DEVELOPMENT OF A STEER AXLE TIRE BLOWOUT MODEL
FOR TRACTOR SEMITRAILERS IN TRUCKSIM

THESIS

Presented in Partial Fulfillment of the Requirements for the Degree Master of Science in the Graduate School of The Ohio State University

By

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The Ohio State University

2013

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ABSTRACT

Tractor Semitrailer handling is one of the key issues in today’s highway traffic safety research. When accidents happen with tractor semitrailers, possibilities of multiple vehicle crashes are always high. Thus it is important to study the handling and control of tractor trailers in accident scenarios. Tire blowout is one of the most common types of failure which may cause vehicle crashes. With experimental testing for such studies being expensive, vehicle dynamic simulation goes a long way in supplementing the capabilities of real field testing.

The primary goal of this thesis is to develop a tire blowout model for a tractor semitrailer in TruckSim™. Experimental data from a left steer axle tire blowout of a tractor trailer is considered for modeling. The effect of tire blowout on vehicle dynamic aspects of the tire like rolling resistance, effective rolling radius, vertical stiffness and other tire forces are studied. The tractor semitrailer model is developed from previously conducted braking simulation models in TruckSim.

From the experimental data, the behavior of the tractor trailer and the left steer axle tire are studied. A tire blowout model for the left steer axle of the tractor is created within TruckSim for simulation. The process of the blowout is split into discrete steps for simulation. Transient tire models are created to simulate the conditions of the left steer axle tire during the transient period of the blowout. These tire models are swapped at the
appropriate time steps to create a tire blowout sequence. The entire experimental maneuver is simulated in TruckSim by importing measured driver input data like vehicle speed, brake chamber pressure and steering input.

Simulink is used as an interface to transfer simulation data from TruckSim to MATLAB workspace. All analysis and data processing are carried out in MATLAB workspace. The results obtained from TruckSim simulation are compared with the experimental results and data from HVE simulation. Error analysis is done to identify areas of disagreement between experimental and simulation model and reasons identified. From the validated blowout model, similar models are created and simulations carried out for trailer and drive axles to qualitatively study tractor trailer behavior under these conditions. From the observed results, conclusions are derived and scope for further development of this model is presented.
DEDICATION

To my father
who always believes in me and never tells no

To my mother
who always pushes me to achieve more

To my grandfather
for being such an inspiration in life
ACKNOWLEDGMENTS

At this point I would like to acknowledge a number of people for their help and support without whom this thesis would not have seen the light of the day. Submitted under one name, this thesis is actually a product of team effort. To start with, my academic advisor, Prof. Dennis A. Guenther was the pillar of my graduate career. Supporting me throughout my graduate research with his expertise, help and most important of all, his faith towards me, he helped me in bringing the best out of myself. Dr. Gary Heydinger, as my adjunct advisor was always there when I needed him for any technical queries. His in-depth knowledge and urge for perfection was an important component in the success of this research.

Special mention must go to Dr. Ashley Dunn, SEA Ltd., who guided me throughout this research at all times of the day and stayed back to help me finish my work beyond his normal work hours. I would like to thank my fellow graduate students Sage Wolfe, Joshua Every, Scott Zagorski, Sughosh Rao and Shreesha Rao, OSU for sharing their TruckSim knowledge and being a wonderful group to work and have lunch with. I would also like to thank all engineers and staff at SEA Ltd., Columbus for their help and support.

Thanking my father, Veeraraghavan Chakravarthy and mother Ramamani, who never said no for anything I asked and put up with all my nonsense throughout these 23 years and for years to come, is the least I can do. Finally I would like to thank my
friends, whom there are too many to list here for their love, support and being a source of inspiration for me.
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2007 to 2011........................................... Bachelor of Technology(B.Tech),

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1.1 Motivation

Tractor-semi-trailers continue to be one of the most efficient and flexible modes of cargo transport in the USA. According to the National Highway Traffic Safety Administration’s (NHTSA) statistics, in the year 2009, large trucks were involved in approximately 3,215 fatal crashes accounting for 7.1% of the total number of fatal crashes occurring in the USA [1]. In the year 2010, fatalities in crashes involving large trucks increased by 9% from 2009 [2]. Also Tractor-trailers create a very dangerous environment for other vehicles on the road if not driven safely. In the year 2010, more than 82% of fatal vehicle crashes involving large trucks were multiple vehicle crashes clearly illustrating the dangers posed by tractor-trailers [2]. This called for detailed study, experimental testing and development of simulation models of different driving scenarios to understand model deficiencies and give feedback to the product development cycle.

Tire blowout is one of the most common failure scenarios in accidents involving tractor-trailers and multiple experimental testing has been done in this regard to study the vehicle dynamic behavior and driver response in such cases. S-E-A Ltd., a forensic engineering company specializing in failure analysis, research and testing conducted a set of experimental blowout tests at the Transportation Research Center (TRC) facilities at East Liberty, Ohio with an International 9400i SBA truck pulling a 2000 Trailmobile
tandem axle flatbed semitrailer. Properties of the tractor semitrailer are discussed in Chapter 2.

Not many vehicle dynamics simulation software have the capabilities to simulate and analyze vehicle response in a tire blowout scenario. The primary goal of this research was to simulate a tire-blowout model for TruckSIM, a robust vehicle dynamics simulation software for trucks and tractor trailers, based on the previously conducted experiments. By understanding the behavior of tire properties in the event of a blowout, similar subroutines were created for tires of different axles and the response of the tractor trailers analyzed.

1.2 Past Studies

Various experiments and studies have been done in the past with respect to tractor-trailers to analyze and understand its vehicle dynamic behavior and develop simulation models of different dynamic components under different conditions. Though experimental testing had been carried out across different automotive platforms with respect to tire blowout, not much has been done on the simulation front.

Dr. Dale Andreatta et.al [3] studied the time taken for a tire to get completely deflated for given initial conditions. Through their research, they developed simple mathematical models to predict the internal pressure of the tire as a function of time in case of a blowout. The model was developed based on the assumption that the air flow out of the orifice of a tire occurs in two phases namely choked flow and subsonic flow.
The model took into account the volume of the tire, atmospheric pressure and area of cross section of the orifice.

William Blythe et.al developed a complete 3-Dimensional simulation model of a tire-blowout for general vehicles for the Engineering Dynamics Vehicle Simulation Model (EDVSM) software [4]. This model involved developing maps for cornering stiffness, camber stiffness, radial tire stiffness, rolling resistance and aligning torque during the transient period of a tire-blowout. A complete new module was created as an add-on to the EDVSM software to simulate tire blowout at any wheel at any given time during simulation. Various maneuvers were also performed to study parametric effects of the tire-blowout model.

Zbigniew Lozia had studied the HVE blowout model proposed by Blythe et.al [4] and had used the model to test biaxial vehicle motion after a tire blowout [5]. His tests involved fine tuning the studied model and using it in steady state circular motion and ramped angular steering input on a biaxial vehicle. The HVE blowout was performed for inner and outer wheels in circular motion and the text discussed the effects with similar maneuvers without tire blowout.

Dr. Ashley Dunn had previously developed a braking model for tractor-semitrailers in normal conditions for his doctoral dissertation [6]. Jiantao Deng in his Masters’ thesis [7] had created TruckSIM models of the tractor trailer and analyzed braking performance under different load and braking conditions. He used the braking torque models developed by Dr. Ashley Dunn for his analysis.
1.3 Objective

The primary objective of this research was to develop a tire blowout routine to simulate a left steer axle tire blowout in a tractor semi-trailer on TruckSIM on a straight ahead constant speed and the braking maneuver was under the Half Gross Combined Weight (HGCW) conditions. The simulation model, built in TruckSIM, uses a vehicle model built earlier to perform and study straight ahead braking behaviors under extreme braking with select brakes disabled. The model was then modified to suit the experimental testing conditions pertinent to the vehicle under consideration. A secondary objective of this project was to examine the blowout phenomenon from the calibrated model and apply it to the drive-axle and trailer axle wheels to simulate a blowout and study the vehicle behavior under standard test procedures. In conclusion, this research provides a detailed procedure for modeling a steer tire blow-out in a tractor semi-trailer and provides suggestions for further refinement of the model in TruckSIM.

