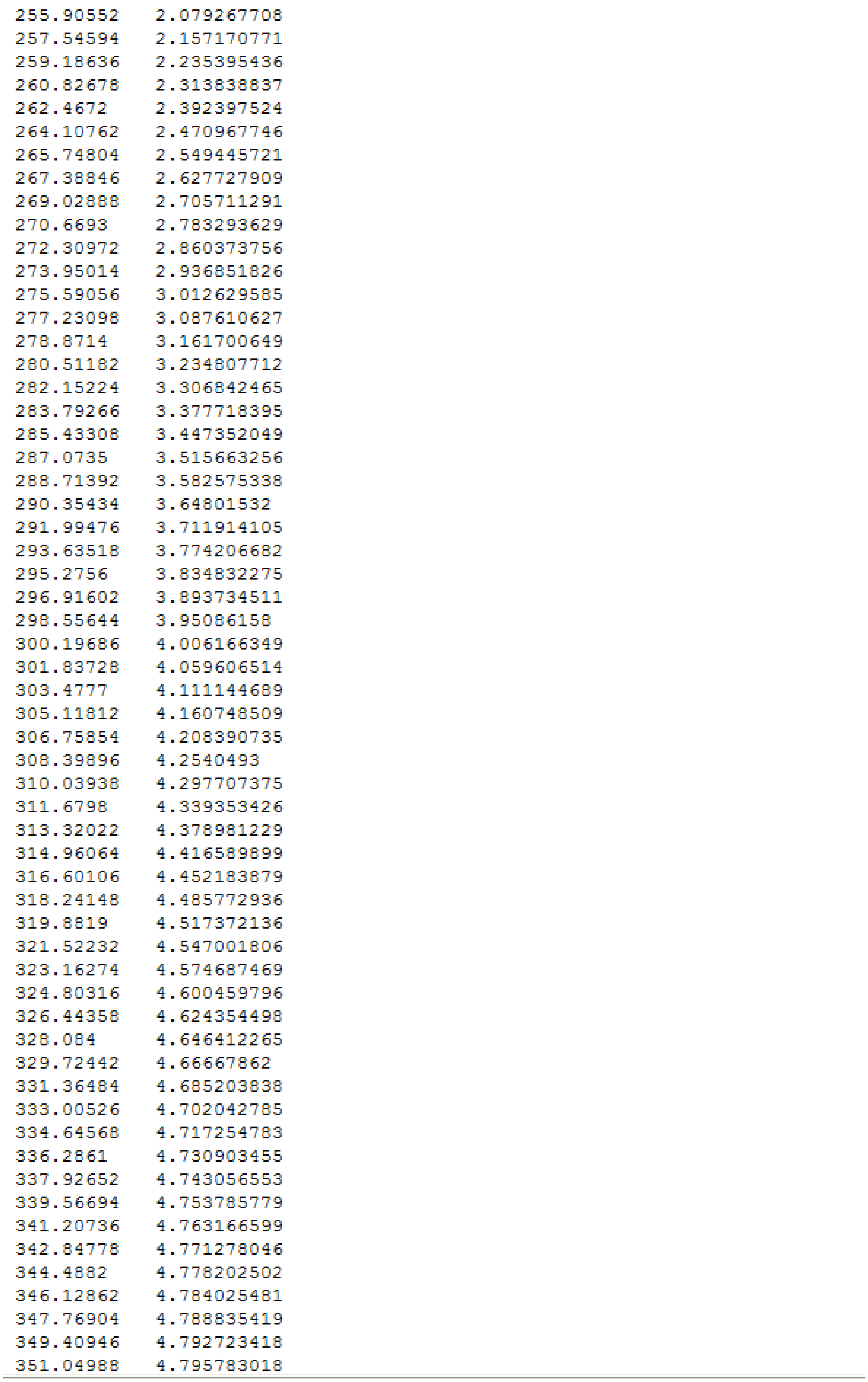

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339.56694   4.753785779
341.20736   4.763166599
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344.4882    4.778202502
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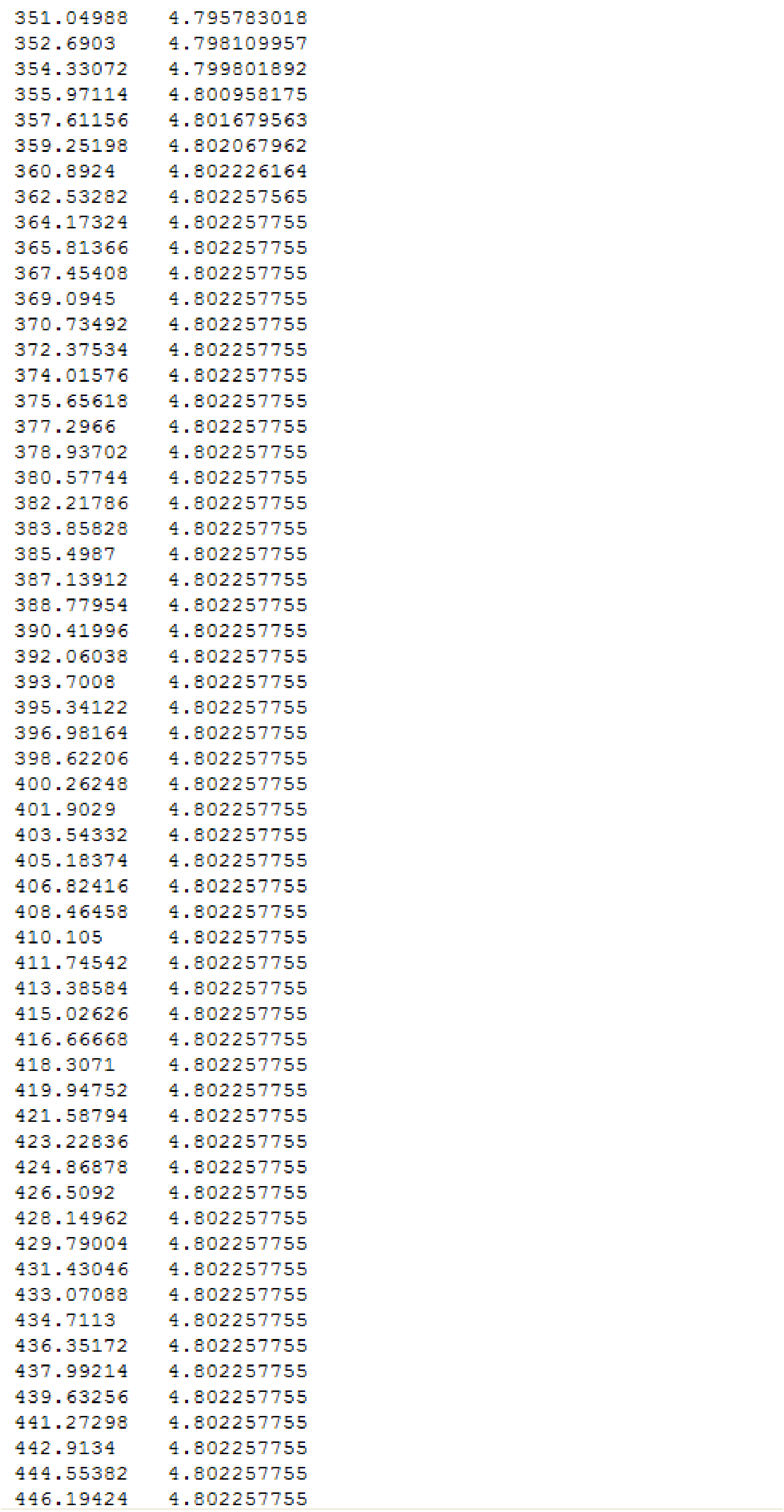