1.4 Thesis Overview

Chapter 2 in this thesis focuses on the experimental field test data and the procedure of the actual blow-out test at TRC. It covers information on the tractor semitrailer and the test conditions too. It also discusses the experimental results obtained. Chapter 3 covers the TruckSim modeling section of the thesis. The first section of this chapter explains the previously generated TruckSIM model developed by Deng [7]. It also covers the main features of TruckSIM software and the limitations of the absence of a reliable tire blowout model.
The second section consists of a thorough description of the tire blowout subroutine and the design of the event procedure as conducted experimentally for the steer-axle tire blowout maneuver. In this, it covers the design of a tire blowout model from a TruckSIM point of view taking into account the parameters that could be modified in real time within TruckSIM. In the last section, a detailed description on the setup of the event procedure specific to the blowout test on TruckSIM is given.

In chapter 4, the discussion, sections provide a thorough analysis of the data from the simulation and provide comparisons with experimental data. In the first section, the discussion is focused on the post processing options available in TruckSim and the methodology employed in this research. It also discusses the data obtained from the simulation and the required filters for comparison with the experimental test data. In the second section, a detailed analysis of the results obtained from the simulation model along with an error analysis with respect to experimental conditions is presented. In the third section, the results obtained from the secondary simulations are discussed along with the observations in the final section of this chapter.

Finally, Chapter 5 draws conclusions from the simulations and validation of the model with respect to TruckSIM. Observed dynamic characteristics in secondary simulations are shown and discussed. In addition, suggestions for further studies in blowout modeling and refinements to the model are given.
CHAPTER 2 EXPERIMENTAL TEST DATA AND TRUCKSIM VEHICLE MODEL

2.1 Experimental Test Vehicle

The test vehicle used in this research consisted of a 2006 International 9400i 6X4 conventional tractor, pulling a 2000 Trailmobile 2-axle, 48-foot (14.6 m) long, flat bed semitrailer. The vehicle is shown in Figure 1. During the tire blowout test, the left steer axle tire was compromised. Weights were placed on the semitrailer to achieve the axle weights similar to those seen in typical use. This vehicle was loaded to half the Gross Axle Weight rating i.e., 52000 lbs. The vehicle was loaded using calibrated weights at the Transportation Research Center in East Liberty, Ohio.

The vehicle brakes had been properly maintained and were in good working order at the time of the tests. The only brakes to be applied during the test procedure were the trailer brakes and it was activated using a hand lever by the driver. The vehicle was equipped with tires that were in generally good condition, that were properly inflated and exhibited adequate tread depth at the time of the test.
Figure 1 Image of tractor semitrailer immediately after the left steer axle tire was compromised

Table 1 and Table 2 list all the properties of the tractor and semitrailer.
Table 1 Vehicle Information for the 2006 International 9400i 6X4 tractor

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross Vehicle Weight Rating (GVWR) (lb)</td>
<td>52,000</td>
</tr>
<tr>
<td>Unloaded Curb weight (lb)</td>
<td>17,523 (includes fuel)</td>
</tr>
<tr>
<td>Wheelbase (in)</td>
<td>236</td>
</tr>
<tr>
<td>Front Suspension</td>
<td>12,000 # 2 Leaf Spring</td>
</tr>
<tr>
<td>Rear Suspension</td>
<td>40,000 # Pneumatic</td>
</tr>
<tr>
<td>ABS System</td>
<td>Bendix 4s/4m w/ trailing axle side control</td>
</tr>
<tr>
<td>Steer axle tires</td>
<td>275/80R22.5 Michelin Pilot XZA2 rib</td>
</tr>
<tr>
<td>Drive axle tires</td>
<td>295/75R22.5 Goodyear G372LHD</td>
</tr>
<tr>
<td>Engine</td>
<td>Cummins ISX series 435 hp</td>
</tr>
<tr>
<td>Mileage at beginning of test (mi)</td>
<td>281,337</td>
</tr>
<tr>
<td>Parameter</td>
<td>Value</td>
</tr>
<tr>
<td>------------------------------------------------</td>
<td>--------------------------------------------</td>
</tr>
<tr>
<td>Gross Vehicle Weight Rating (GVWR) (lb)</td>
<td>80,000</td>
</tr>
<tr>
<td>Approximate Unloaded Curb Weight (lb)</td>
<td>12,000</td>
</tr>
<tr>
<td>Wheelbase (in)</td>
<td>Variable</td>
</tr>
<tr>
<td>Track width f/r (in)</td>
<td>77.5</td>
</tr>
<tr>
<td>Lead axle suspension</td>
<td>20,000 # 2-Leaf spring trailing arm</td>
</tr>
<tr>
<td>Trailing axle suspension</td>
<td>20,000 # 2-Leaf spring trailing arm</td>
</tr>
<tr>
<td>ABS system</td>
<td>Eaton 2S1M</td>
</tr>
<tr>
<td>Lead axle tires</td>
<td>11R22.5 Goodyear / Bridgestone mix</td>
</tr>
<tr>
<td>Trailing axle tires</td>
<td>11R22.5 Goodyear / Bridgestone mix</td>
</tr>
<tr>
<td>Mileage at beginning of test (mi)</td>
<td>22,701</td>
</tr>
</tbody>
</table>

**2.2 Test Facility**

The test facility was the concrete Skid Pad at the Transportation Research Centre (TRC), located in East Liberty, Ohio. The Skid Pad is a 84-ft by 9000-ft facility and contains 5 smooth lanes for braking flanked by two lanes used for rough road durability testing [1]. The section of the Skid Pad that was used in this testing, the braking lanes, was measured to have nominal ASTM peak and slide traction levels of 0.93 and 0.82, respectively. A representative sketch of the Skid Pad is shown in Figure 2.
2.3 Experimental Test Procedure

The vehicle was accelerated to an initial test speed of approximately 55 mph on the Skid Pad. The left front tire was suddenly blown without the driver being warned, by an engineer with a switch. The switch passed an electrical signal through a slip ring on the left front steer position, which in turn fired an explosive charge and triggered the data acquisition system. The operator of the tractor-semitrailer was not aware exactly when the impending tire failure would occur, but was instructed to maintain control of the
vehicle at all times. This was to replicate the real world response of the driver and record the corresponding handling of the vehicle.

Following the blowout, the operator removed his foot from the accelerator pedal and steered the vehicle slightly to maintain control. Approximately 5 seconds after the tire was blown, the test driver began to apply the trailer brakes and slow the combination vehicle to a controlled final rest position. The tractor brakes were never applied after the blowout event occurred. The vehicle was outfitted with several data acquisition sensors and systems as discussed in the recorded data section.

2.4 Recorded Data

The initial speed and the integrated stopping distance were registered by the Labeco 625 track test unit which uses a precision built fifth wheel assembly and a performance monitor. Apart from this the following parameters were measured:

1. Tractor position (x, y and z) near the Centre of Gravity (CG).
2. Longitudinal, lateral, and vertical accelerations (Ax, Ay and Az) near the CG of the semitrailer.
3. Longitudinal and Lateral accelerations (Ax and Ay) near the CG of the tractor.
4. Tractor roll, yaw and pitch angles and rates.
5. Semitrailer roll, yaw and pitch rates.
6. Tractor speed in the longitudinal and lateral directions (Vx and Vy) near the CG.
7. Semitrailer longitudinal and lateral speed (Vx and Vy) and composite (resultant) speed.
8. Individual wheel speeds on the tractor and semitrailer.
9. Brake pressures on the semitrailer right axle #4
10. Tractor Primary and Secondary control pressures.
11. Semitrailer control pressure.
12. Tractor drive axle brake stroke (1 brake).
13. Hand wheel steer angle.

Tractor dynamic parameters (speeds, accelerations, rate of rotations) were digitally recorded from an OXTS RT-3000 GPS-based inertial measurement unit (IMU) mounted near the tractor’s unloaded C.G. Semitrailer dynamic parameters (accelerations and rates) were measured via a Crossbow 6-axis IMU that was mounted halfway between the kingpin and rear tandems, on the lateral centerline of the semitrailer.

Semitrailer speeds were measured at the same location using a Datron 2-axis Optical fifth wheel. Brake pressures were measured using calibrated pressure gauges. Wheel speeds on all ten axles ends were measured via DC tachometers and filtered with a 10-Hz, zero-phase digital low pass filter that emulates a 12-pole Butterworth. Brake pressure signals were similarly low pass filtered at 15 Hz. Steering wheel angle angles were also recorded by a Sensor Developments instrumented hand-wheel.

2.5 Experimental results

The test results showed that the sudden failure of the left steer axle tire on the test vehicle was a controllable event. The experimentally measured speed profile throughout the event of the combined vehicle is shown in Figure 3. The time of recording of data
starts 4.92 seconds before the blowout and therefore the time of blowout is taken as origin for all measurements.

Figure 3 Combined Longitudinal Speed (Vx) of Vehicle with time

There was continuous throttle input from the driver from the start time of recording the data until about 3 seconds after the blowout. Throughout this period the driver as instructed was attempting maintain the vehicle at about 55 mph. Also we can note that the vehicle speed starts decreasing even under the control of the driver after the blowout. About 3 seconds after the blowout, the driver stops accelerating the vehicle and the vehicle starts coasting to about 50 mph for the next 2 seconds. At approximately 5
seconds after blowout, the driver applies the trailer brakes and the longitudinal speed of the vehicle starts decreasing rapidly from then till 10 seconds, the time to which vehicle dynamics data were recorded.

The yaw rate response, which significantly determines the handling of the vehicle post failure, gives an interesting picture. The yaw rate of the tractor measured is shown in Figure 4.

![Figure 4 Yaw rate of Vehicle vs Time](image)

**Figure 4 Yaw rate of Vehicle vs Time**

The steering input data recorded is presented in Figure 5. Immediately following the blowout, there was a period of approximately 1 second after which the yaw velocity reached approximately 2.5 degrees per second. This increase in yaw velocity resulted in a
slight but measurable counterclockwise rotation of the vehicle. After the driver’s perception and reaction to the blowout, the steer angle that the driver utilized to control the combination vehicle was increased to approximately 40 degrees to the right for a brief duration of approximately 1 second to arrest the counterclockwise yaw motion. For the subsequent approximately 2 seconds that steering input to the right resulted in a slight clockwise yaw velocity.

![Steering angle vs Time](image)

**Figure 5 Steering Angle measured vs Time**

Approximately 3 seconds after the tire failure, the steering wheel angle was held more constant at approximately 25 degrees to the right; however, the yaw velocity
returned to nominally 0 degrees per second. At this point, the vehicle was in a post-failure steady-state condition and was traveling in a straight line. The average deceleration from the tire blowout and engine drag was less than 0.03 g's for the 5 seconds following the tire failure prior to the application of the trailer brakes.

The overall effect of these dynamic parameters on the vehicle trajectory is shown in Figure 6. It is a trace of the vehicle path which was taken from the GPS system attached to the vehicle. The Skid Pad is oriented in a Geographical Northwest – Southeast direction and the GPS co-ordinates recordings were initially with respect to true geographical North. The heading of the vehicle was measured and the co-ordinates were transformed to the x-y plane of the Skid Pad. The Skid Pad frame of reference has the longitudinal orientation as x-axis and lateral orientation as y-axis.

With respect to SAE vehicle co-ordinates, the x-axis of the plot is the longitudinal axis of the vehicle and the y-axis is the lateral axis of the vehicle. The vertical axis of the vehicle goes into the x-y plane. From the plot we observe that, over the total recorded longitudinal distance of approximately 1053 ft., the vehicle was maintained in a near straight line by the driver. The lateral displacement of about 16 ft. was caused due to the slightly clockwise yaw velocity over the duration of 2 seconds explained earlier.
Figure 6 Transformed vehicle trajectory in the Skid Pad frame of reference
CHAPTER 3 TRUCKSIM MODEL AND BLOWOUT MODEL

3.1 TruckSim Software Overview

TruckSim is a software package for simulating and analyzing the behavior of heavy trucks and combination vehicles in response to steering, braking and acceleration inputs. It uses a modular and open architecture for modeling and simulating vehicle dynamic responses and allows the user to build and modify dynamic subsystems and components and perform runs in a 3-D environment. The basic TruckSim package used in this research has pre-programmed data of almost all the major trucks and combination vehicles in dynamically linked libraries.

Each component is defined by a dataset. These datasets are classified based on the components and the kind of attributes they have. The relations between these components are predefined in the datasets and this linkage follows a hierarchical manner. Thus, a dataset of a tractor tire could only be opened through the particular tractor dataset and is stored under the tires subsection. Since these follow a hierarchical manner, any modification to the subsystem or parameter of a component affects the entire hierarchy of the vehicle model dataset and all other vehicle models under which the particular component is linked. Therefore, duplication of a subsystem requires duplication of every parent subsystem and their datasets individually.
Events to run the vehicle and the post processing tools are also defined by datasets and classified by their own attributes. In the events part, events are classified based on the combination of steering, acceleration and braking and standard NHTSA vehicle dynamic tests specified. The desired output parameters to be studied also in many cases determine the classification of events. TruckSim also combines events to give procedures and new procedures could be created by modifying the above mentioned events and combining them on a timeline.

The post processing section of TruckSim consists of two parts. First, the animation section animates the entire procedure or event that the vehicle undergoes and replicates the kinematics and dynamics of all major subcomponents on a scaled 3D environment. Second, the plots section plots all major parameters usually required in a vehicle dynamic analysis. The plot datasets are classified based on the parameter type and the component type of the output parameters.

Apart from this, real time input and output of data and parameters during simulation can be done from the TruckSim environment to other environments like Simulink. These are useful for Hardware In the Loop (HIL) testing where data from a real-time subcomponent experiment is used. Likewise Software In the Loop (SIL) testing can be done, where some vehicle dynamic phenomena could be programmed in a different environment like the working of the Anti-Lock Braking System (ABS) on Simulink.
3.2 TruckSim Tractor Semitrailer model

In this section, a detailed description of the tractor semitrailer model based on Jiantao Deng’s model [7] is given. The TruckSim vehicle model was created using direct measurements and estimated parameters on an International 9400i tractor and the 2-axle semitrailer. Throughout this research, this vehicle model under half-payload condition was used as the base model to create a tire blowout sub-routine for the left steer-axle tire. In some cases, like road conditions, dynamic behaviors of sub components and suspension and compliance parameters default values were used. The experimentally recorded steering wheel input, brake chamber pressure and measured speed were imported to the test event and used as input directly. The ABS model and brake torque models were replicated from Deng’s model with minor modifications which is explained in detail in the ABS and Brakes subsection. Vehicle output data, including vehicle speed, yaw rates etc. were transferred to MATLAB workspace via Simulink for post processing and analysis.

3.2.1 Wheelbase

The wheelbase and track width of the vehicle were directly taken from the manufacturer’s specifications to assure accuracy. Tractor-semitrailer axle position dimensions are shown in Table 3. Tractor and Semitrailer wheelbases were measured from the center of each tandem.
### Table 3 Tractor Semitrailer Axle Locations

<table>
<thead>
<tr>
<th></th>
<th>Wheel base</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inches</td>
<td>Millimeters</td>
</tr>
<tr>
<td>Steer Axle</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; &amp; 2&lt;sup&gt;nd&lt;/sup&gt; Drive Axle</td>
<td>236</td>
<td>5994</td>
</tr>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt; &amp; 2&lt;sup&gt;nd&lt;/sup&gt; Trailer Axle</td>
<td>442</td>
<td>11226.5</td>
</tr>
</tbody>
</table>

The exact distances of the tandem drive axles from the steer axle were calculated from the wheel radius and the clearance from the two wheels.