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365.81366   4.802257755
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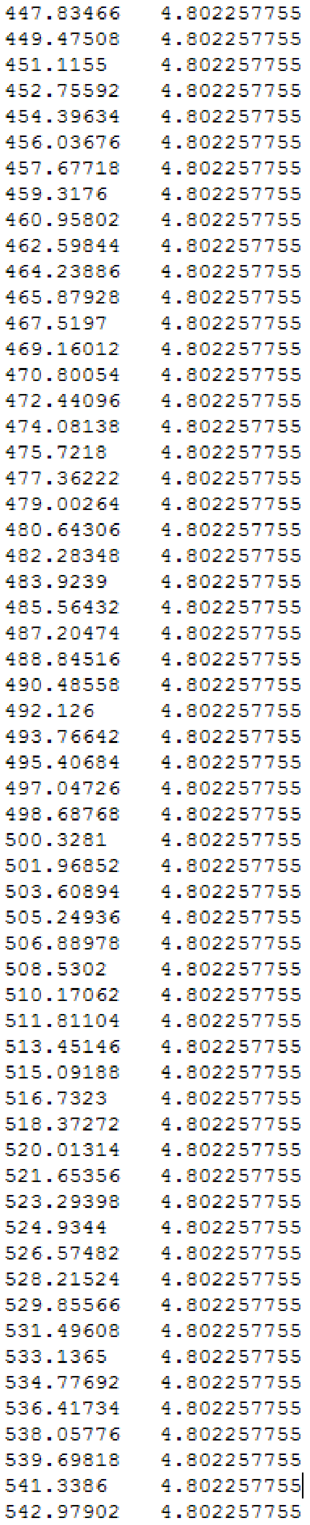

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459.3176    4.802257755
460.95802   4.802257755
462.59844   4.802257755
464.23886   4.802257755
465.87928   4.802257755
467.5197    4.802257755
469.16012   4.802257755
470.80054   4.802257755
472.44096   4.802257755
474.08138   4.802257755
475.7218    4.802257755
477.36222   4.802257755
479.00264   4.802257755
480.64306   4.802257755
482.28348   4.802257755
483.9239    4.802257755
485.56432   4.802257755
487.20474   4.802257755
488.84516   4.802257755
490.48558   4.802257755
492.126     4.802257755
493.76642   4.802257755
495.40684   4.802257755
497.04726   4.802257755
498.68768   4.802257755
500.3281    4.802257755
501.96852   4.802257755
503.60894   4.802257755
505.24936   4.802257755
506.88978   4.802257755
508.5302    4.802257755
510.17062   4.802257755
511.81104   4.802257755
513.45146   4.802257755
515.09188   4.802257755
516.7323    4.802257755
518.37272   4.802257755
520.01314   4.802257755
521.65356   4.802257755
523.29398   4.802257755
524.9344    4.802257755
526.57482   4.802257755
528.21524   4.802257755
529.85566   4.802257755
531.49608   4.802257755
533.1365    4.802257755
534.77692   4.802257755
536.41734   4.802257755
538.05776   4.802257755
539.69818   4.802257755
541.3386    4.802257755
542.97902   4.802257755
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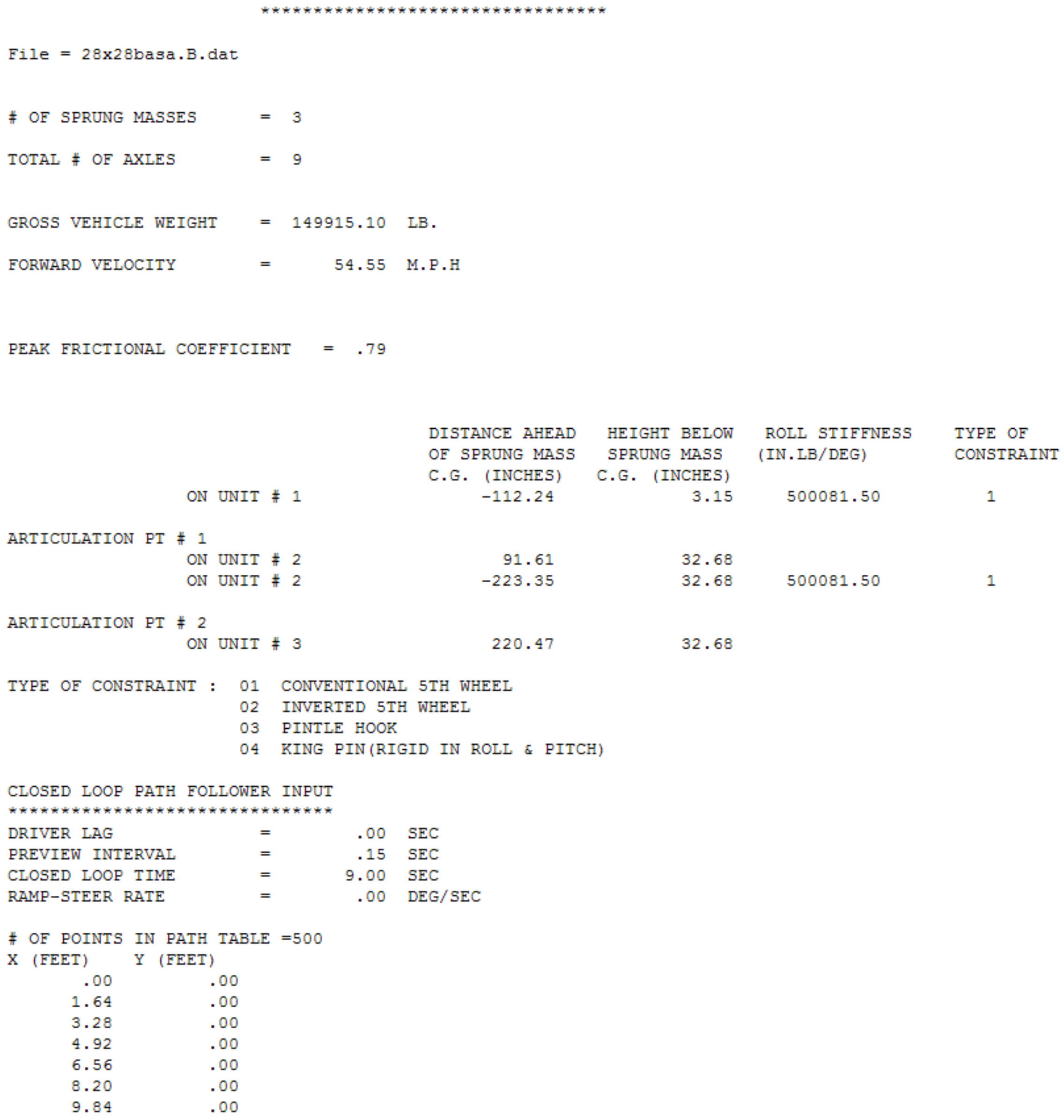
C.2 Output .OUT File for B-double SAE Lane Change Simulation



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                        ********************************

File = 28x28basa.B.dat


# OF SPRUNG MASSES       =  3

TOTAL # OF AXLES         =  9


GROSS VEHICLE WEIGHT     =  149915.10  LB.

FORWARD VELOCITY         =      54.55  M.P.H



PEAK FRICTIONAL COEFFICIENT   =  .79



                                        DISTANCE AHEAD   HEIGHT BELOW   ROLL STIFFNESS    TYPE OF
                                        OF SPRUNG MASS   SPRUNG MASS   (IN.LB/DEG)        CONSTRAINT
                                        C.G. (INCHES)   C.G. (INCHES)
                 ON UNIT # 1                 -112.24           3.15     500081.50          1

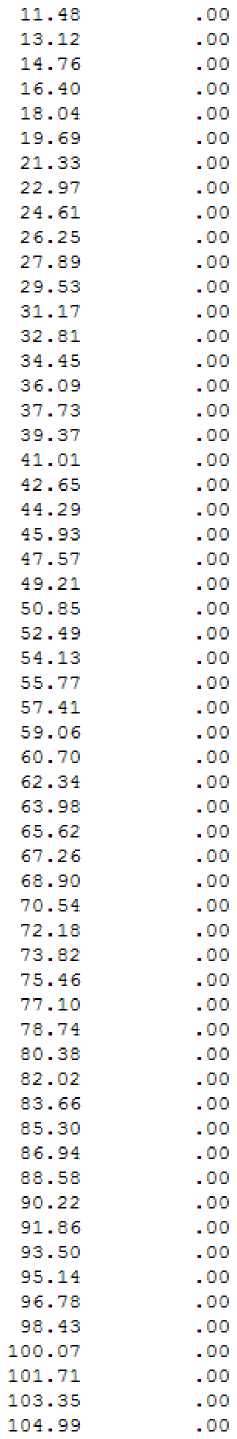
ARTICULATION PT # 1
                 ON UNIT # 2                   91.61          32.68
                 ON UNIT # 2                 -223.35          32.68     500081.50          1

ARTICULATION PT # 2
                 ON UNIT # 3                  220.47          32.68

TYPE OF CONSTRAINT :  01  CONVENTIONAL 5TH WHEEL
                      02  INVERTED 5TH WHEEL
                      03  PINTLE HOOK
                      04  KING PIN(RIGID IN ROLL & PITCH)