**Figure 7 Screenshot of the Tractor dataset**

Figure 7 shows the Tractor dataset modeled for this research. The exact distances of the tandem drive axles from the steer axle is presented. The dynamic relations between
the subcomponents in the tractor are defined internally in the tractor dataset based on the type of the tractor chosen.

3.2.2 Mass Properties

Unsprung mass is the mass of components that are not supported by the suspension. Some unsprung mass properties are included in Table 4.

<table>
<thead>
<tr>
<th></th>
<th>Unsprung mass (kg)</th>
<th>Axle Roll &amp; Yaw Inertia (kg·m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steer Axle</td>
<td>527</td>
<td>612</td>
</tr>
<tr>
<td>1st Drive Axle</td>
<td>1004</td>
<td>579</td>
</tr>
<tr>
<td>2nd Drive Axle</td>
<td>973</td>
<td>584</td>
</tr>
<tr>
<td>1st Trailer Axle</td>
<td>735</td>
<td>586</td>
</tr>
<tr>
<td>2nd Trailer Axle</td>
<td>735</td>
<td>593</td>
</tr>
</tbody>
</table>

The sprung mass is the mass supported on the axles by the suspension. To better understand the sprung mass definition, the sprung mass equation is shown in Equation 3.1.

\[
M_{sprung\ mass} = M_{GVW} - M_{steer\ unsprung} - M_{Drive\ unsprung} - M_{Trailer\ unsprung}
\]

(Eq. 3.1)

Where:

\[
M_{sprung\ mass} = \text{sprung mass}
\]

\[
M_{GVW} = \text{Gross Vehicle Weight of tractor-semi trailer}
\]

\[
M_{steer\ unsprung} = \text{unsprung mass of steer axle}
\]
The sprung mass properties of the tractor are mentioned in Table 5

### Table 5 Sprung Mass properties of Tractor model

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sprung Mass</td>
<td>6483 kg</td>
</tr>
<tr>
<td>Centre of Gravity (CG) Height</td>
<td>1070 mm</td>
</tr>
<tr>
<td>Roll Inertia ($I_{XX}$)</td>
<td>6879 kg-m²</td>
</tr>
<tr>
<td>Pitch Inertia ($I_{YY}$)</td>
<td>21711 kg-m²</td>
</tr>
<tr>
<td>Yaw Inertia ($I_{ZZ}$)</td>
<td>19665 kg-m²</td>
</tr>
</tbody>
</table>

Figure 8 shows the tractor sprung mass dataset explaining the co-ordinate system and the mass properties as input parameters.
The sprung mass properties of the semitrailer are derived from Deng’s model and are presented in Table 6.
### Table 6 Sprung Mass properties of Semitrailer model

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sprung Mass</td>
<td>5927 kg</td>
</tr>
<tr>
<td>Centre of Gravity Height</td>
<td>1000 mm</td>
</tr>
<tr>
<td>Roll Inertia ($I_{xx}$)</td>
<td>9959.7 kg-m²</td>
</tr>
<tr>
<td>Pitch Inertia ($I_{yy}$)</td>
<td>171336 kg-m²</td>
</tr>
<tr>
<td>Yaw Inertia ($I_{zz}$)</td>
<td>179992 kg-m²</td>
</tr>
</tbody>
</table>

The sprung mass dataset of the semitrailer is in Figure 9. It is important to note that the CG of the semitrailer entered in this dataset is with respect to the semitrailer dataset.

![Figure 9 Sprung Mass dataset of Semitrailer](image)
The origin of the tractor coordinate system starts at the steer axle. The coordinates of the CG of tractor are defined in the sprung mass dataset of the tractor with respect to the steer axle as shown in Figure 8. Next, the location of the hitch/fifth wheel is also defined with respect to the steer axle of the tractor as mentioned in the Tractor dataset in Figure 7. The co-ordinate of the hitch is taken as the origin of the semitrailer in the sprung mass dataset of the semitrailer (Figure 9). From this, the coordinates of the CG of the sprung mass and the semitrailer axles are measured.

3.2.3 Modeling Half GVW condition

The Half of maximum Gross Vehicle Weight condition is modeled by adding weights to the semitrailer. Each weight could be added as a payload dataset to the semitrailer. This dataset has the following parameters.

a) Mass of the payload.
b) Dimensions of the payload.
c) Centre of Gravity of the payload.

Other properties like Roll inertia, Pitch inertia and Yaw inertia are calculated from these properties. These payloads are treated as separate to that of the sprung mass of the trailer but internally used along by TruckSim for calculations. This is to calculate the sagging of the sprung mass due to changes in load distribution. The parameters of the load are illustrated as in Table 7.
Table 7 Payload parameters

<table>
<thead>
<tr>
<th></th>
<th>Payload 1</th>
<th>Payload 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (kg)</td>
<td>3978</td>
<td>5967</td>
</tr>
<tr>
<td>Height of CG (mm)</td>
<td>1575</td>
<td>1575</td>
</tr>
<tr>
<td>Length (mm)</td>
<td>1574</td>
<td>4089</td>
</tr>
<tr>
<td>Breadth (mm)</td>
<td>1828</td>
<td>1828</td>
</tr>
<tr>
<td>Height (mm)</td>
<td>610</td>
<td>610</td>
</tr>
<tr>
<td>Longitudinal Distance of CG (mm)</td>
<td>200</td>
<td>10500</td>
</tr>
</tbody>
</table>

The height of the CG mentioned here is the height of the CG from the trailer bed in the z-direction. Similarly, the longitudinal distance of the CG is the distance of the CG of the payload from the hitch of the semitrailer.

3.2.4 TruckSim Coordinate System

TruckSim has its own vehicle axis system which differs from the SAE (Society of Automotive Engineers) standard. Figure 10 and Figure 11 are representations of the TruckSim and the SAE vehicle axis system.
Figure 10 TruckSim Coordinate System (courtesy: TruckSim)

Figure 11 SAE Vehicle Axis System (courtesy: Fundamentals of Vehicle Dynamics, T.D. Gillespie)
3.2.5 Wheels and Tires

The international 9400i tractor was equipped with 22.5 inch diameter wheels. The drive axles had dual wheels. The dual wheel spacing was 328 mm measured from the center to center distance between adjacent dual tires.

The tractor-semitrailer was mounted with a total of 18 tires with dual tires mounted on drive and semitrailer axles. The steer axle was mounted with 275/80R22.5 Michelin Pilot XZA2 RV tires. The drive axles were mounted with 295/75R22.5 Goodyear G372 line haul drive tires. Four different tires were used on the semitrailer axles. They were Bridgestone 11R22.5 14PR R194 and Goodyear 11R22.5 G362, G314, and G357. Since the tires mounted on the steer axle and semitrailer axles were similar, they shared the same set of tire properties in the TruckSim simulation. Table 8 presents the spring rates and rolling radius on the tractor-semitrailer tires.

Table 8 Tractor Semitrailer Tire Spring Rates and Effective Rolling Radius

<table>
<thead>
<tr>
<th>Axle</th>
<th>Effective Rolling Radius (mm)</th>
<th>Spring Rate (N/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steer</td>
<td>491</td>
<td>980</td>
</tr>
<tr>
<td>Drive</td>
<td>481</td>
<td>980</td>
</tr>
<tr>
<td>Trailer</td>
<td>491</td>
<td>980</td>
</tr>
</tbody>
</table>
3.2.6 Brake Torque Model and ABS Model

TruckSim allows users to import brake torque models in the simulation. The brake torque used in this simulation was derived from models developed in previous studies by Dr. Ashley Dunn [6]. The brake torque was modeled as a quadratic function of brake pressure. For this simulation, the brake torque curve for 60mph was used. It is worth mentioning that the brake torque output used in this simulation was based on constant coefficients that were based on braking initial speed. Thus the brake torque versus pressure relationship does not change with respect to speed in the TruckSim environment. The current setup is accurate since this is how braking reacts in a real truck braking application.