CLOSED LOOP PATH FOLLOWER INPUT
*******************************
DRIVER LAG               =        .00  SEC
PREVIEW INTERVAL         =        .15  SEC
CLOSED LOOP TIME         =       9.00  SEC
RAMP-STEER RATE          =        .00  DEG/SEC

# OF POINTS IN PATH TABLE =500
X (FEET)    Y (FEET)
       .00        .00
      1.64        .00
      3.28        .00
      4.92        .00
      6.56        .00
      8.20        .00
      9.84        .00
```



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 13.12         .00
 14.76         .00
 16.40         .00
 18.04         .00
 19.69         .00
 21.33         .00
 22.97         .00
 24.61         .00
 26.25         .00
 27.89         .00
 29.53         .00
 31.17         .00
 32.81         .00
 34.45         .00
 36.09         .00
 37.73         .00
 39.37         .00
 41.01         .00
 42.65         .00
 44.29         .00
 45.93         .00
 47.57         .00
 49.21         .00
 50.85         .00
 52.49         .00
 54.13         .00
 55.77         .00
 57.41         .00
 59.06         .00
 60.70         .00
 62.34         .00
 63.98         .00
 65.62         .00
 67.26         .00
 68.90         .00
 70.54         .00
 72.18         .00
 73.82         .00
 75.46         .00
 77.10         .00
 78.74         .00
 80.38         .00
 82.02         .00
 83.66         .00
 85.30         .00
 86.94         .00
 88.58         .00
 90.22         .00
 91.86         .00
 93.50         .00
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 98.43         .00
100.07         .00
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103.35         .00
104.99         .00
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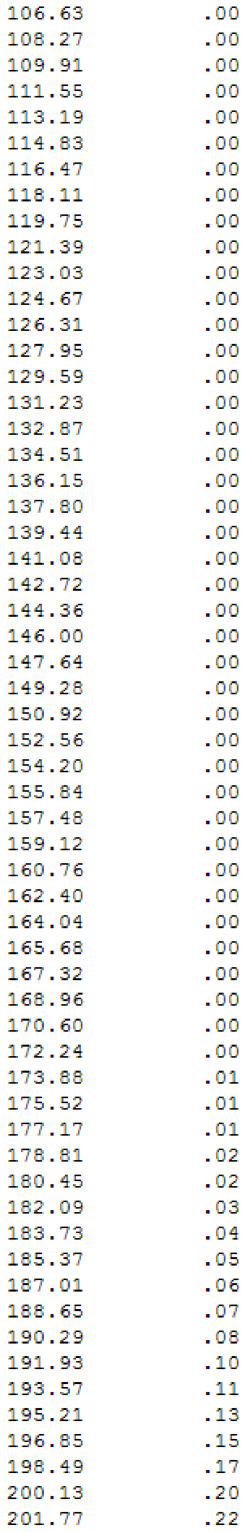

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111.55          .00
113.19          .00
114.83          .00
116.47          .00
118.11          .00
119.75          .00
121.39          .00
123.03          .00
124.67          .00
126.31          .00
127.95          .00
129.59          .00
131.23          .00
132.87          .00
134.51          .00
136.15          .00
137.80          .00
139.44          .00
141.08          .00
142.72          .00
144.36          .00
146.00          .00
147.64          .00
149.28          .00
150.92          .00
152.56          .00
154.20          .00
155.84          .00
157.48          .00
159.12          .00
160.76          .00
162.40          .00
164.04          .00
165.68          .00
167.32          .00
168.96          .00
170.60          .00
172.24          .00
173.88          .01
175.52          .01
177.17          .01
178.81          .02
180.45          .02
182.09          .03
183.73          .04
185.37          .05
187.01          .06
188.65          .07
190.29          .08
191.93          .10
193.57          .11
195.21          .13
196.85          .15
198.49          .17
200.13          .20
201.77          .22
```

```
201.77          .22
203.41          .25
205.05          .28
206.69          .31
208.33          .34
209.97          .38
211.61          .41
213.25          .45
214.90          .50
216.54          .54
218.18          .58
219.82          .63
221.46          .68
223.10          .73
224.74          .78
226.38          .84
228.02          .90
229.66          .95
231.30         1.01
232.94         1.08
234.58         1.14
236.22         1.21
237.86         1.27
239.50         1.34
241.14         1.41
242.78         1.48
244.42         1.55
246.06         1.62
247.70         1.70
249.34         1.77
250.98         1.85
252.62         1.92
254.27         2.00
255.91         2.08
257.55         2.16
259.19         2.24
260.83         2.31
262.47         2.39
264.11         2.47
265.75         2.55
267.39         2.63
269.03         2.71
270.67         2.78
272.31         2.86
273.95         2.94
275.59         3.01
277.23         3.09
278.87         3.16
280.51         3.23
282.15         3.31
283.79         3.38
285.43         3.45
287.07         3.52
288.71         3.58
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291.99         3.71
293.64         3.77
295.28         3.83
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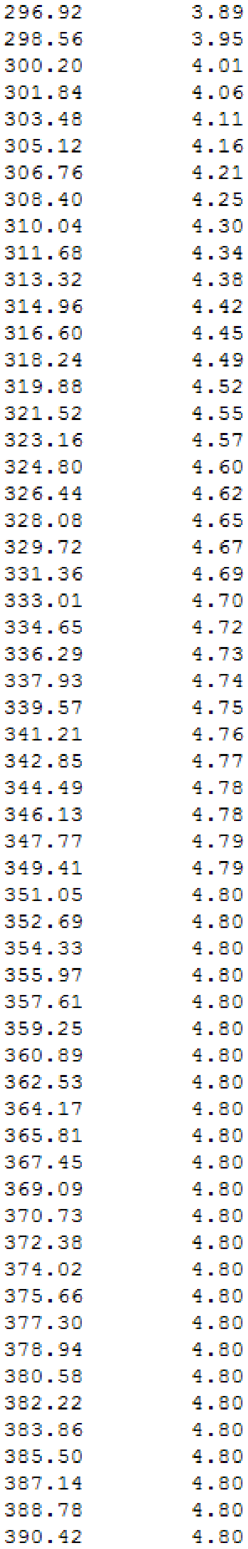

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301.84          4.06
303.48          4.11
305.12          4.16
306.76          4.21
308.40          4.25
310.04          4.30
311.68          4.34
313.32          4.38
314.96          4.42
316.60          4.45
318.24          4.49
319.88          4.52
321.52          4.55
323.16          4.57
324.80          4.60
326.44          4.62
328.08          4.65
329.72          4.67
331.36          4.69
333.01          4.70
334.65          4.72
336.29          4.73
337.93          4.74
339.57          4.75
341.21          4.76
342.85          4.77
344.49          4.78
346.13          4.78
347.77          4.79
349.41          4.79
351.05          4.80
352.69          4.80
354.33          4.80
355.97          4.80
357.61          4.80
359.25          4.80
360.89          4.80
362.53          4.80
364.17          4.80
365.81          4.80
367.45          4.80
369.09          4.80
370.73          4.80
372.38          4.80
374.02          4.80
375.66          4.80
377.30          4.80
378.94          4.80
380.58          4.80
382.22          4.80
383.86          4.80
385.50          4.80
387.14          4.80
388.78          4.80
390.42          4.80
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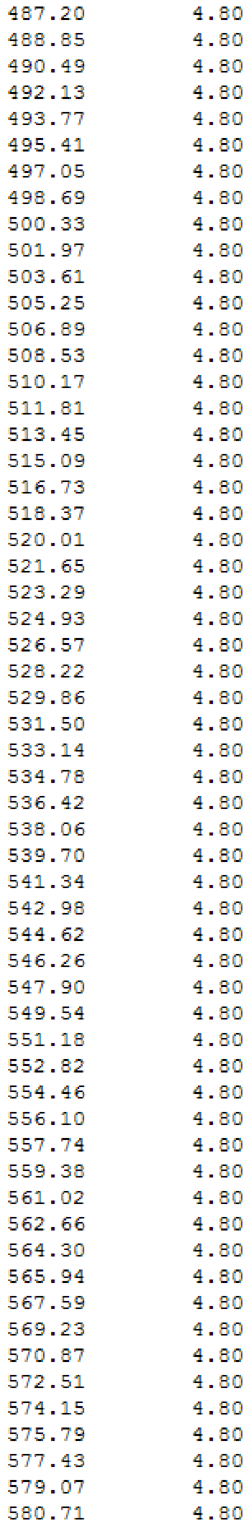
392.06	4.80
393.70	4.80
395.34	4.80
396.98	4.80
398.62	4.80
400.26	4.80
401.90	4.80
403.54	4.80
405.18	4.80
406.82	4.80
408.46	4.80
410.11	4.80
411.75	4.80
413.39	4.80
415.03	4.80
416.67	4.80
418.31	4.80
419.95	4.80
421.59	4.80
423.23	4.80
424.87	4.80
426.51	4.80
428.15	4.80
429.79	4.80
431.43	4.80
433.07	4.80
434.71	4.80
436.35	4.80
437.99	4.80
439.63	4.80
441.27	4.80
442.91	4.80
444.55	4.80
446.19	4.80
447.83	4.80
449.48	4.80
451.12	4.80
452.76	4.80
454.40	4.80
456.04	4.80
457.68	4.80
459.32	4.80
460.96	4.80
462.60	4.80
464.24	4.80
465.88	4.80
467.52	4.80
469.16	4.80
470.80	4.80
472.44	4.80
474.08	4.80
475.72	4.80
477.36	4.80
479.00	4.80
480.64	4.80
482.28	4.80
483.92	4.80
485.56	4.80



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488.85         4.80
490.49         4.80
492.13         4.80
493.77         4.80
495.41         4.80
497.05         4.80
498.69         4.80
500.33         4.80
501.97         4.80
503.61         4.80
505.25         4.80
506.89         4.80
508.53         4.80
510.17         4.80
511.81         4.80
513.45         4.80
515.09         4.80
516.73         4.80
518.37         4.80
520.01         4.80
521.65         4.80
523.29         4.80
524.93         4.80
526.57         4.80
528.22         4.80
529.86         4.80
531.50         4.80
533.14         4.80
534.78         4.80
536.42         4.80
538.06         4.80
539.70         4.80
541.34         4.80
542.98         4.80
544.62         4.80
546.26         4.80
547.90         4.80
549.54         4.80
551.18         4.80
552.82         4.80
554.46         4.80
556.10         4.80
557.74         4.80
559.38         4.80
561.02         4.80
562.66         4.80
564.30         4.80
565.94         4.80
567.59         4.80
569.23         4.80
570.87         4.80
572.51         4.80
574.15         4.80
575.79         4.80
577.43         4.80
579.07         4.80
580.71         4.80
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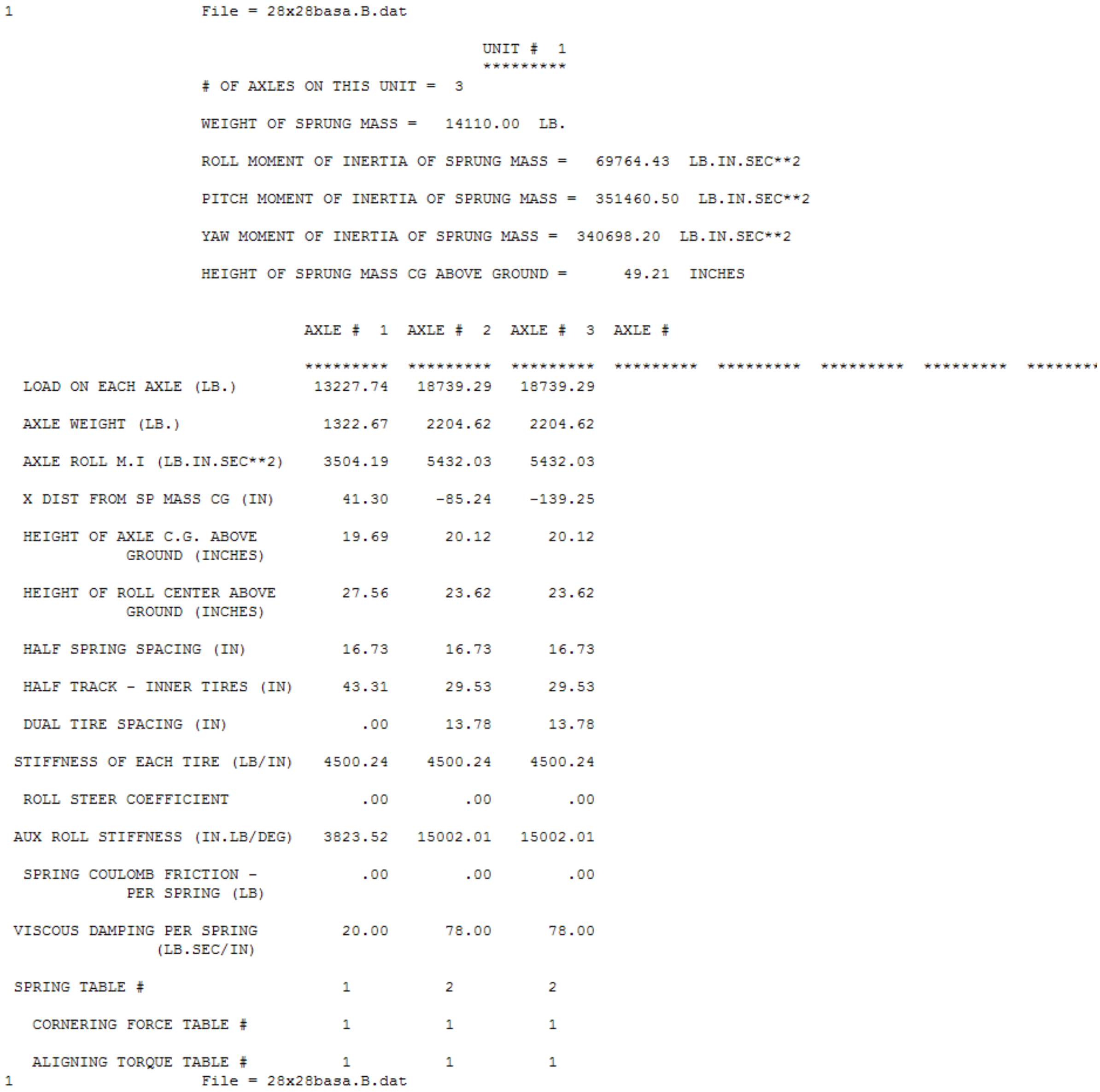

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1                    File = 28x28basa.B.dat

                                                   UNIT #  1
                                                   *********
                     # OF AXLES ON THIS UNIT =  3

                     WEIGHT OF SPRUNG MASS =   14110.00  LB.

                     ROLL MOMENT OF INERTIA OF SPRUNG MASS =   69764.43  LB.IN.SEC**2

                     PITCH MOMENT OF INERTIA OF SPRUNG MASS =  351460.50  LB.IN.SEC**2

                     YAW MOMENT OF INERTIA OF SPRUNG MASS =  340698.20  LB.IN.SEC**2

                     HEIGHT OF SPRUNG MASS CG ABOVE GROUND =      49.21  INCHES


                                AXLE #  1  AXLE #  2  AXLE #  3  AXLE #

                                *********  *********  *********  *********  *********  *********  *********  ********
  LOAD ON EACH AXLE (LB.)         13227.74   18739.29   18739.29

  AXLE WEIGHT (LB.)                1322.67    2204.62    2204.62

  AXLE ROLL M.I (LB.IN.SEC**2)     3504.19    5432.03    5432.03

  X DIST FROM SP MASS CG (IN)        41.30     -85.24    -139.25

  HEIGHT OF AXLE C.G. ABOVE          19.69      20.12      20.12
             GROUND (INCHES)

  HEIGHT OF ROLL CENTER ABOVE        27.56      23.62      23.62
             GROUND (INCHES)

  HALF SPRING SPACING (IN)           16.73      16.73      16.73

  HALF TRACK - INNER TIRES (IN)      43.31      29.53      29.53

  DUAL TIRE SPACING (IN)               .00      13.78      13.78

 STIFFNESS OF EACH TIRE (LB/IN)    4500.24    4500.24    4500.24

  ROLL STEER COEFFICIENT               .00        .00        .00

 AUX ROLL STIFFNESS (IN.LB/DEG)    3823.52   15002.01   15002.01

  SPRING COULOMB FRICTION -            .00        .00        .00