Since only the trailer brakes were employed during braking after the blowout, modifications were applied only to the trailer brakes model. Figure 12 shows the quadratic brake torque model for the trailer axles at 60mph.
Figure 12 Quadratic Brake Torque Model for Semitrailer Axle Brakes at 60mph

The ABS used in this simulation was based on the inbuilt ABS model in TruckSim. The initial tuning of this system was done by Deng in his braking research. But since the tractor brakes were never employed and only trailer brakes were used, all of the brake chamber force was directed to the trailer brakes. The ABS controller works by turning OFF the trailer brakes when the slip ratio coefficients reach 0.08 and turning the brakes back ON when the slip ratio drops below 0.06. The ABS controller turns off (all brakes on) when the vehicle speed drops below the specified cut-off. The Fluid Dynamics Time Constant and Fluid Transport Delay were also modified from the default
value of 0.3 sec to 0.1 sec. This modification could be attributed to the use of trailer only braking model.

### 3.2.7 Suspension

The suspension stiffness parameters used in the simulation were chosen from Deng’s model. Deng’s model uses the National Highway Traffic Safety Administration (NHTSA) spring data for compression and extension of the steer axle, drive axle and trailer axle springs. The TruckSim shock absorbers damping coefficients are linear and identical for both left and right sides on all axles and have a value of 30 kN-s/m. Figures 13, 14 and 15 show the spring data of steer, drive and trailer axles respectively. For the steer and trailer axles the values were taken for a standard static vertical load of 12,000 lb and 20,000 lb respectively. For the air springs used in the drive axle suspension data from 5 different vertical static loads were used for a broader value range.
The vertical load values used for the air spring in drive axle are 12,000, 18,000, 24,000, 30,000 and 35,000 lbs respectively.
Figure 14 Spring data for Drive Axle Air Suspension
3.3 Tire Blowout model

TruckSim by itself does not have a tire blowout model and all tires in TruckSim have the same static and dynamic properties throughout the simulation since these are predefined in their datasets. But TruckSim allows the user to change the tire datasets during any time of simulation any number of times. This means that if the properties of
the blown tire are known, then one can easily replace the normal tire at any axle and side uniquely with the blown tire.

Now we know from Dr. Dale Andreatta’s research [3] that the time taken for a tire to blowout completely is dependent on the initial conditions of tire like initial tire pressure and volume of the tire tube. For a similar simulation of the tire blowout in Human Vehicle Environment (HVE) by Anthony Cornetto et.al [8], which was done in parallel to this research, the time taken for the tire blowout to occur completely was estimated at 0.5 sec. Thus swapping of tire dataset at the left steer axle at a single instant doesn’t account for the tire dynamics during the transient time. It produces a shock at the hub of the left steer axle from the tire blowout effect. To overcome this, the transient time range of 0.5 sec was split into 10 equal parts. Tire datasets were created with properties that the blowing tire would have at each of these time steps and the tires were swapped at these instants sequentially. This gives a relatively fair transition of the left steer axle tire from a fully inflated tire to a fully deflated tire.

3.3.1 Parameters affected in a Tire Blowout

During a tire blowout many tire parameters that significantly affect the dynamics and handling of the vehicle change. In this section we will discuss how each of these parameters changes during a blowout.

The most important change when a tire deflates is the decrease in internal tire pressure or inflation of the tire. Vehicle dynamic parameters like cornering stiffness, camber stiffness, radial Tire stiffness, rolling resistance and Self-Aligning torque of the
vehicle get affected significantly by the change in the Tire pressure. Also the effective radius of the tire also reduces with time. With respect to the vertical tire stiffness, the stiffness drops initially before it starts increasing at the final stages when the tire layer starts to get in contact with the wheel rim [4]. The variation in parameters as deduced by William Blythe is shown in Figure 16.

![Figure 16 Tire parameters variation in a blowout [4]](image)

From the HVE simulation [8], we know that the vertical stiffness of the vehicle increases 100 times more than the initial value after the tire blowout. The final effective radius of the fully deflated tire was taken as the rim radius of the wheel. The effective radius was linearly reduced between these two values over the 10 different tire datasets.
The values of the vertical tire stiffness and effective rolling radius of the different transient tire models are noted in Table 9 and the corresponding graphic data shown in Figure 17.

**Table 9 Effective rolling radius and Vertical Stiffness of the Transient tires**

<table>
<thead>
<tr>
<th>Tire number</th>
<th>Time instant after blowout when employed for simulation (sec)</th>
<th>Effective Rolling radius (mm)</th>
<th>Vertical Stiffness (N/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inflated normal tire</td>
<td>0</td>
<td>491</td>
<td>980</td>
</tr>
<tr>
<td>Tire 1</td>
<td>0.05</td>
<td>471.9</td>
<td>700</td>
</tr>
<tr>
<td>Tire 2</td>
<td>0.10</td>
<td>452.8</td>
<td>500</td>
</tr>
<tr>
<td>Tire 3</td>
<td>0.15</td>
<td>433.7</td>
<td>300</td>
</tr>
<tr>
<td>Tire 4</td>
<td>0.20</td>
<td>414.6</td>
<td>300</td>
</tr>
<tr>
<td>Tire 5</td>
<td>0.25</td>
<td>395.5</td>
<td>300</td>
</tr>
<tr>
<td>Tire 6</td>
<td>0.30</td>
<td>376.4</td>
<td>3000</td>
</tr>
<tr>
<td>Tire 7</td>
<td>0.35</td>
<td>357.3</td>
<td>10000</td>
</tr>
<tr>
<td>Tire 8</td>
<td>0.4</td>
<td>338.2</td>
<td>50000</td>
</tr>
<tr>
<td>Tire 9</td>
<td>0.45</td>
<td>319.1</td>
<td>90000</td>
</tr>
<tr>
<td>Tire 10</td>
<td>0.5</td>
<td>300</td>
<td>98000</td>
</tr>
</tbody>
</table>
The cornering stiffness of the tire decreases with the reduction in tire pressure [4]. This parameter is represented in the tire dataset as a Lateral Force map in TruckSim. This 3D graph maps the Absolute Lateral Tire Force with respect to Tire Slip angle for different vertical loads. For our simulation, the values in this map were scaled down in the fully blown tire by a factor of 10. The values for the transient tires were linearly scaled down accordingly. The Lateral Force maps for the fully inflated tire and fully deflated tire are shown in Figure 18 and Figure 19.
Figure 18 Absolute Tire Force Map for a fully inflated Tire
The self-aligning torque of the tire increases with decrease in tire pressure [4]. This parameter is represented in TruckSim directly as a 3D map recording the Aligning moment (N-m) with respect to Tire slip angle and Vertical Load. The Aligning Torque Maps in TruckSim for the Fully Inflated Tire and Fully Blown out tire are shown in Figure 20 and 21 respectively. The maps were scaled linearly between these two limits for the transient tires.
Figure 20 Aligning Torque Map for a fully inflated tire
The Rolling resistance of the tire increases with the deflation of the tire [4]. This occurs due to the increased surface area of contact of the tire with the road surface and the change in component of sliding friction. In TruckSim the rolling resistance of the tire is given as a linear function of the velocity of the tire. The coefficients of this relation are modified in this simulation to describe the increase in rolling resistance. In TruckSim, the force due to rolling resistance is given by equation 3.2.
Where, $M_{RR}$ is the Rolling resistance moment, $F_Z$ is the vertical load on the tire, $R_{RE}$ is the effective rolling radius and $R_{RC}$ and $R_{RV}$ are the rolling resistance coefficients of TruckSim. A linear increase in the coefficients is employed and the values are as given in Table 10.