             PER SPRING (LB)

 VISCOUS DAMPING PER SPRING          20.00      78.00      78.00
                (LB.SEC/IN)

 SPRING TABLE #                     1          2          2

   CORNERING FORCE TABLE #          1          1          1

   ALIGNING TORQUE TABLE #          1          1          1
1                    File = 28x28basa.B.dat
```

```
                                                   UNIT #  2
                                                   *********
                     # OF AXLES ON THIS UNIT =  3

                     WEIGHT OF SPRUNG MASS =   44313.00  LB.

                     ROLL MOMENT OF INERTIA OF SPRUNG MASS =  279129.00  LB.IN.SEC**2

                     PITCH MOMENT OF INERTIA OF SPRUNG MASS = 2941483.00  LB.IN.SEC**2

                     YAW MOMENT OF INERTIA OF SPRUNG MASS = 2847647.00  LB.IN.SEC**2

                     HEIGHT OF SPRUNG MASS CG ABOVE GROUND =      78.74  INCHES


                                AXLE #  4  AXLE #  5  AXLE #  6  AXLE #

                                *********  *********  *********  *********  *********  *********  *********  *****
  LOAD ON EACH AXLE (LB.)        16534.67   16534.67   16534.67

  AXLE WEIGHT (LB.)               1763.70    1763.70    1763.70

  AXLE ROLL M.I (LB.IN.SEC**2)    4095.87    4095.87    4095.87

  X DIST FROM SP MASS CG (IN)     -170.19    -219.41    -268.62

  HEIGHT OF AXLE C.G. ABOVE         20.24      20.24      20.24
             GROUND (INCHES)

  HEIGHT OF ROLL CENTER ABOVE       28.11      28.11      28.11
             GROUND (INCHES)

  HALF SPRING SPACING (IN)          19.69      19.69      19.69

  HALF TRACK - INNER TIRES (IN)     29.53      29.53      29.53

  DUAL TIRE SPACING (IN)            13.78      13.78      13.78

 STIFFNESS OF EACH TIRE (LB/IN)   4500.24    4500.24    4500.24

  ROLL STEER COEFFICIENT              .00        .00        .00

 AUX ROLL STIFFNESS (IN.LB/DEG)  83020.00   83020.00   83020.00

  SPRING COULOMB FRICTION -           .00        .00        .00
             PER SPRING (LB)

 VISCOUS DAMPING PER SPRING         78.00      78.00      78.00
                (LB.SEC/IN)

 SPRING TABLE #                     3          3          3

   CORNERING FORCE TABLE #          1          1          1

   ALIGNING TORQUE TABLE #          1          1          1
1                    File = 28x28basa.B.dat
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```
                                                UNIT #  3
                                                *********
                      # OF AXLES ON THIS UNIT =  3

                      WEIGHT OF SPRUNG MASS =   75178.00  LB.

                      ROLL MOMENT OF INERTIA OF SPRUNG MASS =  473555.00  LB.IN.SEC**2

                      PITCH MOMENT OF INERTIA OF SPRUNG MASS = 5731668.00  LB.IN.SEC**2

                      YAW MOMENT OF INERTIA OF SPRUNG MASS = 5572473.00  LB.IN.SEC**2

                      HEIGHT OF SPRUNG MASS CG ABOVE GROUND =      78.74  INCHES


                                 AXLE #  7  AXLE #  8  AXLE #  9  AXLE #

                                 *********  *********  *********  *********  *********  *********  *********  *********
   LOAD ON EACH AXLE (LB.)        16534.67   16534.67   16534.67

   AXLE WEIGHT (LB.)               1763.70    1763.70    1763.70

   AXLE ROLL M.I (LB.IN.SEC**2)    4095.87    4095.87    4095.87

   X DIST FROM SP MASS CG (IN)     -104.33    -153.54    -202.76

   HEIGHT OF AXLE C.G. ABOVE         20.24      20.24      20.24
              GROUND (INCHES)

   HEIGHT OF ROLL CENTER ABOVE       28.11      28.11      28.11
              GROUND (INCHES)

   HALF SPRING SPACING (IN)          19.69      19.69      19.69

   HALF TRACK - INNER TIRES (IN)     29.53      29.53      29.53

   DUAL TIRE SPACING (IN)            13.78      13.78      13.78

  STIFFNESS OF EACH TIRE (LB/IN)   4500.24    4500.24    4500.24

   ROLL STEER COEFFICIENT              .00        .00        .00

  AUX ROLL STIFFNESS (IN.LB/DEG)  83020.00   83020.00   83020.00

   SPRING COULOMB FRICTION -           .00        .00        .00
              PER SPRING (LB)

  VISCOUS DAMPING PER SPRING         78.00      78.00      78.00
                 (LB.SEC/IN)

  SPRING TABLE #                   3          3          3

    CORNERING FORCE TABLE #        1          1          1

    ALIGNING TORQUE TABLE #        1          1          1
1            SPRING TABLE # 1
            ****** *******
|           FORCE        DEFLECTION
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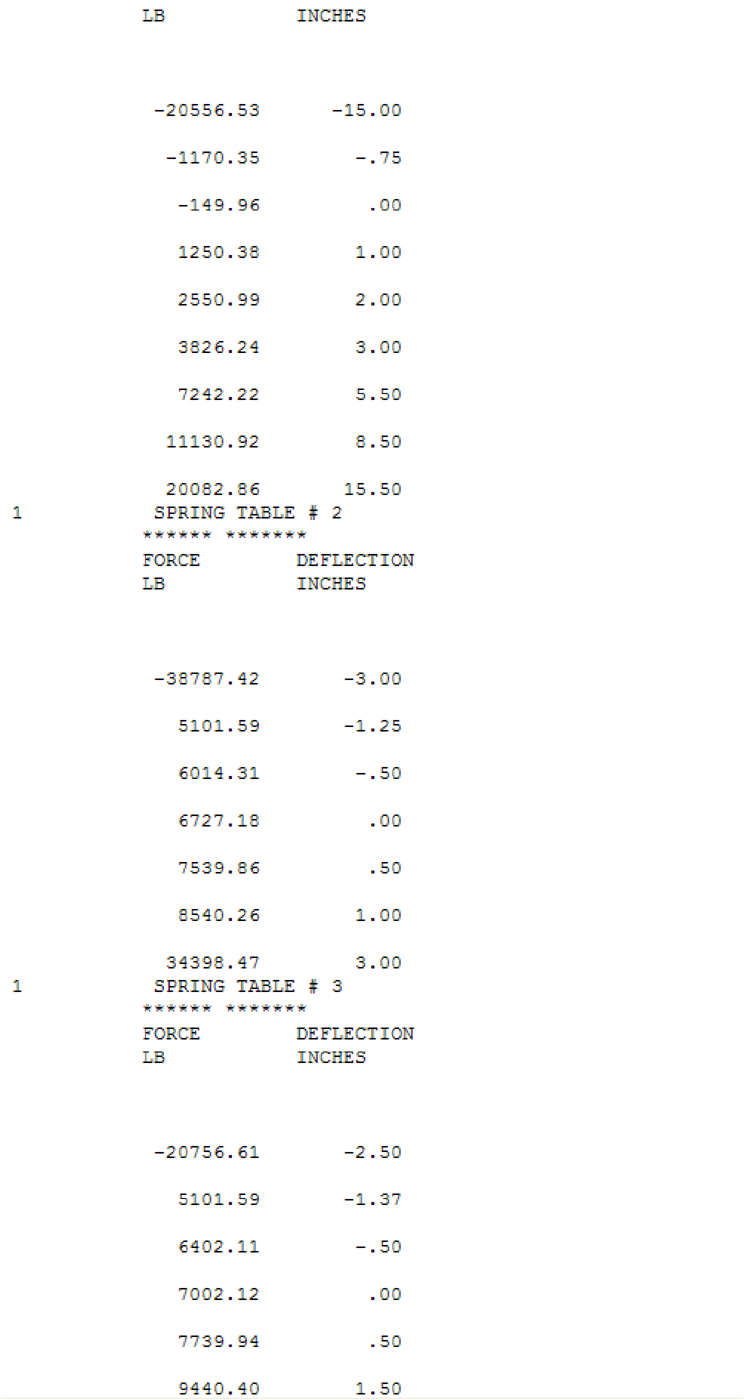

```
           LB           INCHES


            -20556.53      -15.00

             -1170.35        -.75

              -149.96         .00

              1250.38        1.00

              2550.99        2.00

              3826.24        3.00

              7242.22        5.50

             11130.92        8.50

             20082.86       15.50
1           SPRING TABLE # 2
           ****** *******
           FORCE        DEFLECTION
           LB           INCHES


            -38787.42       -3.00

              5101.59       -1.25

              6014.31        -.50

              6727.18         .00

              7539.86         .50

              8540.26        1.00

             34398.47        3.00
1           SPRING TABLE # 3
           ****** *******
           FORCE        DEFLECTION
           LB           INCHES


            -20756.61       -2.50

              5101.59       -1.37

              6402.11        -.50

              7002.12         .00

              7739.94         .50

              9440.40        1.50
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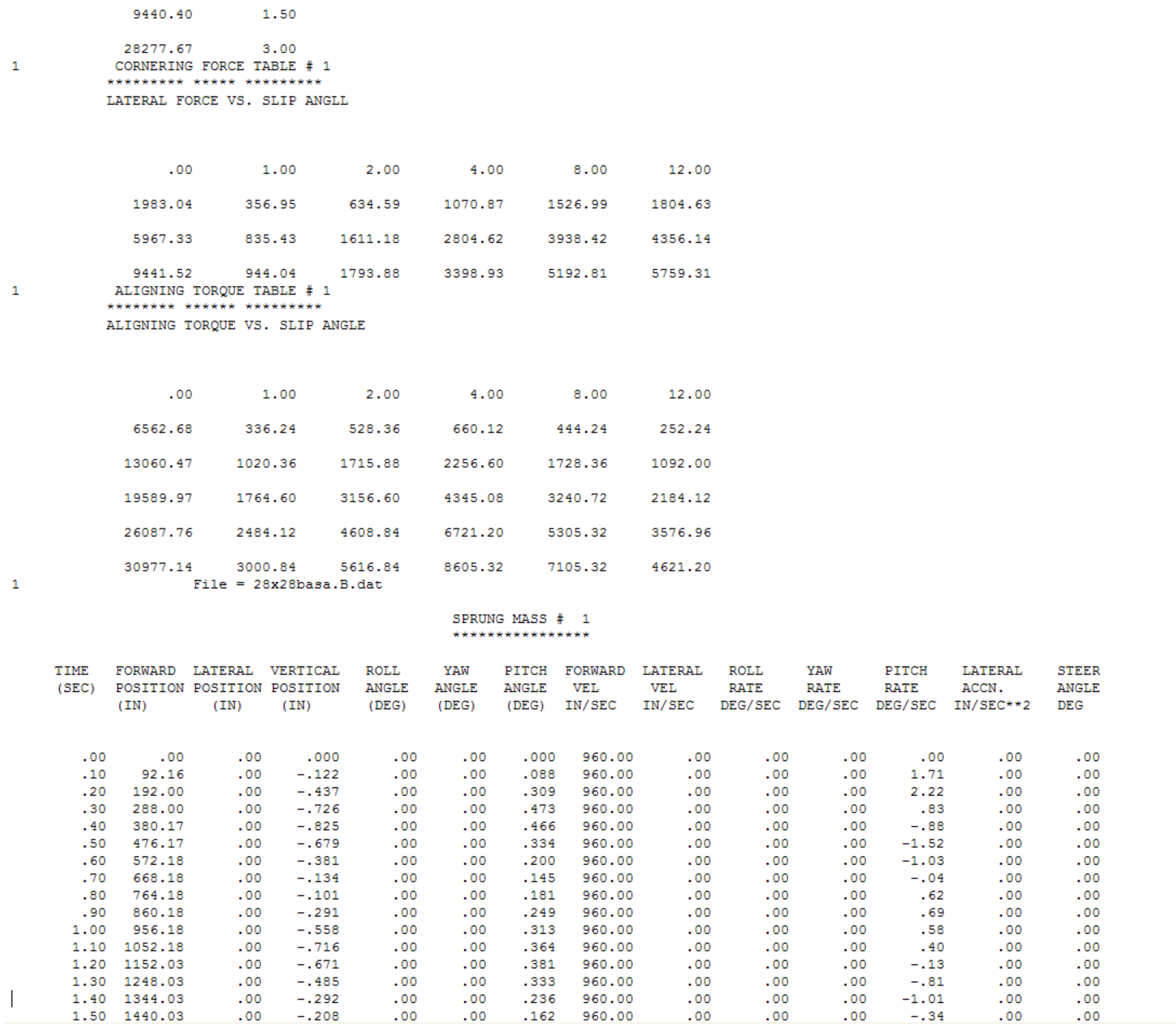

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              9440.40        1.50

             28277.67        3.00
1           CORNERING FORCE TABLE # 1
           ********* ***** *********
           LATERAL FORCE VS. SLIP ANGLL



                  .00        1.00        2.00        4.00        8.00       12.00

              1983.04      356.95      634.59     1070.87     1526.99     1804.63

              5967.33      835.43     1611.18     2804.62     3938.42     4356.14

              9441.52      944.04     1793.88     3398.93     5192.81     5759.31
1           ALIGNING TORQUE TABLE # 1
           ******** ****** *********
           ALIGNING TORQUE VS. SLIP ANGLE



                  .00        1.00        2.00        4.00        8.00       12.00

              6562.68      336.24      528.36      660.12      444.24      252.24

             13060.47     1020.36     1715.88     2256.60     1728.36     1092.00

             19589.97     1764.60     3156.60     4345.08     3240.72     2184.12

             26087.76     2484.12     4608.84     6721.20     5305.32     3576.96

             30977.14     3000.84     5616.84     8605.32     7105.32     4621.20
1                    File = 28x28basa.B.dat

                                                   SPRUNG MASS #  1
                                                   ****************

     TIME   FORWARD  LATERAL  VERTICAL   ROLL    YAW     PITCH  FORWARD  LATERAL   ROLL     YAW      PITCH    LATERAL    STEER
     (SEC)  POSITION POSITION POSITION   ANGLE   ANGLE   ANGLE   VEL      VEL      RATE     RATE     RATE     ACCN.      ANGLE
            (IN)       (IN)    (IN)      (DEG)   (DEG)   (DEG)  IN/SEC   IN/SEC   DEG/SEC  DEG/SEC  DEG/SEC  IN/SEC**2   DEG