### Table 10 Rolling resistance coefficients for various transient tire models

<table>
<thead>
<tr>
<th>Tire</th>
<th>Time instant after blowout when employed for simulation (sec)</th>
<th>$R_{RC}$</th>
<th>$R_{RV}$ (h/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fully Inflated Tire</td>
<td>0</td>
<td>0.0041</td>
<td>0.0000256</td>
</tr>
<tr>
<td>Tire 1</td>
<td>0.05</td>
<td>0.01025</td>
<td>0.000064</td>
</tr>
<tr>
<td>Tire 2</td>
<td>0.10</td>
<td>0.0164</td>
<td>0.0001024</td>
</tr>
<tr>
<td>Tire 3</td>
<td>0.15</td>
<td>0.02255</td>
<td>0.0001408</td>
</tr>
<tr>
<td>Tire 4</td>
<td>0.20</td>
<td>0.0287</td>
<td>0.0001792</td>
</tr>
<tr>
<td>Tire 5</td>
<td>0.25</td>
<td>0.03485</td>
<td>0.0002176</td>
</tr>
<tr>
<td>Tire 6</td>
<td>0.30</td>
<td>0.041</td>
<td>0.000256</td>
</tr>
<tr>
<td>Tire 7</td>
<td>0.35</td>
<td>0.04715</td>
<td>0.0002944</td>
</tr>
<tr>
<td>Tire 8</td>
<td>0.4</td>
<td>0.0533</td>
<td>0.0003228</td>
</tr>
<tr>
<td>Tire 9</td>
<td>0.45</td>
<td>0.05945</td>
<td>0.0003712</td>
</tr>
<tr>
<td>Tire 10</td>
<td>0.5</td>
<td>0.0656</td>
<td>0.0004096</td>
</tr>
</tbody>
</table>
The tire dataset in TruckSim also allows for defining the dynamic properties of
the tire like Wheel spin moment of inertia, and distance rolled to achieve the response.
The values were modified to a value of 0 for all the transient tire models since the tire
changing time step is 0.05 sec and these tire models are used only in that time step. The
camber stiffness of the tire though decreasing is very less in magnitude when compared
to the other forces. Therefore it did not have much effect on the model and the default
TruckSim camber stiffness map was retained for all tire models.

3.3.2 The Tire Blowout subroutine

From the above tire models a tire blowout subroutine specific to the left steer axle
could be created as an event in the Procedures section of TruckSim. First the left steer
axle of the tractor needs to be identified. This is possible because there is a unique code
for all components of a Vehicle in TruckSim. The tractor is defined as <UNIT 1> while
the subsequent trailers are identified as Unit 2 and 3 and so on. The steer axle is the first
axle in tractor and is identified as <AXLE 1>. With respect to the sides of the axle, the
left side is identified as Side 1 and the right side as Side 2. In case of dual tires, looking
into the longitudinal direction of the vehicle the left tire is Tire 1 and right tire is Tire 2.
Therefore the left steer axle of the tractor trailer is mentioned as,

IUNIT 1
IAXLE 1
ISIDE 1
ITIRE 1.

45
This code when mentioned in the text section of the event identifies the corresponding parsfile (parameter file of a dataset) of the tire and replaces it with the dataset of the tire mentioned in the event.

A screenshot of the event dataset of the first swap is shown in Figure 22. These event datasets could be combined to a single dataset that initiates all the ten tire swap events at the appropriate time. Thus the entire left steer axle tire blowout could be modeled as a single event subroutine as shown in Figure 23.

![Event dataset of swapping the tire at 1st time step](image)

**Figure 22 Event dataset of swapping the tire at 1st time step**
3.4 Modeling testing Procedure

The entire test simulation was modeled as a series of events in a single procedure dataset. For compatibility with the experimental data output and the HVE simulation output the blowout was designed to occur at simulation time 0 sec and the simulation actually started from -4.92 sec. TruckSim gives the option for the vehicle to follow a given speed profile and the experimental vehicle speed was input for the vehicle to follow until blowout. The clutch was disengaged for the vehicle to follow its own speed after 3 sec at which time it was assumed that the driver removed throttle input in the experimental test. The brake chamber pressure recorded was input directly to the event as an open loop input. This is shown in Figure 24.
With respect to the steering input, the data was transformed to TruckSim vehicle axis system and fed as an open loop steer input by the driver. This is shown in Fig 25.
The tractor brakes which are in the ON position by default in TruckSim was used for speed control initially and switched off at -1 sec from the blowout. This is done by individually turning the brake pressure in the brake chamber to zero at each tire using the above mentioned tire identifying nomenclature. Therefore 6 datasets each for switching off the brake pressures of the 6 tires in the tractor axles were created and were combined into a single tractor brakes disengaging dataset as shown in Figure 26.
Figure 26 Tractor brakes disengaging dataset

A screen shot of the complete procedure dataset is shown in Figure 27. Also a pic of the TruckSim animation of the Tractor semitrailer model with after the blowout is presented in Figure 28. Note the deflated left steer axle of the tractor.
Figure 27 The Complete blowout procedure dataset

Figure 28 TruckSim animation of the Tractor Semitrailer with the Steer axle tire blowout
CHAPTER 4 RESULTS AND DISCUSSION

4.1 Post Processing Methodology

There are multiple ways to post-process the simulation data from TruckSim for further analysis and study of vehicle dynamic behavior. There is the in-built Post processing section that allows for plotting vehicle dynamic parameters as well as to animate the entire maneuver to visualize the simulation. Results of multiple simulations could be compared in the same plots to study outcomes of different cases. The same is applicable for animation too, where multiple cases could be animated in the same environment and compare the kinematics subjectively.

The plotting section is an extensive post processing tool that allows study of more than a hundred different parameters from brake chamber pressures to yaw rates of tractors and trailers. Each of these parameters is classified based on their vehicle dynamic aspect. Each of these parameters has its unique TruckSim name by which it is identified. One can also set a new group of these parameters for comparison.

The other way is to transfer the required data from the TruckSim environment to MATLAB workspace and post process in MATLAB. Transferring data to MATLAB has lot of advantages. First, all of MATLAB’s data processing capabilities which are absent in TruckSim could be used for performing analysis beyond TruckSim’s traditional capabilities. Secondly, and most importantly, real world experimental data and simulation data from a variety of other Vehicle Dynamic software cannot be imported onto
TruckSim. This renders the comparison of the simulation model with the experimental model practically impossible.

To transfer the simulation data from TruckSim to MATLAB, Simulink was used as an interface. TruckSim has a Simulink interface function that can send all of real time simulation data to TruckSim through a single channel. Through Simulink, these could be transferred onto MATLAB workspace as arrays and can be used for analysis. The Simulink file for this simulation is shown in Appendix 1. The experimental and the HVE data for this blowout test were imported onto the MATLAB environment in .mat format. The time intervals at which the experimental and HVE data were collected were 0.01 sec. The TruckSim simulation is run at 0.001 sec and transferred to MATLAB at 0.005 sec interval by Simulink setting. For further reduction, a MATLAB code was written to condense the data for the same time points as that of experimental and HVE data. The source code is added in Appendix B.

The data exported onto MATLAB are:

1. Longitudinal Speed of Tractor and Trailer
2. Lateral Speed of Tractor and Trailer
3. Simulation time.
4. Yaw rate of Tractor and Trailer.
5. X and Y coordinates of Tractor and Trailer.
7. Wheel speeds of left and right steer axle wheels.
4.2 Left Steer Axle Tire Blowout Simulation Results

Simulation accuracy is judged based on both experimental results as well as with the tested existing inbuilt blowout model in HVE for this maneuver. The steer angle data are presented in Figure 29, where the TruckSim simulation data are co-plotted against the experimental and HVE data. It is important to note that the steering wheel angle in Figure 29 is given in SAE coordinates. With TruckSim’s vehicle coordinates being different, the actual modified steering wheel angle input given is shown in Figure 30.