        .00      .00      .00     .000      .00     .00    .000   960.00      .00      .00      .00      .00      .00      .00
        .10    92.16      .00    -.122      .00     .00    .088   960.00      .00      .00      .00     1.71      .00      .00
        .20   192.00      .00    -.437      .00     .00    .309   960.00      .00      .00      .00     2.22      .00      .00
        .30   288.00      .00    -.726      .00     .00    .473   960.00      .00      .00      .00      .83      .00      .00
        .40   380.17      .00    -.825      .00     .00    .466   960.00      .00      .00      .00     -.88      .00      .00
        .50   476.17      .00    -.679      .00     .00    .334   960.00      .00      .00      .00    -1.52      .00      .00
        .60   572.18      .00    -.381      .00     .00    .200   960.00      .00      .00      .00    -1.03      .00      .00
        .70   668.18      .00    -.134      .00     .00    .145   960.00      .00      .00      .00     -.04      .00      .00
        .80   764.18      .00    -.101      .00     .00    .181   960.00      .00      .00      .00      .62      .00      .00
        .90   860.18      .00    -.291      .00     .00    .249   960.00      .00      .00      .00      .69      .00      .00
       1.00   956.18      .00    -.558      .00     .00    .313   960.00      .00      .00      .00      .58      .00      .00
       1.10  1052.18      .00    -.716      .00     .00    .364   960.00      .00      .00      .00      .40      .00      .00
       1.20  1152.03      .00    -.671      .00     .00    .381   960.00      .00      .00      .00     -.13      .00      .00
       1.30  1248.03      .00    -.485      .00     .00    .333   960.00      .00      .00      .00     -.81      .00      .00
       1.40  1344.03      .00    -.292      .00     .00    .236   960.00      .00      .00      .00    -1.01      .00      .00
       1.50  1440.03      .00    -.208      .00     .00    .162   960.00      .00      .00      .00     -.34      .00      .00
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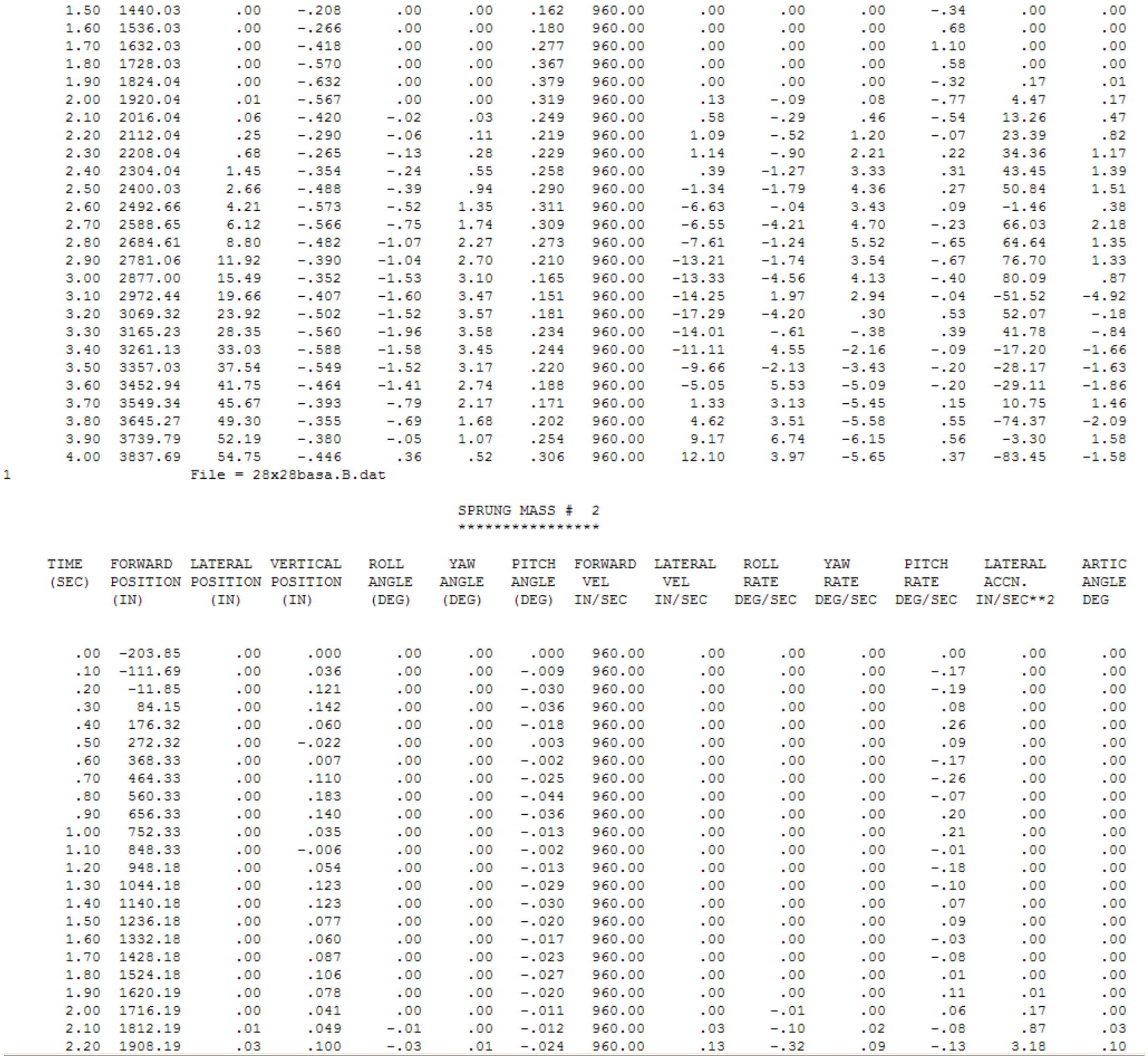

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         1.50   1440.03       .00     -.208       .00      .00     .162    960.00       .00       .00       .00      -.34       .00       .00
         1.60   1536.03       .00     -.266       .00      .00     .180    960.00       .00       .00       .00       .68       .00       .00
         1.70   1632.03       .00     -.418       .00      .00     .277    960.00       .00       .00       .00      1.10       .00       .00
         1.80   1728.03       .00     -.570       .00      .00     .367    960.00       .00       .00       .00       .58       .00       .00
         1.90   1824.04       .00     -.632       .00      .00     .379    960.00       .00       .00       .00      -.32       .17       .01
         2.00   1920.04       .01     -.567       .00      .00     .319    960.00       .13      -.09       .08      -.77      4.47       .17
         2.10   2016.04       .06     -.420      -.02      .03     .249    960.00       .58      -.29       .46      -.54     13.26       .47
         2.20   2112.04       .25     -.290      -.06      .11     .219    960.00      1.09      -.52      1.20      -.07     23.39       .82
         2.30   2208.04       .68     -.265      -.13      .28     .229    960.00      1.14      -.90      2.21       .22     34.36      1.17
         2.40   2304.04      1.45     -.354      -.24      .55     .258    960.00       .39     -1.27      3.33       .31     43.45      1.39
         2.50   2400.03      2.66     -.488      -.39      .94     .290    960.00     -1.34     -1.79      4.36       .27     50.84      1.51
         2.60   2492.66      4.21     -.573      -.52     1.35     .311    960.00     -6.63      -.04      3.43       .09     -1.46       .38
         2.70   2588.65      6.12     -.566      -.75     1.74     .309    960.00     -6.55     -4.21      4.70      -.23     66.03      2.18
         2.80   2684.61      8.80     -.482     -1.07     2.27     .273    960.00     -7.61     -1.24      5.52      -.65     64.64      1.35
         2.90   2781.06     11.92     -.390     -1.04     2.70     .210    960.00    -13.21     -1.74      3.54      -.67     76.70      1.33
         3.00   2877.00     15.49     -.352     -1.53     3.10     .165    960.00    -13.33     -4.56      4.13      -.40     80.09       .87
         3.10   2972.44     19.66     -.407     -1.60     3.47     .151    960.00    -14.25      1.97      2.94      -.04    -51.52     -4.92
         3.20   3069.32     23.92     -.502     -1.52     3.57     .181    960.00    -17.29     -4.20       .30       .53     52.07      -.18
         3.30   3165.23     28.35     -.560     -1.96     3.58     .234    960.00    -14.01      -.61      -.38       .39     41.78      -.84
         3.40   3261.13     33.03     -.588     -1.58     3.45     .244    960.00    -11.11      4.55     -2.16      -.09    -17.20     -1.66
         3.50   3357.03     37.54     -.549     -1.52     3.17     .220    960.00     -9.66     -2.13     -3.43      -.20    -28.17     -1.63
         3.60   3452.94     41.75     -.464     -1.41     2.74     .188    960.00     -5.05      5.53     -5.09      -.20    -29.11     -1.86
         3.70   3549.34     45.67     -.393      -.79     2.17     .171    960.00      1.33      3.13     -5.45       .15     10.75      1.46
         3.80   3645.27     49.30     -.355      -.69     1.68     .202    960.00      4.62      3.51     -5.58       .55    -74.37     -2.09
         3.90   3739.79     52.19     -.380      -.05     1.07     .254    960.00      9.17      6.74     -6.15       .56     -3.30      1.58
         4.00   3837.69     54.75     -.446       .36      .52     .306    960.00     12.10      3.97     -5.65       .37    -83.45     -1.58
1                      File = 28x28basa.B.dat

                                                        SPRUNG MASS #  2
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      TIME  FORWARD   LATERAL   VERTICAL    ROLL       YAW     PITCH   FORWARD   LATERAL    ROLL      YAW       PITCH     LATERAL     ARTIC
      (SEC) POSITION  POSITION  POSITION    ANGLE     ANGLE    ANGLE    VEL       VEL       RATE      RATE      RATE      ACCN.       ANGLE
             (IN)        (IN)     (IN)      (DEG)     (DEG)    (DEG)   IN/SEC    IN/SEC    DEG/SEC   DEG/SEC   DEG/SEC   IN/SEC**2   DEG