![Steering Input vs Time](image)

**Figure 29** Steering Wheel angle measured reading from field test, TruckSim and HVE simulations.
Linear interpolation was used for finding intermediate points. In the figures 31, 32, 33, 34 the tire blowout is marked by a vertical black line at time $T = 0$. Figure 31 shows the speeds of the simulated tractor semitrailer compared to the recorded test speed. The difference between the recorded speed of the test vehicle and the longitudinal speeds of the simulated test vehicle was no more than 0.6 mph during the 15 seconds of recorded data.
time. This is shown in Figure 32 which gives a plot of longitudinal speed error of the simulated vehicles with recorded test speeds with time.

![Longitudinal Speed vs Time](image)

**Figure 31 Longitudinal Speed of the Tractor Semitrailer with time**

From Figure 31 and Figure 32 we can see that the vehicle speeds of the simulated vehicle and the recorded test speeds are almost same. The deviation on speed starts to occur from 3 seconds after the blowout, which by itself is very minimal and is confined to, as stated above, 0.6 mph. This could be attributed to the random selection of disengagement of the clutch at 3 seconds after blowout since the actual time at which the driver stops applying the throttle is not accurately known.
During the same time, the largest difference between the lateral speed of the simulated vehicles and the test vehicle was no more than 0.5 mph as shown in Figure 33. The lateral speed error of the vehicle has remained positive throughout the simulation. And this later tends to reduce with time.
Figure 33 Lateral Speed Error vs Time

Figure 34 shows the yaw velocity of the simulated tractor and the test tractor illustrating a similar response to the steering inputs and the tire blowout event. Interestingly, neither the HVE nor the TruckSim simulations reproduced the approximately - 2.5 degree/second peak in yaw rate experienced by the test vehicle approximately 1 second after the actual blowout.
At this point it is important to note that the magnitudes of yaw rates recorded here are extremely small compared to the values experienced in day to day driving of heavy trucks. More experiments need to be conducted with yaw rates of higher magnitudes to more thoroughly study vehicle dynamic effects.

The trajectories of the tested and simulated vehicle CGs are plotted on an X-Y grid in Figure 35. The relative lateral position, which is a function of lateral speed and yaw velocity, differed by less than 1 foot between the simulated vehicle and the test vehicle in case of HVE and about 3 feet in the case of TruckSim.
The difference in the relative longitudinal position (versus time) of the simulated and test vehicles, which is predominately a function of vehicle speed, was less than 0.3 feet in the case of HVE (see Figure 36). The higher error in the TruckSim model of approximately 1.6 feet could be attributed to the discretized blowout model, and the higher longitudinal speed error. The vehicles covered a total longitudinal distance of approximately 1053 feet during the event from the start of data recording, which is 4.92 seconds before the blowout.
A plot of the brake chamber pressures of all the brake cylinders (Figure 37) shows us the working of operation of the braking system in this maneuver. We can clearly see that the pressure from the master cylinder goes only to the 4 wheels in the trailer and the tractor brakes remain disengaged. Also the operation of the ABS is clearly seen. As mentioned earlier, the ABS model used in Deng’s research was used as the basis and with the absence of data on the ABS present in the actual test vehicle, comparisons in braking is not possible.
4.3 Trailer Axle Blowout Simulation

With the tire blowout model and methodology discussed earlier for the steer axle tire, a similar model was created for the trailer axle tires. This was used to qualitatively study the vehicle response of the same tractor trailer model in a step turn during blowout. Both left and right side trailer wheels were blown in separate simulation cases. In both cases, the dual wheels were blown together. The maneuver consisted of the tractor trailer initially travelling in a straight line at speed of 31 mph. After 2 seconds a steering wheel angle input of 180 degrees is given and is then maintained throughout. 3 seconds into the
turn, the duals tires at either side of the leading trailer axle are blown and the vehicle is maintained in a closed loop speed control system with the steer input still on.

It is important to note here that since the wheels of the axle are dual, the tire blowout subroutine in TruckSim needs to be modeled separately for each of the two tires and initiated. Since the tire models used in the trailer axles were the same as the models used for the steer axle blowout, the same set of transient tire models were used for simulation. In the absence of experimental test data for these maneuvers a quantitative detailed analysis of vehicle dynamic parameters is impossible. Therefore the left and right trailer axle tire blowout simulations are compared to a normal case where the tractor semitrailer completes the step turn maneuver without any tire failure.

From the trajectory plot (Figure 38) we can see that when the trailer tire gets blown in a counterclockwise circular maneuver, the vehicle starts laterally deviating towards the direction of the blowout. When the left trailer axle tire is blown, initially the trailer yaws away from the normal design path but pulls the tractor into the direction of turn thus making a smaller turn. When the right trailer axle tire is blown, the trailer continues to yaw in counterclockwise direction and the trailer moves away from the design path and makes the turn with much larger turning radius. From the yaw rate plots (Figure 39 and Figure 40), the effect of outer trailer tire failure seems to have more effect than that of the inner tire.
Figure 38 Trailer Axle Tire Blowout Trajectories

In all the cases below, the black vertical line represents the time of blowout.
Figure 39 Yaw rates of the tractor and semitrailer in left trailer axle dual tire blowout

Figure 40 Yaw rates of the tractor and trailer in the right trailer axle dual tire blowout
4.4 Drive Axle Blowout Simulation

In this section, the methodology used for trailer axle blowout was employed on the drive axle of the tractor trailer to qualitatively observe the effect of the drive axle blowout in a step steer maneuver. In this case the left leading drive axle tires and right leading drive axle tires were blown for analysis and compared with a normal counterclockwise step steer maneuver without any tire compromise.

From the trajectory plot of the three cases (Figure 41) we can see that when either of the drive axle tires is blown, the vehicle tends to yaw more in the direction of the turn. When the left leading drive axle tires are blown, the vehicle tends to yaw more than when the right leading drive axle tires are blown in a left step steer maneuver. The Yaw rate plots for the three cases (Figure 42 and Figure 43) confirm this aspect. Without experimental data, it is difficult to validate these outcomes.
Figure 41 Vehicle trajectory plots for leading drive axle tire blowout

Figure 42 Yaw rates of Tractor and Trailer in Left Drive Axle Dual tire Blowout
4.5 Comparison between Single Tire and Dual Tire Blowouts

Since both trailer tires and drive axle tires were dual, the idea of comparing the dynamics of a single wheel blowout and dual wheel blowout turned out to be an interesting avenue of analysis. In this case, the left leading trailer axle was taken into consideration. Only the outer tire was blown for the same counterclockwise circular maneuver and path (Figure 44) and yaw rates (Figure 45) compared.
Figure 44 Vehicle Path for Leading Trailer Axle Left Single and Dual Wheel blowout

Figure 45 Yaw Rates of Tractor and Trailer for Left Leading Trailer Axle Single Wheel blowout and Normal tractor trailer
From this simulation we could see that the tire failure of a single wheel in a dual wheel axle does not greatly affect the vehicle dynamics much and the path and yaw rates of the tractor trailer in case of a single trailer axle wheel blowout remains the same as that of a normal tractor trailer. This may be attributed to the fact that, in case of dual wheel tires being compromised, the tire forces and effective radius at that wheel change completely. While in case of a single tire being compromised at one end of an axle, the other tire being inflated doesn’t allow the deflated tire to come in contact with the ground. Therefore neither does the tire force at that wheel change a lot nor is there a change in the trailer axle orientation.
CHAPTER 5 CONCLUSION

The aim of this research was to develop a tire blowout model for a Tractor Semitrailer in TruckSim and validate it using experimental data. With TruckSim’s cross platform capabilities with SimuLink and other vehicle dynamics software, it is possible to model an external tire blowout sequence and include it in every simulation. But one of the aims of this research was to model the blowout within the TruckSim environment itself. The research was successful in modeling a tire blowout subroutine for the left steer axle of a tractor semitrailer and validated it with experimental results.

First the experimental data and results were analyzed. Data from a parallel blowout simulation in HVE for the same test were also used in understanding the effects of a tire blowout. The various parameters that affect the vehicle dynamic aspect of the tractor trailer due to the tire blowout were identified and their phenomena studied. It was important to understand the working of TruckSim with respect to dataset relationships to identify the dependent parameters and the independent parameters.