          .00   -203.85       .00      .000       .00      .00     .000    960.00       .00       .00       .00       .00       .00       .00
          .10   -111.69       .00      .036       .00      .00    -.009    960.00       .00       .00       .00      -.17       .00       .00
          .20    -11.85       .00      .121       .00      .00    -.030    960.00       .00       .00       .00      -.19       .00       .00
          .30     84.15       .00      .142       .00      .00    -.036    960.00       .00       .00       .00       .08       .00       .00
          .40    176.32       .00      .060       .00      .00    -.018    960.00       .00       .00       .00       .26       .00       .00
          .50    272.32       .00     -.022       .00      .00     .003    960.00       .00       .00       .00       .09       .00       .00
          .60    368.33       .00      .007       .00      .00    -.002    960.00       .00       .00       .00      -.17       .00       .00
          .70    464.33       .00      .110       .00      .00    -.025    960.00       .00       .00       .00      -.26       .00       .00
          .80    560.33       .00      .183       .00      .00    -.044    960.00       .00       .00       .00      -.07       .00       .00
          .90    656.33       .00      .140       .00      .00    -.036    960.00       .00       .00       .00       .20       .00       .00
         1.00    752.33       .00      .035       .00      .00    -.013    960.00       .00       .00       .00       .21       .00       .00
         1.10    848.33       .00     -.006       .00      .00    -.002    960.00       .00       .00       .00      -.01       .00       .00
         1.20    948.18       .00      .054       .00      .00    -.013    960.00       .00       .00       .00      -.18       .00       .00
         1.30   1044.18       .00      .123       .00      .00    -.029    960.00       .00       .00       .00      -.10       .00       .00
         1.40   1140.18       .00      .123       .00      .00    -.030    960.00       .00       .00       .00       .07       .00       .00
         1.50   1236.18       .00      .077       .00      .00    -.020    960.00       .00       .00       .00       .09       .00       .00
         1.60   1332.18       .00      .060       .00      .00    -.017    960.00       .00       .00       .00      -.03       .00       .00
         1.70   1428.18       .00      .087       .00      .00    -.023    960.00       .00       .00       .00      -.08       .00       .00
         1.80   1524.18       .00      .106       .00      .00    -.027    960.00       .00       .00       .00       .01       .00       .00
         1.90   1620.19       .00      .078       .00      .00    -.020    960.00       .00       .00       .00       .11       .01       .00
         2.00   1716.19       .00      .041       .00      .00    -.011    960.00       .00      -.01       .00       .06       .17       .00
         2.10   1812.19       .01      .049      -.01      .00    -.012    960.00       .03      -.10       .02      -.08       .87       .03
         2.20   1908.19       .03      .100      -.03      .01    -.024    960.00       .13      -.32       .09      -.13      3.18       .10
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        2.20   1908.19       .03      .100      -.03      .01    -.024    960.00       .13      -.32       .09      -.13      3.18       .10
        2.30   2004.19       .10      .131      -.07      .02    -.033    960.00       .39      -.60       .24      -.02      7.78       .25
        2.40   2100.19       .27      .106      -.15      .06    -.028    960.02       .87      -.96       .51       .10     14.43       .49
        2.50   2196.20       .61      .055      -.26      .13    -.016    960.04      1.54     -1.39       .92       .11     22.67       .81
        2.60   2288.84      1.17      .025      -.42      .24    -.008    960.08      2.15     -1.72      1.41       .04     31.02      1.11
        2.70   2384.85      2.05      .030      -.58      .41    -.007    960.10      2.79     -1.66      1.97      -.05     35.77      1.33
        2.80   2480.86      3.34      .042      -.81      .64    -.009    960.13      2.86     -3.11      2.71      -.02     45.00      1.62
        2.90   2577.34      5.13      .022     -1.12      .95    -.004    960.16      2.86     -2.27      3.26       .01     56.43      1.75
        3.00   2673.34      7.35     -.014     -1.27     1.29     .005    960.19      2.50     -1.63      3.67       .02     52.25      1.81
        3.10   2768.83     10.16     -.072     -1.54     1.69     .018    960.16      1.23     -3.26      4.23       .02     52.37      1.79
        3.20   2865.75     13.56     -.096     -1.75     2.11     .022    960.14      -.14      -.51      4.13      -.19     55.83      1.46
        3.30   2961.69     17.32     -.065     -1.76     2.52     .013    960.08     -2.13      -.73      3.98      -.19     42.30      1.06
        3.40   3057.60     21.64     -.072     -1.90     2.91     .013    960.02     -4.47      -.97      3.69      -.08     41.51       .54
        3.50   3153.49     26.18     -.080     -1.80     3.22     .013    960.00     -6.37      2.70      2.63      -.12     24.28      -.06
        3.60   3249.38     30.89     -.068     -1.54     3.44     .010    959.99     -8.56      2.00      1.70      -.07      6.55      -.70
        3.70   3345.74     35.74     -.040     -1.32     3.55     .005    960.01    -10.27      3.07       .48      -.12     -3.08     -1.38
        3.80   3441.64     40.37      .031      -.91     3.53    -.010    960.00    -11.37      4.38     -1.01      -.14    -24.65     -1.85
        3.90   3536.12     44.73      .087      -.50     3.37    -.021    960.06    -11.44      4.42     -2.26      -.07    -30.89     -2.30
        4.00   3633.98     48.83      .113       .03     3.06    -.027    960.07    -10.58      5.66     -3.63      -.02    -49.62     -2.54
1                      File = 28x28basa.B.dat

                                                        SPRUNG MASS #  3
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     TIME   FORWARD  LATERAL  VERTICAL    ROLL      YAW     PITCH  FORWARD  LATERAL     ROLL      YAW      PITCH    LATERAL     ARTIC
    (SEC)   POSITION POSITION POSITION    ANGLE    ANGLE    ANGLE    VEL      VEL       RATE      RATE      RATE     ACCN.      ANGLE
             (IN)      (IN)     (IN)      (DEG)    (DEG)    (DEG)  IN/SEC   IN/SEC   DEG/SEC   DEG/SEC   DEG/SEC  IN/SEC**2   DEG


         .00   -647.67       .00      .000       .00      .00     .000    960.00       .00       .00       .00       .00       .00       .00
         .10   -555.51       .00      .001       .00      .00     .000    960.00       .00       .00       .00      -.01       .00       .00
         .20   -455.67       .00      .002       .00      .00    -.001    960.00       .00       .00       .00       .00       .00       .00
         .30   -359.67       .00      .001       .00      .00     .000    960.00       .00       .00       .00       .02       .00       .00
         .40   -267.50       .00     -.003       .00      .00     .002    960.00       .00       .00       .00       .01       .00       .00
         .50   -171.50       .00     -.005       .00      .00     .002    960.00       .00       .00       .00      -.01       .00       .00
         .60    -75.49       .00     -.001       .00      .00     .000    960.00       .00       .00       .00      -.02       .00       .00
         .70     20.51       .00      .004       .00      .00    -.002    960.00       .00       .00       .00      -.01       .00       .00
         .80    116.51       .00      .005       .00      .00    -.002    960.00       .00       .00       .00       .01       .00       .00
         .90    212.51       .00      .001       .00      .00     .000    960.00       .00       .00       .00       .03       .00       .00
        1.00    308.51       .00     -.005       .00      .00     .002    960.00       .00       .00       .00       .01       .00       .00
        1.10    404.51       .00     -.005       .00      .00     .002    960.00       .00       .00       .00      -.02       .00       .00
        1.20    504.36       .00      .000       .00      .00     .000    960.00       .00       .00       .00      -.02       .00       .00
        1.30    600.36       .00      .004       .00      .00    -.002    960.00       .00       .00       .00       .00       .00       .00
        1.40    696.36       .00      .003       .00      .00    -.001    960.00       .00       .00       .00       .02       .00       .00
        1.50    792.36       .00      .000       .00      .00     .001    960.00       .00       .00       .00       .01       .00       .00
        1.60    888.36       .00     -.002       .00      .00     .001    960.00       .00       .00       .00       .00       .00       .00
        1.70    984.36       .00     -.001       .00      .00     .001    960.00       .00       .00       .00      -.01       .00       .00
        1.80   1080.36       .00      .000       .00      .00     .000    960.00       .00       .00       .00       .00       .00       .00
        1.90   1176.37       .00     -.001       .00      .00     .000    960.00       .00       .00       .00       .00       .00       .00
        2.00   1272.37       .00     -.001       .00      .00     .000    960.00       .00       .00       .00       .00       .01       .00
        2.10   1368.37       .00      .001       .00      .00     .000    960.00       .00      -.01       .00      -.01      -.01       .00
        2.20   1464.37       .00      .002       .00      .00    -.001    960.00      -.01      -.07       .01       .00      -.16       .01
        2.30   1560.37       .01      .002      -.02      .00     .000    960.00      -.06      -.23       .02       .01      -.38       .02
        2.40   1656.37       .03     -.001      -.05      .00     .001    960.02      -.16      -.52       .05       .01      -.41       .05
        2.50   1752.38       .06     -.003      -.13      .01     .001    960.04      -.32      -.95       .12       .00       .08       .12
        2.60   1845.03       .11     -.003      -.24      .03     .001    960.08      -.55     -1.45       .24      -.01      1.27       .21
        2.70   1941.04       .21      .000      -.41      .06     .000    960.11      -.82     -1.92       .42      -.01      4.64       .35
        2.80   2037.05       .38      .003      -.62      .12    -.001    960.15     -1.09     -2.26       .70      -.01      8.19       .52
        2.90   2133.55       .66      .005      -.87      .20     .000    960.19     -1.55     -2.75      1.01      -.01     12.00       .74
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