Since it is not possible to create continuous functions for parameters to simulate the transient effects of the tire blowout, a discretization method was used. The transient period was split into equal time intervals and transient tire models for each of these intervals were created. Then an event sequence was used to initiate the swapping of the tire models during the period of blowout to simulate transient conditions. The vehicle
model used in this simulation was pre designed and tuned by Deng for his braking tests. To achieve accuracy of the model, the ABS and braking systems were modified to match the experimental conditions in this test.

Steering wheel input, throttle input and brake pressure input were imported from the experimental data set onto TruckSim and used directly with modifications to account for the change in coordinate system for TruckSim.

In general, TruckSim simulations provided good correlation with the full scale steer axle blowout test performed at 55 mph on a dry-road. This thesis shows that with appropriate input variables, it is possible to create a tire specific blowout subroutine within TruckSim itself and accurately simulate tire blowout events in it. Test data from only a single test run was available, so detailed quantitative evaluation of the accuracy and repeatability of the test data was not possible. The absence of accurate data on the driver throttle release and braking time likely contributed to some disagreement between the experimental and simulated data.

The steer axle tire blowout subroutine thus modeled was replicated onto trailer axle and drive axle tires to qualitatively study the effect of tire blowouts in tractor semitrailers. In the absence of experimental test data, the results of these simulations could not be validated. Since little literature exists with respect to tire blowouts, predicted vehicle dynamic changes in parameters and data from the available literature were used to model this steer axle blowout subroutine.

This model was carried on to simulate drive axle and trailer axle tire blowouts for standard step counterclockwise circular motion maneuvers and the vehicles’ paths and
yaw rates were analyzed. The effects of blowing outer wheel dual tires and inner wheel dual tires in circular motion were studied. Also comparison was carried out between dynamics of a single wheel tire blowout and dual wheel tire blowout on the tractor trailer.

Further refinement of this model is definitely possible. This includes measuring the exact time duration of the actual blowout and measurement of pressure loss and change in frictional characteristics of the tire after the blowout. These will go a long way in creating an accurate isolated TruckSim tire blowout subroutine. Further tests could be done to study the handling of vehicles due to blowout in other standard maneuvers like double lane change and fishhook maneuvers.

As of now tire blowout phenomena and its effects vary case to case and testing could be done to validate the blowout model in other conditions like curved path, change in payload and other truck types. These need to be supported with real time testing with the blown tire being instrumented to analyze tire blowout effects on the vehicle dynamic parameters like tire forces and moments. This will help in bringing out a more generic understanding of the phenomena and to predict its effects accurately using simulations.
REFERENCES

[1] NHTSA; “Highlights of 2009 Motor Vehicle Crashes”; DOT HS 811 363; National Center for Statistics and Analysis; Springfield; VA; 2010


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APPENDIX A - MATLAB CODE FOR PROCESSING AND PLOTTING TRUCKSIM DATA ALONG WITH EXPERIMENTAL AND HVE DATA

% Written by Krishnan V. Chakravarthy at OSU, January 2013.
%Loading HVE data
load('hve.mat');

%Loading Experimental data
load('exp.mat');

%Running the TruckSim steer axle blowout simulation via Simulink
sim('Vel_long.mdl');

blowt = [0 0];

%TruckSIM
offset = 2;
timet = zeros(1499,1);
vxt = zeros(1499,1);
vvt = zeros(1499,1);
xtr = zeros(1499,1);
yt = zeros(1499,1);
yawt = zeros(1499,1);
xnew = zeros(1499,1);
ynew = zeros(1499,1);

%Processing of TruckSim data
for i = 0:1498
    timet(i+1) = time_t(offset + (10*i));
vxt(i+1) = vx_t(offset + (10*i))/1.60934;
vvt(i+1) = vyt1_t(offset + (10*i))/1.60934;
xtr(i+1) = 5.2274 + xtrac_t(offset + (10*i))*3.28084;
yt(i+1) = ytrac_t(offset + (10*i))*3.28084;
yawt(i+1) = -yaw_t(offset + (10*i));
xnew(i+1) = xtrac_t(offset + (10*i))/0.3048;
ynew(i+1) = ytrac_t(offset + (10*i))/0.3048;
end
% first values
timet(1) = -4.92;
vxt(1) = vx_t(3)/1.60934;
vyt(1) = vy_t(3)/1.60934;
xt(1) = 5.2274 + xtrac_t(3)*3.2884;
yt(1) = ytrac_t(3)*3.28084;
yawt(1) = -yaw_t(3);
xnew(1) = xtrac_t(3)/0.3048;
ynew(1) = ytrac_t(3)/0.3048;

% error analysis
dvx_t = vxt - vx_e;
dvx_h = vx_h - vx_e;
dvy_t = vyt - vy_e;
dvy_h = vy_h - vy_e;
dyaw_t = yawt - yaw_e;
dyaw_h = yaw_h - yaw_e;

% Longitudinal speed
blowy = [30 55];
plot(time_e,vx_e,'r','linewidth',2);
hold on;
plot(timet,vxt,'linewidth',2);
plot(time_e,vx_h,'g','linewidth',2);
plot(blowt, blowy,'k','linewidth',2);
title('Longitudinal Speed vs Time');
legend('Experimental','TruckSIM', 'HVE', 'Blowout');
xlabel('Time (sec)');
ylabel('Speed (mph)');
grid on;
hold off;

% Yaw Rate
blowy = [-3 3];
figure;
plot(time_e,yaw_e,'r','linewidth',2);
hold on;
plot(timet,yawt,'linewidth',2);
plot(time_e,yaw_h,'g','linewidth',2);
plot(blowt, blowy,'k','linewidth',2);
title('Yaw Rate vs Time');
legend('Experimental','TruckSIM', 'HVE', 'Blowout');
xlabel('time (sec)');
ylabel('Yaw rate (deg/sec)');
grid on;
hold off;

% Longitudinal Speed error
blowy = [-1 1.5];
figure;
plot(timet,dvx_t,'linewidth', 2);
hold on;
plot(time_e,dvx_h,'r','linewidth', 2);
plot(blowt, blowy,'k', 'linewidth',2);
title('Longitudinal Speed Error vs Time');
legend('TruckSIM', 'HVE', 'Blowout');
xlabel('time (sec)');
ylabel('Longitudinal Speed Error (mph)');
grid on;
hold off;

% Lateral Speed error
blowy=[0 0.7];
figure;
plot(timet, dvy_t,'linewidth', 2);
hold on;
plot(time_e, dvy_h,'r','linewidth', 2);
plot(blowt, blowy,'k', 'linewidth',2);
title('Lateral Speed Error vs Time');
legend('TruckSIM', 'HVE', 'Blowout');
xlabel('time (sec)');
ylabel('Lateral Speed Error (mph)');
grid on;
hold off;

% Yaw rate error
blowy=[-1 3.5];
figure;
plot(timet, dyaw_t,'linewidth', 2);
hold on;
plot(time_e, dyaw_h,'r','linewidth', 2);
plot(blowt, blowy,'k', 'linewidth',2);
title('Yaw Rate Error vs Time');
legend('TruckSIM', 'HVE', 'Blowout');
xlabel('time (sec)');
ylabel('Yaw Rate Error (deg/sec)');
grid on;
hold off;
%Plotting vehicle trajectories
xnew = xnew + 2.0672;
y_e = -y_e;
figure;
blowt = [378.29 378.29];
blowy = [-100 100];
plot(xnew,ynew,'linewidth',2);
hold on;
plot(x_h,y_h,'g','linewidth',2);
plot(x_e, y_e,'r','linewidth',2);
plot(blowt, blowy,'k', 'linewidth',2);
title('Trajectory');
legend('TruckSIM', 'HVE','Experimental','Blowout');
grid on;
hold off;
dty = y_e - ynew;
dhy = y_e - y_h;
%end of code
Figure 46 Simulink File for Interfacing TruckSim and Matlab